May 2020

A Parametric Approach to Performative-based Design, Case Study: Earth Tube Ventilation

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A PARAMETRIC APPROACH TO PERFORMATIVE-BASED DESIGN, CASE STUDY:

EARTH TUBE VENTILATION

by

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A Dissertation Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

in Architecture

at

The University of Wisconsin-Milwaukee

May 2020

ABSTRACT

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The University of Wisconsin-Milwaukee, 2020
Under the Supervision of Professor D. Michael Utzinger

As integrated design becomes more prevalent, new workflows develop in the architectural industry. Rather than the traditional sequential pattern, the knowledge is now being applied in parallel. That is, unlike the old baton passing, the players including the architect, the engineer, the consultant, the contractor, etc. play their role simultaneously. To achieve this, an architectural ecosystem needs a compatible digital information exchange approach; an approach that involves the engineer in the strategic design of systems, increases the chances of more creative, more integrated and higher-performing systems.

There are some problems in the current parametric studies such as lack of inclusivity of all building physics facets, lack of validation, and lack of proper visualization in some cases. This dissertation intends to fill in these gaps by proposing a methodology to create a performance model integrated into a popular design tool, Rhinoceros 3D, of a rather rare ventilation system, the Earth Tube Ventilation. The idea is to keep all the simulation pieces in the same place that the 3D modeling happens. The model is further validated using the data from the experiments done on the Aldo Leopold Foundation building located close to Baraboo in Wisconsin. This process can be extended to other aspects of Performative Based Design.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to express my true gratitude to my advisor Professor Michael Utzinger for his unlimited support, flexibility and multi-dimensional perspectives on the subjects. I appreciate how he continuously provided insights on all aspects of the dissertation.

I would like to deeply thank my committee members, Professor Kyle Talbott, Dr. Alstan Jakubiec and Professor James Wasley, as well as Dr. Kevin Renken for their contribution to the direction and richness of this research. I would also like to thank David Bradley for his insights on the Building Simulation 2019 Paper. I would like to thank the Milwaukee I-Corps program team, Professor Brian Thompson, Dr. Ilya Avdeev, Professor Loren Peterson, and Scott Mosley. It has been an honor to work with them all.

I would like to extend my thanks to Joel Krueger, project architect at the Kubala Washatko Architects, Buddy Huffaker, director, and Steve Swenson, ecologist, at the Aldo Leopold Foundation for providing me access to information and their help in setting up the experiment.

I would like to express my appreciation to all my interviewees from different architecture and engineering consultant firms including the Eppstein Uhen Architects (EUA), The Kubala Washatko Architects (TKWA), the Zimmerman Architectural studios, the Tredo Group, the Henneman Engineering Inc., the Harwood Engineering Consultants, the Workshop Architects, the Thermal Energy System Specialists (TESS) LLC., the Foresight Home Performance, Inc., the Bergendy Cooke Architecture Studio (BC+A), the Eaton Hall Architecture (EHA), the Hammel, Green and Abrahamson (HGA), the Hellmuth, Obata + Kassabaum (HOK), the Anderson Brule Architects (ABA), the William Duff Architects (WDA) Inc., the Ring and Duchateau (RD) consulting engineers, the Quinn Evans Architects, the focus on energy group in WI, The Weidt Group Inc. (TWGI), the David Baker Architects (DBA), the K+S Architects (KS), the Ross Barney Architects (r-barc), the Quorum Architects and the Continuum Architecture and Design as well as the architecture faculty of the University of Wisconsin Milwaukee.

Last but not least, I would like to thank my family, my parents and my husband.

1. Introduction

1.1. Background

Over thousands of years, the inhabitants of the earth including human beings were used to the idea that they should adapt themselves to the situation they are living in. They had the power to make changes in their surrounding environment, but only to some extent. Hence, the best approach was to conform in a way that the surrounding situation is tolerable, or even desirable. The adapting technique was based on the very basic human instincts. If there is danger, hide or run. If it is cold, wrap something around yourself. If the sun is too hot, find a shade. If it is raining, stay dry.

After human beings started to settle down, the idea of adjusting themselves to the environment extended to the built environment as well. There was no mechanical help in any way, so they simply made the best out of what they had, nature. They observed nature and invented approaches to serve their needs the best way possible. These approaches were different according to the nature of the context, geography, climate. Maybe, that is why the vernacular architecture in similar climates looks the same, no matter what the regional culture is, because they followed their instincts and the potentials of environment and climate. In all hot arid climates, people tended to use thick layers of thermally massive material, which creates a time lag and serves best to the diurnal air temperature fluctuations. In many humid climates, people tended to maximize the airflow, through either the windows arrangement or wind catchers. In all cold areas, people tended to increase the wall thickness to amplify the thermal resistance of the wall.

The trend was predictable until people started to think more complexly, to invent more elaborate tools, to develop their ideas further than they used to, and finally, to get control over the environment. Instead of the environment controlling human life, now human started to be in charge and control of their surroundings. They started to make significant changes consequences of which were not all clear by then. Some major changes happened in the design of the built environment as well.

The advent of iron, steel, concrete and shift in structural materials, addition of environmental provisions such as chimneys and fireplaces, invention of lamps, eased the way towards controlling the environment.

One of these inventions was the duct. Little by little, the idea of using ducts in buildings became more prevalent. The possibility of producing energy in some place, and use it almost anywhere provided some unseen potentials for the architect. By the advent of ducts and shafts, one could transfer fresh air to any part of the building, and exhaust air from any specific point. Now, the architect could make any arrangements in plan without being much worried about how to provide air for each room. Although this approach cleared the way towards free plans, it also made the architecture more dependent on the shafts and ducts. The more it became dependent on mechanical elements, the further the architecture moved away from a traditional environmental-based design.

Moreover, mechanical engineers became part of the building industry. Gradually, architects got used to the idea that mechanical engineers are in charge of providing thermal comfort through fabulous systems they have. In this process, the architects started to leave that part for the engineers and focus more on the aesthetics, function and other facets of the building design. This was somewhat the start of the separation between disciplines. By leaving thermal comfort to mechanical engineers, the architects had more time to focus on aesthetics, behavioral studies, form, etc. This issue had the potential to separate architecture and engineering into two isolated disciplines. While over centuries, aesthetics had become embedded in nature-friendly design, now aesthetics started to grow apart from environmental issues.

In the United States after World War II, non-residential buildings began to be fully air-conditioned and sealed (no operable windows). At this time in Northern Europe most non-residential buildings were not air-conditioned and operable windows were required by building code. As architects and their design teams began to rethink design solutions for energy efficiency and to reduce carbon dioxide emissions. Sealed buildings began to be questioned and other possible design solutions for building ventilation began to be explored.

1.2. Problem Statement

If we consider integrated design and naturally or partly naturally ventilated buildings as a goal, there are different obstacles on the way. In fact, the trend to avoid natural systems is completely a multi-faceted problem, which requires a more advanced approach. In what follows, different aspects of the problem are mentioned, while I will be mainly focusing on one aspect: how to facilitate the study of the performance of one system in the design process.

Part of the problem is our mind presets. Mechanically-cooled buildings are so commonplace that many people assume that forced-air systems are the only option for efficiency and comfort. When we consider that building owners often incur enormous operating costs for mechanical ventilation and inhabitants usually give up personalized control of such systems, the reality rarely matches the expectation.

The main aspect of the problem seems to be more methodological. Architects and engineers have adopted a design method that leads to the perpetuation of forced-air solutions. In this approach, architects design the building volume, the siting, the shape of the envelope, and then forward it to the engineers at some grand mid-project pivot, which everybody works to conduct only once. Engineers then define ventilation requirements and stuff it all in the given envelope. The typical solution to ventilation design assumes that ventilation has no influence on building form and skin, and that engineers alone are responsible for ventilation design.

This methodological problem is even reflected in the way architecture is taught, i.e., the education. It is a routine to see architectural designs in studios, in which the whole approach to ventilation is just tagging a room as mechanical room. How could we shift into realizing that the HVAC systems are the last or at least part of the solution, which should compensate for the design not being dependent on itself to provide its own needs?

A major part of the methodological problem is related to the available tools during the design process. How much do these tools give us the opportunity and encouragement to consider incorporated passive systems early in the design process? While many of the software we use for drawing provide various icons for form-creation, they lack options for a performance-based approach. Even if there are options for performance evaluation, they are mainly considered as something that follows design, not something that starts the design, and the design is based upon.

The tool problem exacerbates when we notice architects and engineers operate in segregated digital worlds. For architects, their software products emphasize intuitive workflows – for engineers, logical and explicit decision-making. For architects, software empowers making and manipulating geometry – for engineers, the quantitative analysis of geometry. Each is alienated from the other's world in a manner that makes any real collaboration a bitter chore.

As you see, the problem has numerous facets each of which provides a new perspective to look at the problem. The focus of this dissertation is on finding a solution to the methodological problem, specifically, redefining the tool usage.

1.3. Research Significance

This dissertation attempts to answer the methodological problem by introducing a new tool and a new way of using this tool aligned with the existing ones. A new kind of digital tool for ventilation design will be introduced, one that encourages both intuitive play and scientifically rigorous results, simultaneously.

This research proposes a way to a schematic design which incorporates ventilation considerations earlier in the design process. Hopefully, this will bridge the methodological gap in the design process and will prepare a better platform for communications.

The idea behind this method is to keep all the simulation pieces in the same place that the 3D modeling happens, the Rhinoceros. One can design, visualize, evaluate, and even optimize the system in only one platform needless to switch between numerous software.

As a case in point, I studied an Earth Tube system in detail. It is a mechanical fan-based system by nature. However, it can be applied in a mixed ventilation mode. Also, it results in saving heating and cooling energy through passive sensible and latent heat transfer with the soil surrounding the building.

The methodology used here includes of creation of Python-based simulation components in the design software (Rhino), validation and finally optimization of the system is a process which can be extended to other aspects of Performative Based Design (PBD).

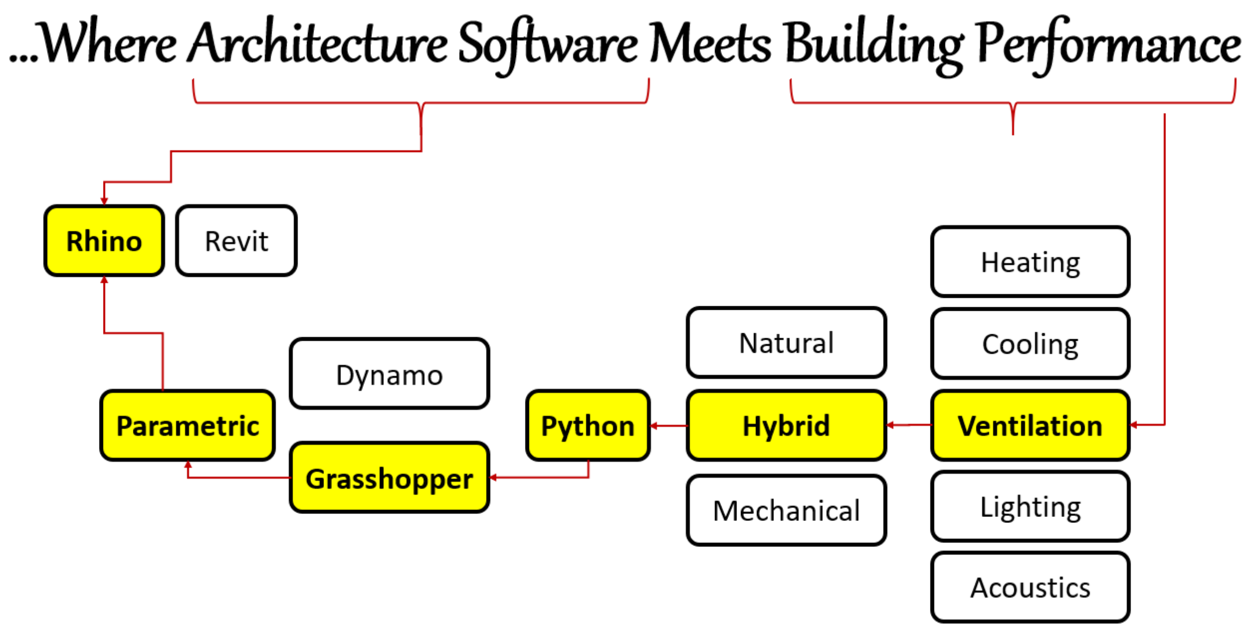

Figure 1. Dissertation Map

1.4. Research Questions

1. How does thinking about performative-based design influence the project methodology and workflow patterns?
2. How can we parametrically simulate natural and mechanical ventilation systems and how can we define a control strategy to model a hybrid ventilation system?
3. How can one design, simulate, validate, visualize and optimize an Earth Tube ventilation system?

1.5. Approach, Scope and Limitations

This research is interested in the performative-based design processes. Hybrid building ventilation systems are the specific focus of performative based building design processes explored in this dissertation. An Earth Tube ventilation system is used to explore the writing and validation of a performative based design component for the RHINO building design environment.

The building performance based design process and the digital technologies, are studied via the interviews with North American architects, engineers and sustainability consultants, as well as architecture professors and students.

For evaluation of natural, mechanical and hybrid ventilation systems, the connection of the parametric Earth Tube script with other existing codes in Grasshopper – mainly Ladybug and Honeybee – has been studied. A few scenarios have been defined in this regard.

To analyze the earth tube system, the Aldo Leopold Foundation building – which applies this system – has been monitored for over a year. Then, a mathematical bulk-flow model has been developed and validated by the collected data. Furthermore, a parametric script has been written in Python, as a series of

Grasshopper components, which not only generates the geometry of this ventilation system, but also calculates the energy saving due to using the Earth Tubes.

The limitation of the work is lack of financial support to provide high-quality measurement devices for the experiment.

1.6. Key Definitions

- **Acceptable indoor air quality:** air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.
- **Air conditioning:** the process of treating air to meet the requirements of a conditioned space by controlling its temperature, humidity, cleanliness, and distribution.
- **Air, ambient:** the air surrounding a building; the source of outdoor air brought into a building.
- **Air, exhaust:** air removed from a space and discharged to outside the building by means of mechanical or natural ventilation systems.
- **Air, indoor:** the air in an enclosed occupiable space.
- **Air, outdoor:** ambient air that enters a building through a ventilation system, through intentional openings for natural ventilation, or by infiltration.
- **Air, supply:** air delivered by mechanical or natural ventilation to a space, composed of any combination of outdoor air, recirculated air, or transfer air.
- **Air, transfer:** air moved from one indoor space to another.
- **Air, ventilation:** that portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable indoor air quality.

- **Conditioned space:** that part of a building that is heated or cooled, or both, for the comfort of occupants.
- **Contaminant:** an unwanted airborne constituent that may reduce acceptability of the air.
- **Natural ventilation:** ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building.
- **Odor:** a quality of gases, liquids, or particles that stimulates the olfactory organ.
- **Ventilation:** the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space.
- **Ventilation zone:** any indoor area that requires ventilation and consists of one or more occupiable spaces with similar occupancy category, occupant density, zone air distribution effectiveness, and zone primary airflow per unit area.

1.7. List of Acronyms

- **AIA:** American Institute of Architects
- **ALF:** Aldo Leopold Foundation
- **ASHRAE:** American Society of Heating, Refrigerating and Air-Conditioning Engineers
- **BIM:** Building Information Modeling
- **CD:** Construction Documents
- **CFD:** Computational Fluid Dynamics
- **CO_2:** Carbon dioxide
- **DD:** Design Development
- **DDX:** Design Data Exchange
- **epw:** EnergyPlus Weather data

- **EUI:** Energy Unit Intensity
- **HETS:** Horizontal Earth Tube System
- **HPB:** High-Performance Buildings
- **HVAC:** Heating, Ventilation & Air-Conditioning
- **IAQ:** Indoor Air Quality
- **LEED:** Leadership in Energy and Environmental Design
- **MSE:** Mean Squared Error
- **PBD:** Performative-Based Design
- **POE:** Post Occupancy Evaluation
- **RAIC:** Royal Architectural Institute of Canada
- **SANC:** Schlitz Audubon Nature Center
- **SBS:** Sick Building Syndrome
- **SD:** Schematic Design
- **TMY:** Typical Meteorological Year

2. Literature Review

2.1. Sustainability and Design Process in North America

Sustainability has various interpretations in architectural language. First, we should have a clear idea of what *sustainability* is. In what follows, early definitions and domains of the word are expounded.

The term “sustainable development” was first coined in the Brundtland Commission report in 1987. “Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.” (Our common future, 1987) The approaches proposed by the Brundtland Commission run the gamut of sustainable economic growth, food security, preservation of species and ecosystems, renewable energy and planetary management, which can be classified into three groups of economic, environmental and social equity.

Five years later, in 1992, an agenda on sustainable development was set in Rio de Janeiro, Brazil. The Earth Summit sets some agenda in four sections: social and economic dimensions, conservation and management of resources, strengthening the role of major groups and means of implementation (Keating, 1992). The four sections follow the main groups of the Brundtland report in a more practical approach.

In 1998, Andrew Scott, from the Massachusetts Institute of Technology declares that the *Dimensions of Sustainability* concerns a range of topical issues in architectural practice: ecology and evolution, real estate and the added value of green development, building typologies that harness natural systems, computer simulation and digital technologies, human rights regarding ecologically sustainable future, and so on (Scott, 1998). *Dimensions of Sustainability* describes examples of effective strategies in different contexts including ecological balance, economic performance , institutional capacity and viable governance (Choucri, 1998).

So far, it seems that the idea of being sustainable is applicable in various contexts. The Brundtland Commission, the Rio conference and the Dimensions of sustainability Symposium consider a broad framework for sustainability in an area where economy, environment and social studies overlap. As we entered the 21st century, the idea of sustainability gradually began to reflect into the design disciplines.

In 2001, Guy and Farmer defined six logics of sustainable architecture as eco-technic, eco-centric, eco-aesthetic, eco-cultural, eco-medical and eco-social. While the six disciplines are elaborated separately, they can overlap, merge, or coinhabit in a design (Guy and Farmer, 2001). In this dissertation, I consider the *techno-rational* approach with the goal of lower environmental impact and energy consumption.

In 2008, Owen and Dovey considered the field of sustainability architecture as *the green antinomy*, which tries to serve both fields of art and science. To win the game, one needs to get a feel for both. However, the paradox of the green antinomy, to play two games on the same field, remains unresolved because it is intrinsic to this field of practice (Owen and Dovey, 2008).

As of today, there does not exist a unanimous definition of sustainability in terms of design and architecture. Due to this dilemma, some authors and architects would rather not use the word *sustainable* and replace it with relatively more accepted terms such as *green* (Kwok and Grondzik, 2018).

This research does not attempt to provide a new definition of sustainable architecture but will investigate the shift in the workflow patterns in the architectural firms caused by environmental consciousness. After all, general awareness about sustainability has been raised. It seems more understandable *why* architects would consider sustainable conceptual ideas integrated with design. On the other hand, there are numerous fabulous buildings that have implemented sustainable approaches. What is still ambiguous is *how* these architects have been successful; *how* they have managed to achieve the goal. Should there be a shift in values, would there also be a shift in the way the architects work? *How* would the workflow paradigms switch to adjust with the new concepts? *How* does the methodology adapt?

AIA and RAIC

Let us look at two national architectural institution in North America, American Institute of Architects (AIA) and Royal Architectural Institute of Canada (RAIC) and their views on sustainability in architecture.

AIA and RAIC were founded more than 160 and 110 years ago, respectively. The environmental awareness and the idea of sustainable development were introduced years later. The two institutions have had made attempts to reflect these ideas into the architects' domain.

In 2002, a non-profit organization was founded called the Architecture 2030. They aim to alternate the role of architecture from a threat to the environment by being one of the main Greenhouse Gas (GHG) producers to a promise of solving the problem.

In 2006, Architecture 2030 initiated *The 2030 Challenge*. "The urban built environment is responsible for 75% of annual global GHG emissions: buildings alone account for 39%. Eliminating these emissions is the key to addressing climate change and meeting Paris Climate Agreement targets."[1] Architecture 2030 invites architects to implement innovative sustainable design strategies to achieve the goal of having Carbon-neutral buildings by 2030.

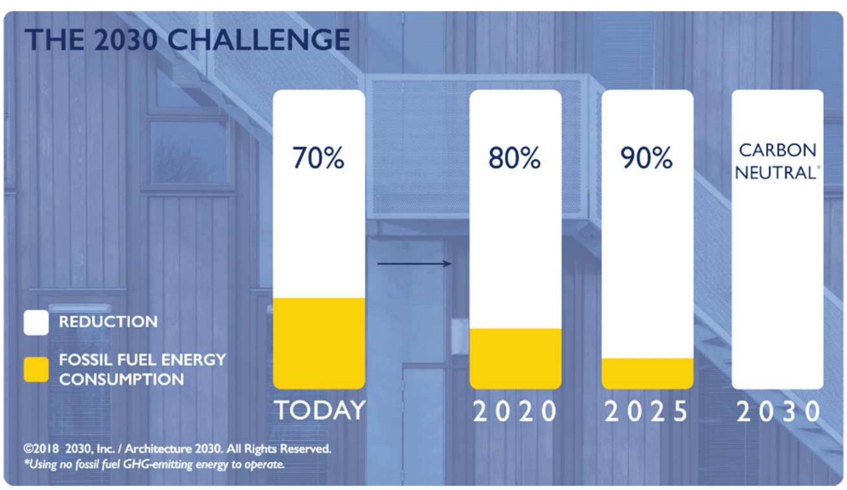

Figure 2. The 2030 Challenge

[1] https://architecture2030.org/2030_challenges/2030-challenge/, visited in February 2019

AIA's values in the last 160 years have included enhancing the nation's quality of life and protecting the public's health, safety and welfare. Today, AIA believes in climate change and advocates environmental protection policies encouraging the design, preservation and construction of High Performing Buildings.[2]

In support of the 2030 challenge, AIA established *The 2030 Commitment*[3], aimed to transform architecture practice into a more holistic one. However, only 2.3% of the AIA firm directory – 548 out of 23904 firms – have committed to energy efficient and carbon neutral design[4], at the time of writing this dissertation.

Advocating for responsible architecture is also an integral part of RAIC's mission. RAIC considers *Environmental Responsibility* as one of its main values: "The RAIC actively promotes sustainable design and operates in the most environmentally sustainable manner possible."[5]

In August 2016, energy efficiency seemed such a significant issue that RAIC and ten other organizations wrote a letter to the federal government of Canada to prepare a proactive plan to augment the energy efficiency of Canada's buildings. The recommendations suggested included modifying the national building code, developing national energy codes, changing tax policy and providing incentives and financial supports.[6]

In March 2018, RAIC presented the study of built environment and the building code in Canada to the Senate Standing Committee on Energy, the Environment and Natural Resources. In this report, some of the barriers were mentioned: "How projects are defined, how consultants are selected, and the relationships with clients all radically shape the potential outcome."[7] These are the items we need to challenge to find new workflow patterns in architecture firms which answer to the sustainability concerns.

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[2] https://www.aia.org/resources/5766-where-architects-stand-a-statement-of-our-va, visited in February 2019
[3] https://www.aia.org/resources/202041-the-2030-commitment, visited in February 2019
[4] https://www.aia.org/2030-directory?query, visited in February 2019
[5] https://www.raic.org/raic/vision-mission-and-values, visited in February 2019
[6] https://www.raic.org/news/raic-joins-call-national-plan-energy-efficient-buildings, visited in February 2019
[7] https://www.raic.org/news/raic-presents-senate-standing-committee-energy-environment-and-natural-resources, visited in February 2019

While the AIA and RAIC's missions regarding sustainability are quite valuable, they do not offer an alternative framework to help achieve the 2030 goals. AIA presents a national metric to quantify the progress which is called Design Data Exchange (DDx)[8]. It is like there is a target, and there are criteria to measure the progress, but there is not a guide on *how* to apply it in practice. We know the start point and we know the end point, but we have no idea of *how* the route looks like yet.

2.2. Parametric Performative Design

Traditionally, building performance evaluation was considered as a phase that follows design and comes after it. Form generation took priority over performance evaluation (Oxman, 2009). Maybe, performance evaluation could be described as a reaction to the design as the main action.

Current trends do not necessarily support this conclusion. New trends tend to prioritize performance in a performance-based design. Oxman considers performative design as an extension to performance-based design. In a performative design, the synthesis is the product of the analytical procedures in a generative process. Oxman claims that technology and advanced digital tools have supported this trend and have made the transition possible. She mentions that traditional CAD models were not capable of integrating the performance evaluation simulations in the process of design generation (Oxman, 2009).

In "Scripting Cultures", Mark Burry talks about new ways of exploring design by means of scripting. He makes sure to use the word "cultures" as a plural word in order that the innovative approach towards scripting would not be limited to a single defining culture (Burry, 2011).

Scripting has so many advantages in design. Although the design always remains at core, scripting will benefit the design process so much that one can consider it as a driving force for 21st century architectural

[8] https://www.aia.org/resources/202041-the-2030-commitment, visited in February 2019

thinking (Burry, 2011). These benefits include but are not limited to saving time, challenging standardization, realizing the potential of creativity, affording multiple outcomes, combining with digital fabrication, freeing the designers from software constrains and turning them into toolmakers rather than tool users.

While scripting is quite promising in all aspects of design process, it seems that scripting tools have mainly assisted the architects in form generation and pattern development. Now that the scripting tools have become more and more accessible, other applications of this tool seem not only possible but also a need. Different people have stated this need in their quotations. Robert Aish indicates that maybe it is time for scripting to become more integrated into design process and less of a distraction. Martin Tamke states that "An environment is missing that integrates representation and simulation-based approaches. It could, for example, connect modelling with physics-based behavior, scripted elements and the generated structure could still communicate as a whole to external environments." (Burry, 2011) Both Aish and Tamke are accentuating on the need for scripting to be integrated with other aspects of design and assist the entire process of design.

One of the applications of scripting is performance evaluation of the model. That is, we could integrate the idea of performative design with parametric design. In this case, not only the form generation happens through the parametric schema, but also the performance study of the prototypes could happen simultaneously. This could be beneficial in a few ways.

First, creating the geometric model and the performative model would happen at the same time. The designer would not need to provide two models. Therefore, future editing will be much more convenient since as soon as changes are made in one of them, the other one would be updated automatically. This causes a huge saving in time and energy for modeling.

Second, the virtual prototypes coming out of the schema not only cover the shape changes, but also run the gamut of performance-driving forces and evaluative criteria. That is, the prototypes can also reveal the merits and demerits in the performance of the model as well as its aesthetics.

Third, parametric performative design results in a holistic approach in which different aspects of the design will be updated simultaneously. This will make it harder for the designer to neglect any of the design factors. Any disadvantages would be divulged early in the process and can be addressed conveniently. The changes would reflect on all other aspects at the same time. Design process will be more integrated and more innovative as well as less time-consuming.

The idea of parametric performative design is highly growing and can integrate into advanced Building Performance Simulation which answers to different needs such as thermal, lighting, acoustic and ventilation performance. This dissertation focuses specifically on performative design of building ventilation systems.

2.3. Ventilation History, Typology and Precedent Analysis

History of Ventilation

While heating and cooling are rooted in human need to thermal comfort, ventilation concerns health. It is as early as the 5th century B.C. when early observations on the relationship between air and diseases were made by Hippocrates, the Greek physician and the “Father of Medicine”.

Awareness about breathing air quality turned into a topical issue in the 18th century. In his book, An *Essay concerning the Effects of Air on Human Bodies*, John Arbuthnot, M.D., quotes from Hippocrates that “It is incumbent on a physician to consider the Situation, Air, and Water of a city, in order to come at the knowledge of their popular diseases.”

In what follows in the book, there are examples cited from Hippocrates of how air and wind affect health. "For instance, that Cities exposed to the sun and winds being well perflated, at the same time supplied with wholesome water, are exempt from many diseases, which those in different circumstances are subject to." (Arbuthnot, 1733)

Hippocrates further scrutinizes the role of wind and moisture on length and severity of diseases in ancient cities. "… That Cities in Greece, shut up from Northerly Winds, were unhealthy; that in a dry Summer, diseases end sooner than in a wet one, in which they are obstinate." (Arbuthnot, 1733)

Arbuthnot meticulously examines Air and particles inside it. He defines Air and distinguishes it from dust: "AIR is that thin fluid which surrounds the Earth in which we move and breathe. Air is not visible. What we see in the stream of light let in by a small aperture into a room, is not Air, but Dust, and other bodies floating in the air. Air is sensible to the touch by its motion, and by its resistance to bodies moved in it."

Arbuthnot also differentiates between Air and Dew: "Dew is another Ingredient of Air. Dew is not mere water, but a composition of all the watery, volatile, oily, saline vapors, which exhale from the Earth, as long as they are agitated by the sun, are not to be seen, but as soon as the Air cools, they become visible."

The definitions of Air, Dust and Dew matter because they show that dust is an excessive items that can be removed from air, without disturbing air function, while moisture can be at times beneficial and at other times adverse to human health.

Further, Arbuthnot consider not only dust and dew, but also earth, salts, perspiration, Sulphur arising from the Earth, etc. as ingredients of air. "Earth is another content of the Air; Earth, calcined, flies off into the Air; the ashes of burning mountains, in volcanos, will be carried to great distances … Salts of all kinds are another ingredient of Air; fixed fossil salts may be digested, rendered volatile, and evaporate in Air … Another ingredient of the Air is the perspirable matter of animals (and humans)".

Arbuthnot considers Sulphur as the most toxic element in the air causing death in some mine workers. “Of all contents of Air, none are more noxious to human bodies than Sulphur. Miners are often hurt by these steams.” Interestingly, Arbuthnot mentions the solutions the miners used: “The remedies of the miners, are the same, which nature uses in like cases, making communication with the whole mass of outward Air, by shafts, perflation with artificial winds and bellows, and setting fire to those Sulphurous steams, after which they are able to go on with their Work.” This could be the very early usage of shafts, the concept which was imported from mining to the buildings later.

Further incidents such as death of prisoners residing in small rooms as well as suffocation of slaves while being transported over the seas made the issue of ventilation even more crucial (Sundell, 1994).

In his article, “the history of ventilation and temperature control”, John Janssen states that the ancient Egyptians noticed that there was a higher chance for the stone carvers working indoors to develop respiratory diseases rather than the ones working outdoors. Stone dust was the source of health problem and reason to fancy ventilation (Janssen, 1999).

One of the first building regulations related to ventilation, arousing from airflow needs, was made by King Charles I in England, 1600. He ordered to build the ceilings higher than 10 ft, and design windows which are higher rather than wider. It was after problems with open fires in fireplaces, when the rule was established to improve smoke removal (Janssen, 1999).

The history of building airflow and indoor air quality suggests that the ventilation of buildings was proposed in response to health and respiratory problems.

Ventilation Definition

While “Air” was described by Arbuthnot in 1733, it was years later when the term “Ventilation” was defined. Dr Jan Sundell suggests that the modern scientific history of indoor air science started with the question “did indoor air pose a threat to health as did outdoor air?” (Sundell, 2017)

Perhaps the first attempts to define ventilation was made at the late nineteenth century (Banham, 1984). It was not as easy to bring "ventilation" into words as "heating" or "cooling". It was not easy to measure ventilation either. Maybe because it was still more of a qualitative idea expressing "freshness" rather than a quantitative measurable figure.

Gradually, the main two offenders of the air had been exposed: Carbon Dioxide, and excessive moisture. The two invisible odorless elements were still too hard to be measured in comparison to heat. Later, other items had been considered as pollution. In 1904, Konrad Meier, a New York heating consultant, declared: "Carbonic acid is not a poison in the ordinary sense of the word, and much larger quantities than generally assumed may be present without causing ill-effect … On the other hand, substances and impurities that cannot be estimated from the presence of carbonic acid, as for instance an excessive amount of vapor of water, sickly odors from respiratory organs, unclean teeth, perspiration, untidy clothing, the presence of microbes due to various conditions, stuffy air from dusty carpets and draperies, and many other factors that may combine, will in most cases cause greater discomfort and greater ill-health." Astonishingly, Meier not only talks about the main factors, carbon dioxide and water vapor, but also distinguishes odors, microbes, and dust as pollutants (Banham, 1984).

ASHRAE defines ventilation as: "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space." ASHRAE considers a wide range of elements as contaminants including:

- Carbon dioxide
- Carbon monoxide (combustion appliances, parking garages, outdoor air)
- Formaldehyde (pressed-wood products, furniture and finishing)
- Lead (paint dust, outdoor air)
- Nitrogen Dioxide (combustion appliances, outdoor air)

- Ozone (electrostatic appliances, office machines, ozone generators, outdoor air)
- Particles in various sizes (combustion, cooking, candles, incense, dust, smoke, outdoor air)
- Radon (soil gas)
- Sulfur dioxide (unvented space heaters, outdoor air)
- Odors (occupants, VOC sources, cooking, sewage, etc.)

Natural, Mechanical and Hybrid Ventilation

While natural Ventilation is essentially based on the supply of fresh air to a space and the dilution of the indoor pollution concentration driven by pressure differences across the building due to wind or buoyancy (Liddament, 1990), mechanical ventilation relies on fans to create the pressure difference to exchange indoor and outdoor air. Although many residential buildings still take advantage of natural ventilation, this is not necessarily the case for offices and commercial buildings. These types of buildings rarely use natural or even hybrid solutions. In what follows, the merits and demerits of natural and mechanical ventilation systems are discussed.

i. Energy Demand, Fan Power and Heat Recovery

Energy consumption and related costs of some naturally ventilated and air-conditioned offices has been compared in the United Kingdom. Analysis indicate that the energy savings due to natural ventilation accounts for about 10% of the total energy costs in the United Kingdom climate. The same study states that fans consume two-thirds of the total cooling energy consumed in UK office buildings (BRECSU, 2000).

On the other hand, heat recovery of the fan has the potential to be the key advantage of the mechanical ventilation systems, especially in colder climates during heating seasons. However, the potential of heat recovery in cooling seasons is not much due to lower temperature differences (Axley, 2001).

ii. Sick Building Syndrome

Some statistical studies revealed that the Sick Building Syndrome is significantly higher (30 - 200%) in air-conditioned buildings, relative to naturally ventilated buildings (Dutton, Et al. 2013), (Seppanen and Fisk, 2002). Accordingly, annual health-related costs due to increased exposure to ozone and particulate matter rise in air-conditioned buildings (Dutton, Et al. 2013).

iii. Occupant Satisfaction and Productivity

Studies reveal that people tend to enjoy natural ventilation better and they even show increase in thermal tolerance when in natural buildings (Rupp, Vasquez and Lamberts, 2015), (Brager and Arens, 2015). People who are under steady conditions in their thermal environment (air-conditioned – AC – environments) have less tolerance and are less able to adapt to the dynamic conditions of naturally ventilated spaces (Candido, Et al. 2013).

However, preference between a natural building and an air-conditioned one could be a matter of habit. People who were constantly exposed to AC preferred this type of conditioning while people accustomed to free-running buildings preferred not to have AC (Candido, Et al. 2013).

"Epidemiological studies consistently show that occupants' complaints are more prevalent in office buildings with more sophisticated HVAC systems. These complaints not only include physical symptoms, but also complaints about indoor air quality and thermal comfort. Since in most cases these more sophisticated systems primarily aim at better compliance with some set of health and comfort standards, the higher complaint levels seem odd. The most frequent explanation of this phenomenon is that more sophisticated HVAC systems contain more potential sources of indoor air pollution, like filter sections, cooling sections and humidifiers." (Leyten and Kurvers, 2006)

iv. Reliability

Reliability seems to be the strongest argument of the supporters of mechanical ventilation. Natural ventilation is either wind-driven or buoyancy driven, none of which is always reliable. This could result in under-ventilated or over-ventilated spaces (Axley, 2001). Recent developments in natural and hybrid ventilation systems attempt to answer this issue.

Obstacles of Natural Ventilation

Air-conditioning seems to be the dominant type of ventilation in modern office buildings. In what follows, the reasons of this issue will be further investigated.

i. Design, Plan and Section

Before air-conditioning became as ubiquitous as it is today, buildings in general and offices in specific were designed according to the natural ventilation requirements. Plans were narrow and rectangular so cross ventilation could happen; ceilingi were higher, so buoyancy-based air circulation could occur (Graca and Linden, 2016). Separation of mechanical design and architectural design lead into plans and section which are not capable of accommodating natural ventilation needs.

Before the advent of modern office blocks, prestigious architects such as Louis Sullivan and Uffizi applied "U" plan form to maximize access to light and air in tall office buildings. A reputable case in point is Sullivan's Wainwright Building in St. Louis (Arnold, 1999).

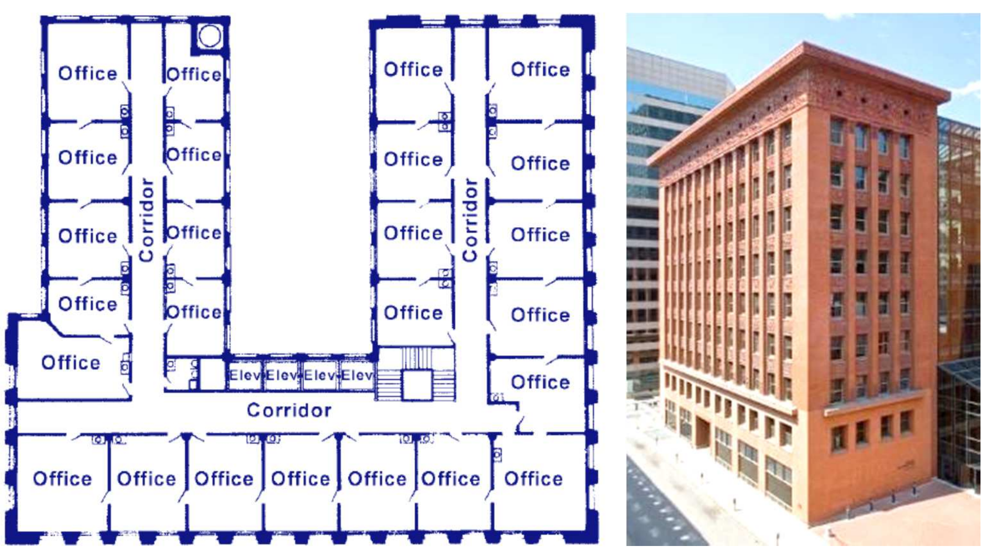

Figure 3. Wainwright Building

ii. Unpredictability

Due to some level of unreliability of natural ventilation, as discussed in the previous section, the tendency to design natural buildings is lower. This issue could be resolved to some extent by a more thoughtful design which analyses the natural conditions and makes the most out of existing wind, pressure and temperature conditions.

“So-called experts will tell you natural ventilation won’t work. What they really mean is that they do not understand it,” mentions Leon Glicksman, Ph.D., professor of building technology and mechanical engineering at the Massachusetts Institute of Technology (Melton, 2014).

Furthermore, it makes it easier knowing that it is almost impossible to make it comfortable for 100% of people 100% of the time and we are not actually responsible to do so. “The gold standard for mechanical engineers is 80% of the people comfortable 80% of the time,” notes Steve Tatge, a lead architect at the University of Washington. “This presumption of ‘air-conditioning equals universal comfort’ is a false one, but it is powerful.” (Melton, 2014)

iii. Initial Cost

The initial costs of a natural building might be higher considering that appropriate design, simulation and analysis are expensive as well as potential additional costs due to different methods of construction. However, considering the lower energy costs after occupancy, and lower maintenance costs of a natural building, the cost issue might be balanced. Basically, it seems that initial costs of a natural building are higher, whilst post-occupancy costs of an air-conditioning one seems to be more significant.

iv. Climate

Axley introduces some examples of elaborate naturally ventilated buildings in the United Kingdom. He further declares that similar strategies can be employed for a number of North American climates (Axley, 2001). While it is more convenient to design natural buildings in milder climates such as coastal California or regions with small annual cooling and ventilation needs such as North Midwest states, it might be a challenge to do it in a hot humid climate such as Florida, although not impossible.

v. Outdoor Air Quality

Natural ventilation uses unfiltered outdoor air which is not necessarily always clean. In some locations, such as centers of highly populated cities, or close to highways, amount of contaminant might be too much to handle natural ventilation. In this situation, it might be the best to close the openings due to health issues enough (Melton, 2014).

vi. Noise Pollution

Sound moves through air. In some urban areas, there is a high potential of noise pollution. There are some design solutions to noise problem. ZGF (Zimmer Gunsul Frasca) Architects addressed outdoor air quality and noise problems by re-orienting the original design to have the naturally ventilated offices face a courtyard rather than the street (Melton, 2014).

Hybrid Ventilation

Considering the limitations of natural ventilation and advantages of air-conditioning systems, there might be an alternative solution to take advantage of both approaches benefits. This solution is known as hybrid ventilation.

It seems that there are two definitions for hybrid strategy in the literature. While the first definition considers the ability of switching from natural to mechanical ventilation in different seasons as the main feature of hybrid ventilation, the second one believes incorporating both natural and mechanical elements at the same time in a single combination is the key aspect of hybrid ventilation. In what follows, first I narrate both definitions, then I would consider both as cases of hybrid strategy.

For the first definition, let us consider Heiselberg quotation: “Hybrid ventilation systems can be described as systems that provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year. In hybrid ventilation mechanical and natural forces are combined in a two-mode system where the operating mode varies according to the season, and within individual days. The main difference between a conventional ventilation system and a hybrid system is the fact that the latter has an intelligent control system that can switch automatically between natural and mechanical modes in order to minimize energy consumption.” (Heiselberg, 2002)

Graca and Linden consider a similar definition. They mention that hybrid strategy takes advantage of natural ventilation in the mild months and uses mechanical ventilation in warmer periods (Graca and Linden, 2016). On the other hand, Chen, Et al. consider hybrid strategy as coupling natural ventilation with mechanical ventilation (Chen, Augenbroe, Song, 2018).

The merits of a hybrid strategy include:

- Occupant control, like natural ventilation
- Energy saving, less energy consumption in comparison to mechanical ventilation
- Reliability, higher than natural ventilation

The demerits of hybrid ventilation are:

- Costs; a hybrid system might be more expensive as it should embed both natural and mechanical ventilation requirements.
- Control; the hybrid system usually needs a good control system. In case the control sensors would not work as expected, the building would not work as meant to. It might even end up being all natural or all mechanical if not switching correctly between the two.

In what follows, I will study some examples successfully using the natural and hybrid ventilation ideas.

Ventilation Systems Precedent Analysis and Typology

Part A: Naturally ventilated projects

1. **Queens Building at De Montfort University**

Figure 4. Queens Building at De Montfort University[9]

- **Architects:** Short, Ford & Associates
- **Environmental engineers:** Max Fordham & Partners
- **Year:** 1993
- **Location:** Leicester, UK
- **Area:** 10,050 m^2 (110,000 ft^2)

The queens building is allocated to the school of engineering and manufacture at De Montfort University, UK. It had won acclaim in Europe for being highly innovative when it was built. Axley considers this building as "the most influential of the first generation of the newer naturally ventilated buildings" (Axley, 2001).

[9] Photo by Michael Utzinger

“The entire building is naturally ventilated, passively cooled and naturally lit, including the two largest auditoria each seating 168 people. Conventional wisdom in the ventilation and heating industry was that this omission of mechanical and electrical equipment was quite impossible.”

“The design process involved physicists from the Cambridge University Dept. of Applied Maths and Theoretical Physics and the Institute of Energy & Sustainability at De Montfort University, co-operating with ourselves and Max Fordham's Environmental Engineering Consultancy. It was a very exciting and enjoyable process, written up by the U.K. Government's Department of Trade and Industry.”[10]

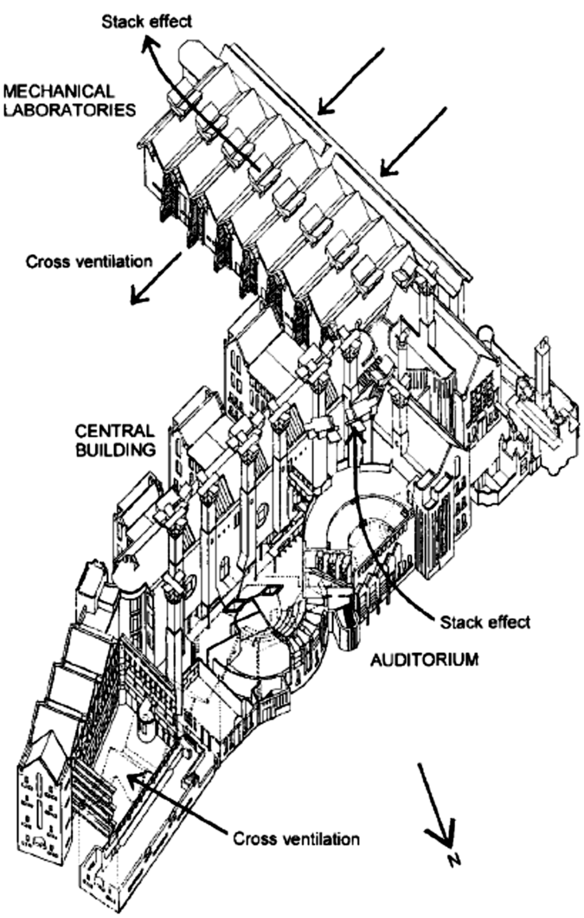

Figure 5. Exposed brickwork[11] (left), Axonometric view, Stack ventilation (right)[12]

[10] http://www.shortandassociates.co.uk/page.asp?pi=28
[11] Photo by Michael Utzinger
[12] http://nesa1.uni-siegen.de/wwwextern/idea/buildings/_buildings/b_040/plan/_zoom/zoom_01.htm

- **Ventilation strategies:**

Indirect Cooling – Night Cooling Strategies: There are usually temperature fluctuations between day and night. These fluctuations could be applicable for natural ventilation purposes, specifically in summer. In summer, the floor slab absorbs heat gains during days and releases heat overnight. Cooled down during night, the floor is ready to absorb the next day's heat gain (Braham, 2000).

Axley uses the term first-generation night cooling for Queens building. That is, the thermal mass is directly exposed to the room air and is not covered by carpet or suspended ceiling. These buildings are characterized by massive exposed ceilings, "ceiling soffits". Masonry material such as brick or tile finishes are employed even for nonstructural elements (Axley, 2001). In fact, the Queens building is known for having exposed internal brickwork and concrete ceilings for maximizing thermal capacity (CIBSE, 1998).

Natural Ventilation System Components – Stack ventilation: Stack-based ventilation systems apply the buoyancy effect of the air. When the air heats up, it goes up and cool air replaces it. It is also called the downdraught cooling.

Downdraught cooling relies on the effect of gravity on the cold air to create circulation between the source of cool air and the occupied space. The source of cool air could be passive or active (Ford, Schiano-Phan, & Francis, 2010). The Queen's Building uses low-speed "Calcutta" fans in its paired stacks to inhibit top-down convective flows. However, it is still considered as a passive system (Axley, 2001). By extending the stack to a level higher than roofs, the wind would act more efficiently. Those fans would effectively aid exhaust at night, enhancing diurnal cooling.

Natural Ventilation System Components – Cross ventilation:

Some spaces, such as narrow electrical laboratories are only cross ventilated via operable windows. The window openings were sized using a low design wind speed of 0.5 m/s, which is the wind speed expected to be exceeded for more than 90% of the time (Thomas, 1999).

Natural Ventilation System Components – Combined stack and cross ventilation:

The building uses a combination of stacks and cross ventilation. Deeper spaces of the central building, which are open to outside air only from one side, are either stack ventilated or, in the case of the ground-floor classrooms and first-floor central laboratory, a combination of operable windows and automated air exhausts via stacks or openable roof-lights. (Thomas, 1999).

In the auditoria, large openings, protected from weather, let the air in after passing through motorized volume control dampers at the building envelope. Then, the air is distributed through finned heating tubes under the seats, and then it finds its way out through a grille made of aluminum mesh (Thomas, 1999).

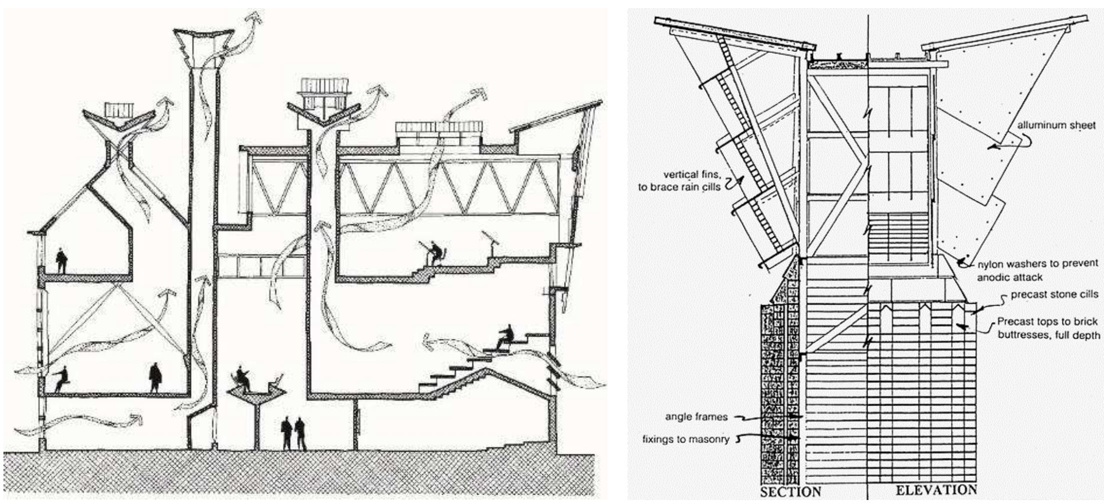

Figure 6. Air passage through auditorium[13] (left), Stack head[14] (right)

Both Thomas and Axley have explained the ventilation systems used in this building. However, Thomas has been more extensive. He has explained how each of the three options including cross ventilation, stack ventilation, and the combination of both, has been employed in different spaces such as atria, laboratories, and classrooms. Figure 7 is a view looking up at one of the east auditorium exhaust stacks and how the rhombus form integrates with the roof truss.

[13] https://santacruzarchitect.wordpress.com/2015/05/16/stack-effect-ventilation/

[14] https://www.pinterest.com/pin/521643569313602926/

Figure 7. east auditorium exhaust stacks

- **Psychrometric chart:**

The closest available weather file to Leicester is Birmingham, UK. Figure 8 illustrates the Climate Consultant psychrometric chart based on the Predicted Mean Vote (PMV) method for April to October.

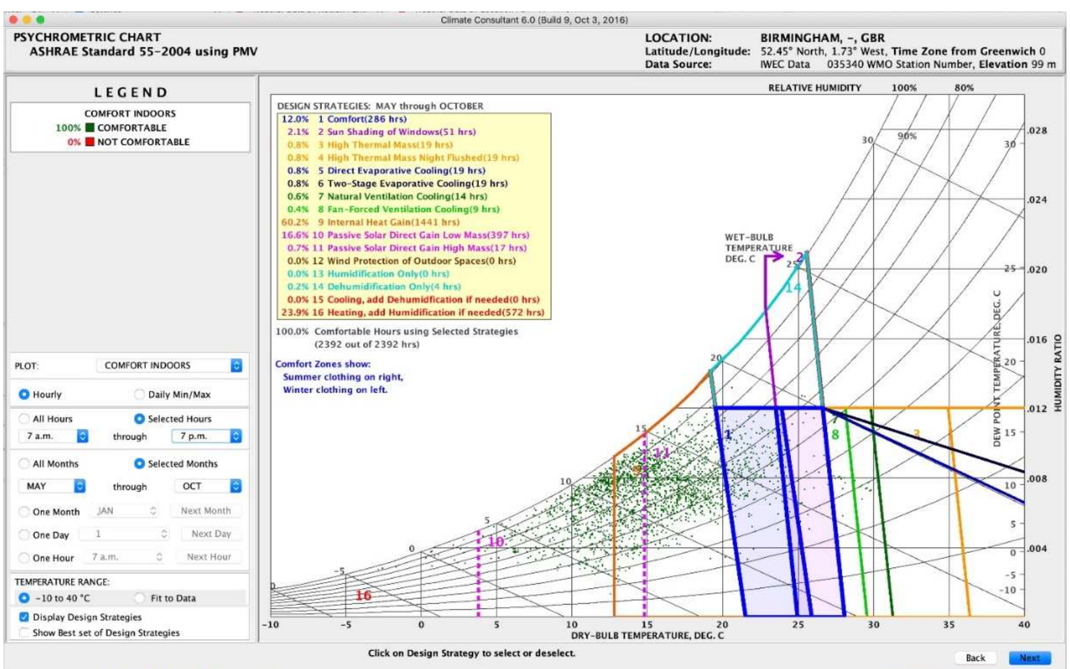

Figure 8. Psychrometric chart, Birmingham, UK – Climate Consultant – 7 AM to 7 PM

What the chart reveals is that in this specific climate, the heating needs are greater than the cooling loads. Therefore, it is quite a reasonable idea to provide all ventilation and cooling needs only by means of passive systems.

Psychrometric chart for 7 P.M. to 7 A.M. represents the night heat flushing potential for De Montfort Queens Building. The annual day night temperature difference in the two plots illustrates the advantage of night cooling.

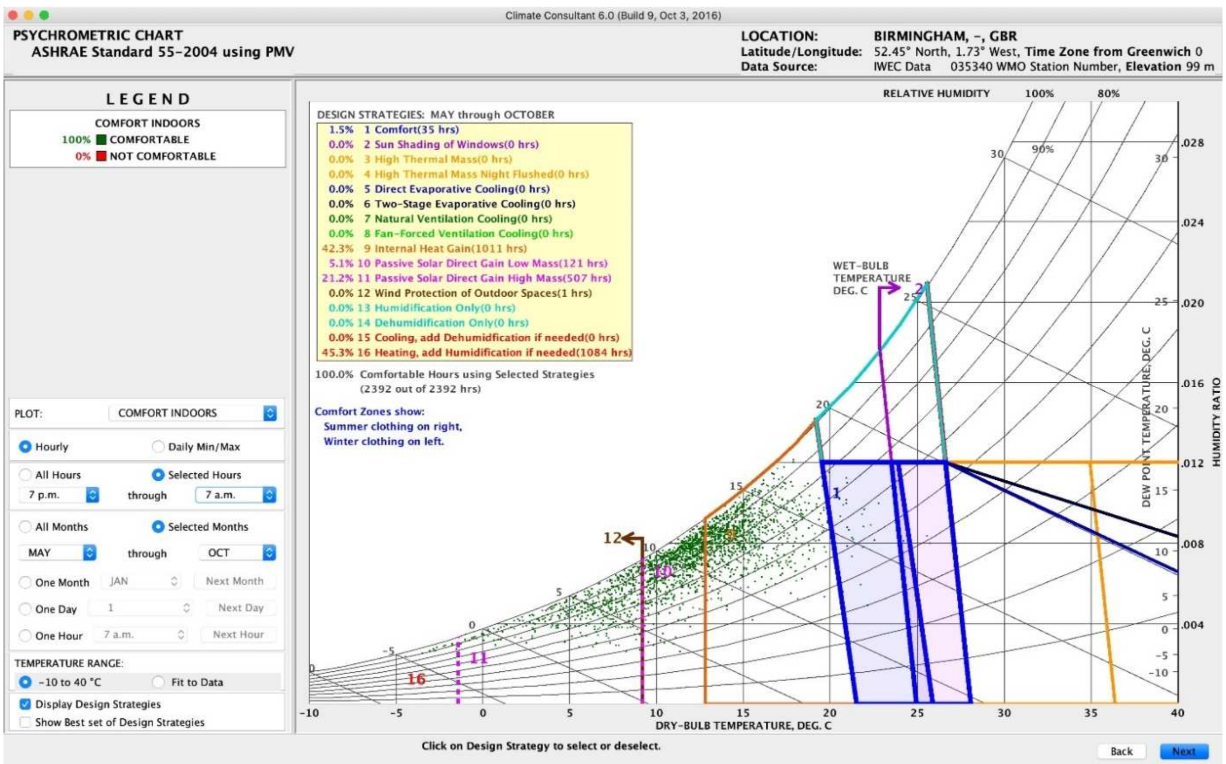

Figure 9. Psychrometric chart, Birmingham, UK – Climate Consultant – 7 PM to 7 AM

Climate Consultant proposes a few passive methods to answer to ventilation, cooling, and heating needs in the central UK area. These methods include natural ventilation cooling, evaporative cooling, shading windows, and high thermal mass, which is flushed at nights for summer; and internal heat gain, solar gain, and wind protection for winter. Almost five out of seven approaches have been applied to Queen's building design.

One could shrewdly observe that some of the passive systems used for winter might increase cooling and ventilation loads in summer, and vice versa. As a case in point, internal heat gain could provide up to 32% of the winter comfort needs in this location. Paradoxically, it could easily result in high cooling needs in summer. The design team of this project have circumvented this problem by adding all sorts of natural ventilation specifically night cooling strategies. In fact, the combination of masonry material with high thermal capacity and highly efficient ventilation systems has turned this paradoxical dilemma into the success key of this project.

It is also important to choose the material wisely to tackle these problems. For the Queens building, 190 mm block (used for structural reasons), 100 mm of Rockwool cavity batts completely filling the cavity and 100 mm external brick, gave a U-value of 0.30 W/m^2 K (Thomas, 1999). An almost 40-centimeter-thick wall has been necessary to provide enough insulation and thermal mass.

Figure 10. Queens building perspective proportions[15]

[15] https://santacruzarchitect.wordpress.com/2015/05/16/stack-effect-ventilation/

Another worthy point to look at is the dimensions and proportions required to estimate the operable windows size as well as the stack height. This is the as-built figures for Queen's building:

- Auditorium average height = 5.1 m
- Stack height = 12.0 m
- Free area of low-level inlets = 4.8% of floor area
- Free area of high-level outlets = 4.8% of floor area (Thomas, 1999)

It seems that a ratio of two or more between the stack and the space height is working perfectly for this building. Most of the central space and classes/auditoria on the sides uses stack ventilation with inlet low and outlet high.

Thomas mentions that the area of inlets and outlets has approximately been about 5 percent of the floor area. This is information is somehow incomplete. Thomas differentiates between spaces with opening on only one side, on both sides, and spaces with combined cross and stack combination. Although this 5% seems to be for the spaces containing openings on both sides, he does not exactly mention so. He does not tell us whether it is also 5% for the two other types of spaces or not.

Let us conclude this building analysis with a story by Andrew Scott: "*Very encouraging heat load tests were conducted in June 1994. In Leicester, this was a one-in-forty-year fantastic heat wave. We found it was very difficult to raise the internal temperature beyond 23.5 °C. The outside temperatures were going towards 31 °C, and the good people of Leicester were really panicking that afternoon because of appalling heat.*" (*Scott, 1998)*

2. Dolat Abad Garden Pavilion

Figure 11. Dolat Abad Garden

- **Architects:** Haj Ali Akbar
- **Year:** 1747
- **Location:** Yazd, Iran
- **Area (of building):** less than 1,000 m^2 (11,000 ft^2)
- **Area (of garden):** 70,000 m^2 (753,500 ft^2)

Dolat Abad garden, which has been registered in UNESCO[16], is known for the architecture of the pavilion, the wind catcher, and how wind and water have been employed to enhance the architectural experience. The almost 34-meter-high wind catcher is the highest brick wind catcher in the world. However, wind is not the only natural element used in this complex.

[16] United Nations Educational, Scientific and Cultural Organization

In that period, Iranian people used water canals called Qanat. Qanat was slightly sloped horizontal water canal, buried in the ground, which transferred water from mountains to central arid cities. They created wells to use the water wherever needed. Dolat Abad garden had access to the 60-kilometer long Dolat Abad Qanat. Wind and water are the main two natural elements employed to create thermal comfort in this complex. Considering the hot arid climate of Yazd, this seems a reasonable decision. The way these elements have been integrated with the architecture is delightful.

The garden is symmetrical as all traditional Iranian gardens are. The most significant pavilion is located at the end of the main pivot. It is the first part that you see when entering the garden. This specific perspective view heightens the importance of the main pavilion. In what follows, I discuss how the architecture provides desirable thermal conditions when no mechanical ventilation was available. Indeed, the idea is further generalized as passive downdraught cooling.

- **Ventilation strategies:**

Natural Ventilation System Components – wind catcher, downdraught evaporative cooling:

Wind catcher has been a main ventilation and cooling device in the Middle East area for the past three thousand years. The wind catchers are for summer use and would be closed in winter (Nouanégué, Alandji, & Bilgen, 2008). It is mainly considered as a traditional vernacular system. However, the concept is revived in some modern innovative systems such as Passive Evaporative Downdraught Cooling (PEDC) (Ford et al., 2010).

The wind catchers vary in height within the range of 5 to 34 meters (Montazeri & Azizian, 2008); the 33.8-meter one belongs to Dolat Abad garden complex. The height of the wind catcher not only indicated the higher social status of the owner, but also admitted faster winds with less dust (Saadatian, Haw, Sopian, & Sulaiman, 2012). Ji et al. claim, “The architectural features of low-energy buildings are very different compared with conventional buildings, for example, tall solar chimneys, light wells or atria are sometimes employed. These structures potentially increase the height of the column of warm air inside the buildings and as a result increase the stack driving force.” (Ji, Cook, & Hanby, 2007)

Li et al. state that “In order to induce more air into the interiors when the wind direction varies, the stack of the wind catcher is usually divided into two halves or four segments.” (Li & Mak, 2007) Interestingly, the Dolat Abad wind catcher has an octagonal plan providing the potential for the wind catcher to draw in the winds from all directions.

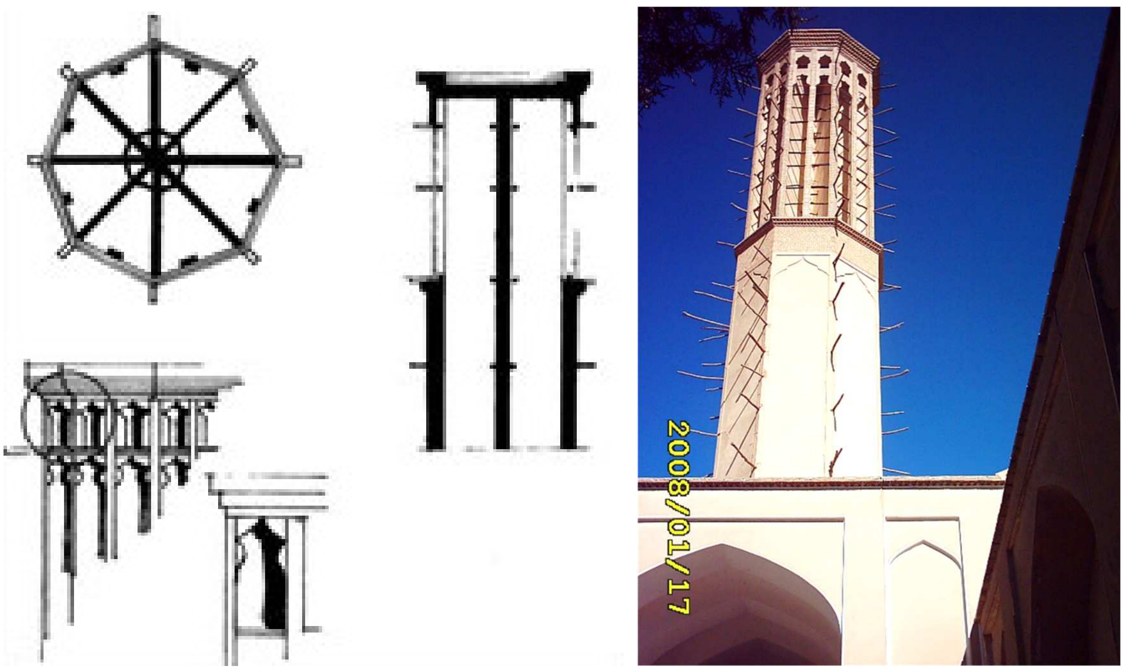

Figure 12. Dolat Abad section, wind catcher section (left) [17], right

The wind enters the wind catcher from the windward side (which could be any of the eight facets). Then dry wind will be drawn into the bottom of the tower facing a pond with a fountain. The fountain maximizes the water and air interaction, hence the evaporative cooling. The air circulates throughout the space. Warm air exits from the openings at the top of the dome due to the dome stack effect.

[17] http://www.cwejournal.org/vol11no2/investigation-of-cultural-eco-technology-in-iranian-traditional-architecture-the-way-of-achieving-a-comprehensive-view-point-regarding-contemporary-architecture-of-iran/

Figure 13. Dolat Abad section, inside wind catcher, looking up

Figure 13 presents a view from inside the windcatcher looking up.

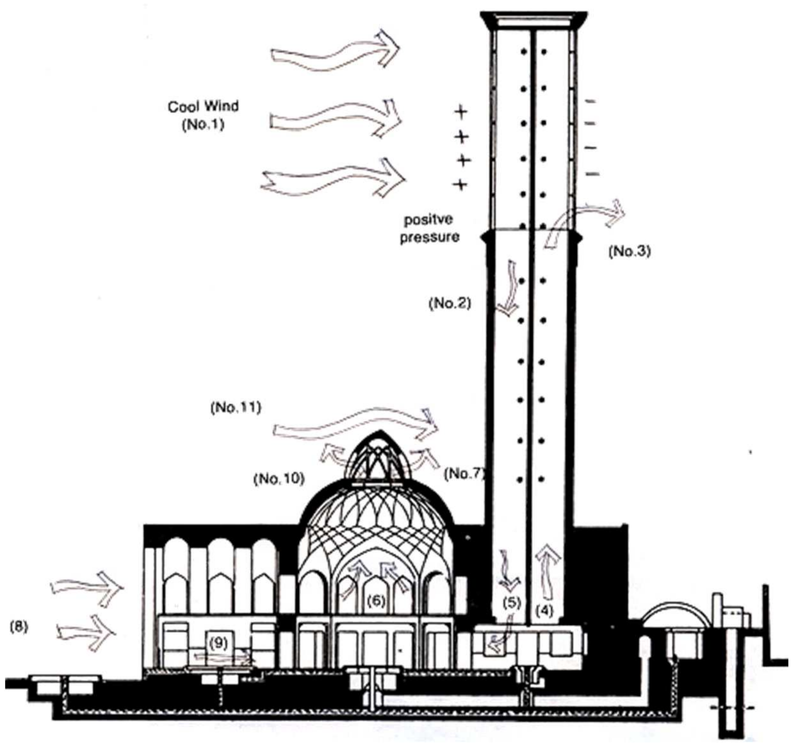

Figure 14. Dolat Abad section, wind catcher and pavilion[18]

[18] http://www.new-learn.info/packages/clear/thermal/buildings/passive_system/passive_cooling/case_study/dowlat_abad.html

Natural Ventilation System Components – Evaporative cross ventilation:

Besides the air coming from the wind catcher, the two-story pavilion is full of openings and porous surfaces on all sides so that the wind could easily circulate in the space. The air also passes over the pond while crossing the room, which results in combining evaporative cooling and cross ventilation.

Natural Ventilation System Components – thermal mass night flushing:

In this particular climate, the day and night temperature vary significantly, up to even 20 °C. Using thermally massive material such as mud and brick causes a seven, 7 to 9 hours of time lag. The walls of the wind catcher start to lose heat through radiation and convection during the night. In the morning, the cold walls cool the air around themselves.[19]

- **Psychrometric chart:**

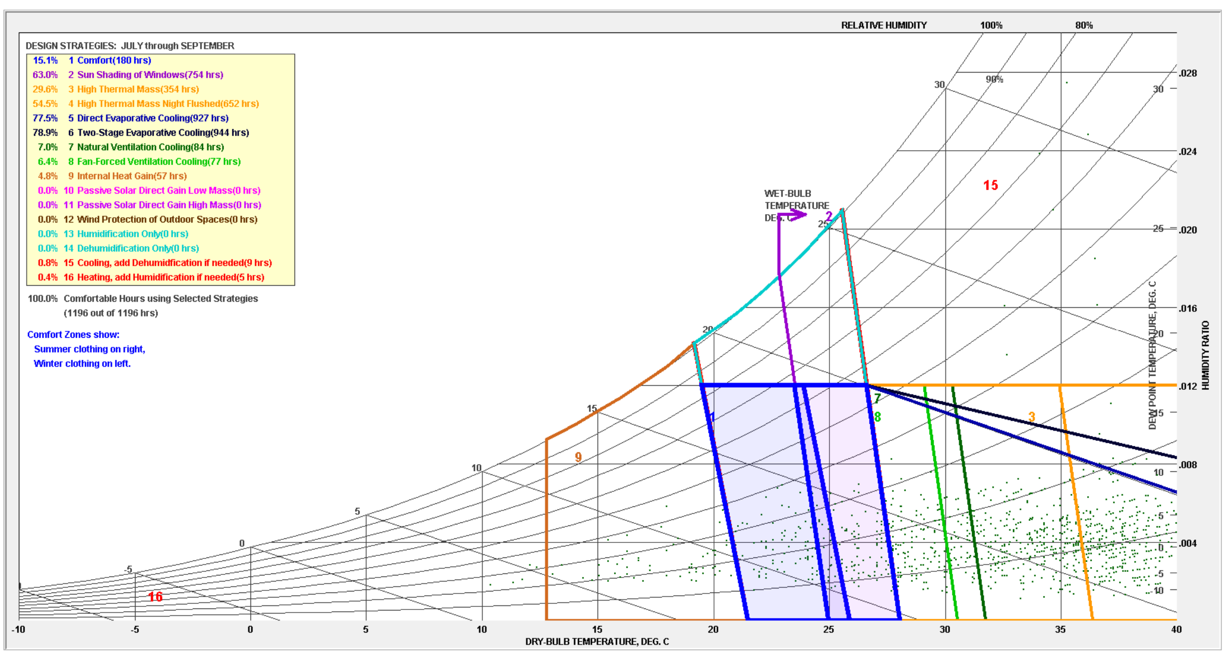

Figure 15. Psychrometric chart, Yazd, Iran – Climate Consultant – July through September, 7 AM to 7 PM

[19] http://www.new-learn.info/packages/clear/thermal/buildings/passive_system/passive_cooling/case_study/dowlat_abad.html

What is interesting in the psychrometric chart of Yazd is that all the dots are close to the X-axis; that is, the air is highly dry and far from saturation. This is the best opportunity to try evaporative cooling since not only the capacity for evaporative cooling is great, but also, we do not need to worry about condensation.

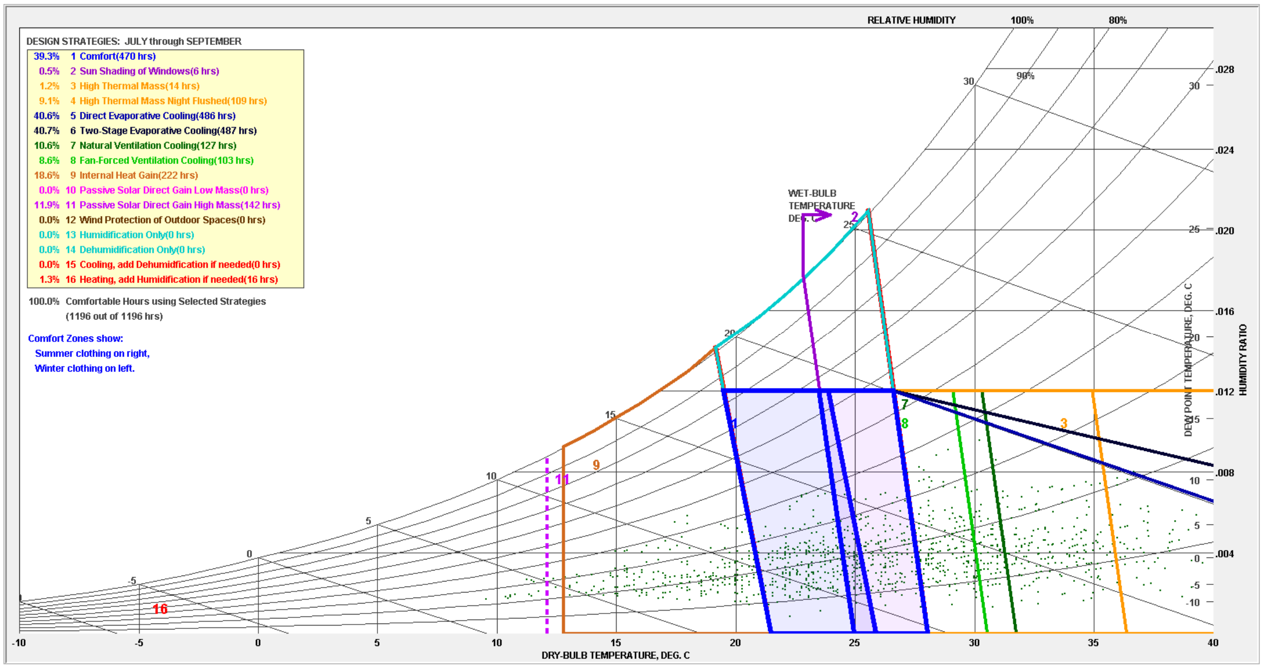

Figure 16. Psychrometric chart, Yazd, Iran – Climate Consultant – July through September, 7 PM to 7 AM

Other passive approaches including night flushed thermal mass and sun shading could answer the rest of the cooling and ventilation needs. Nighttime Psychrometric chart displays the possibility of nighttime flushing. The building also has heating needs. However, it was not used in winter, so heating loads were not a problem in this case.

The amount of the open area can be manipulated by sliding the porous screens. That is the way the occupant could control thermal conditions to optimize the light and ventilation.

Part B: Naturally ventilated spaces, and mechanically ventilated spaces

3. California Academy of Sciences museum

Figure 17. California Academy of Sciences museum[20]

- **Architect:** Renzo Piano Building Workshop, Stantec Architecture
- **Engineering and sustainability:** Ove Arup & Partners
- **Year:** 2008
- **Location:** San Francisco, California
- **Area:** 37,000 m^2 (400,000 ft^2)[21]

The California academy of sciences museum is among the largest natural history museum in the world. One of its unique features is its green living roof. The building has won a couple of prizes including the Urban Land Institute (ULI) award in 2009 for Excellence for the Americas region[22], and LEED[23] Platinum, the highest possible certification of the U.S. Green Building Council in 2008. It is the largest public Platinum-rated building in the world, and with a total score of 54 points, it is also one of the world's most

[20] Photo by Michael Utzinger
[21] https://web.archive.org/web/20130420195934/http://www.calacademy.org/about/
[22] https://americas.uli.org/awards/uli-awards-for-excellence-winners-though-the-years/
[23] Leadership in Energy and Environmental Design

sustainable museum building[24]. The California Academy of Sciences earned points across six different categories of LEED: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation and design process. The building is supposed to use about 30-35% less energy than required by standard building code.

- **Ventilation strategies:**

Natural Ventilation System Components – Combined Wind + Buoyancy-driven Stack Ventilation:

There are two main domes on the building roof. The domes not only simulate a natural topography to be in harmony with the Golden Gate park landscape, but also provide a higher elevation so that the wind could easily enter the space through operable dome windows. However, the dome openings are not enough to provide the pressure difference needed for air to be drawn out of the space. That is why the stack ventilation inside the dome is combined with the dome cross ventilation. The two strategies work together to provide natural ventilation throughout the spaces located below the dome such as the main plaza. The heated floor of the plaza helps the stack effect during winter.

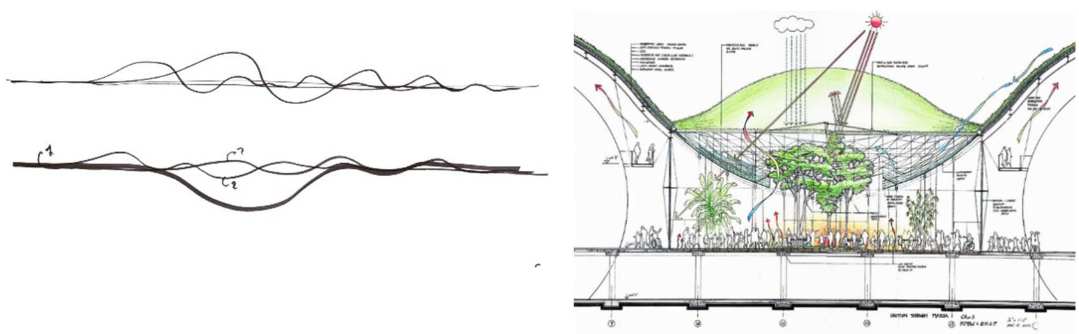

Figure 18. Sketch (left), Main plaza ventilation sketch (right)[25]

The wind crossing the dome openings creates a negative pressure, which amplifies the stack effect. This idea integrates both cross ventilation and stack effect concepts (Axley, 2001).

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[24] https://web.archive.org/web/20130116102014/http://www.calacademy.org/newsroom/releases/2008/leed_platinum.php
[25] https://www.archdaily.com/6810/california-academy-of-sciences-renzo-piano

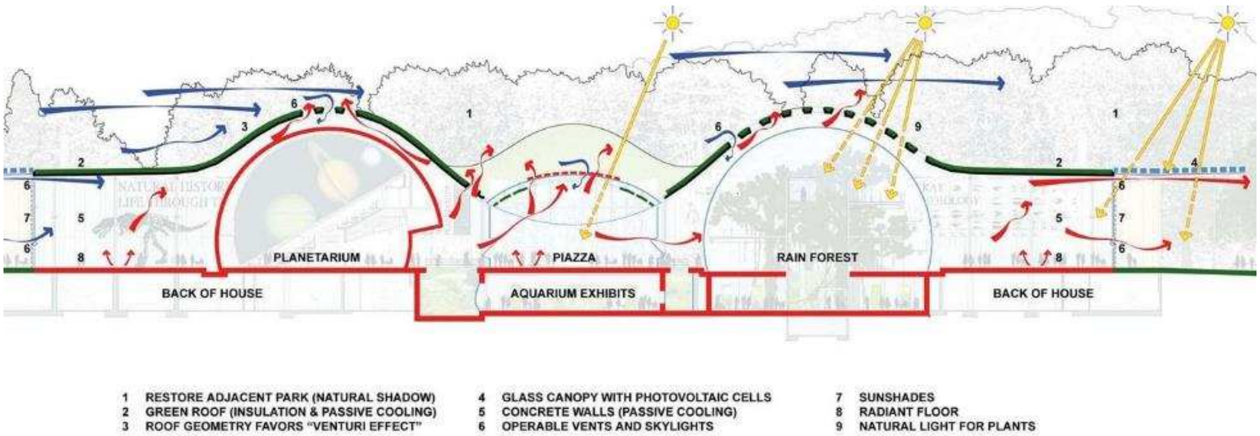

Figure 19. Integrated ventilation strategies[26]

Indirect Cooling – Night Cooling Strategies:

The exhibit spaces are entirely naturally ventilated and conditioned through the radiant slab, which is cooled at night through night purging and, if required, by the hydronic cooling system during the day (Zelenay, Perepelitza, & Lehrer, 2011).

Passive-Mechanical Components:

A fascinating idea about how the ventilation systems work in this building is that even the passive systems, such as 40 operable roof openings, are controlled by sensors. For instance, as soon as the sensors figure out that the CO_2 concentration has reached a critical value, ventilation intensifies automatically. Skylights in the roof automatically open and close to allow cool air to enter when possible. The windows are operable, so it is passive. However, it is motorized to work automatically; hence, it is also mechanical-based. We might be able to consider it as a passive-mechanical element. The items that control ventilation are CO_2 level, room temperature, humidity of the air and the wind conditions.[27]

[26] https://www.archdaily.com/6810/california-academy-of-sciences-renzo-piano
[27] https://www.designboom.com/architecture/renzo-pianos-california-academy-of-science/

Figure 20. Dome operable windows[28]

Green Roof Microclimate effect:

The green roof itself is a passive method to reduce cooling loads. The green roof soil is not only moist, but also thick. Being moist, the soil cools the air around while evaporating. Being thick, it provides thermal inertia and creates a time lag for the heat to enter the space. The plants also cool the air around due to evapotranspiration effect. The combination of soil and plant together creates a spatial microclimate around the roof.

Turbulence-Induced Single-Sided Natural Ventilation:

The office spaces are located along the building's southeast elevation (the building is rotated 45° from the cardinal directions) (Zelenay et al., 2011). The side offices have operable windows and can use one-sided ventilation. As Axley explains, the single-sided ventilation affects the envelope pressure leading to minute turbulences, which may have enough force to cause air circulation (Axley, 2001).

Moreover, the shading around the building helps to prevent solar radiation. The exterior shading type is Nysan automated exterior roller shades, PV canopy at south and north elevations (Zelenay et al., 2011).

These two strategies minimize the ventilation needs on the offices. In fact, 90% of office space has natural light and ventilation[29].

[28] https://www.archdaily.com/6810/california-academy-of-sciences-renzo-piano
[29] https://www.designboom.com/architecture/renzo-pianos-california-academy-of-science/

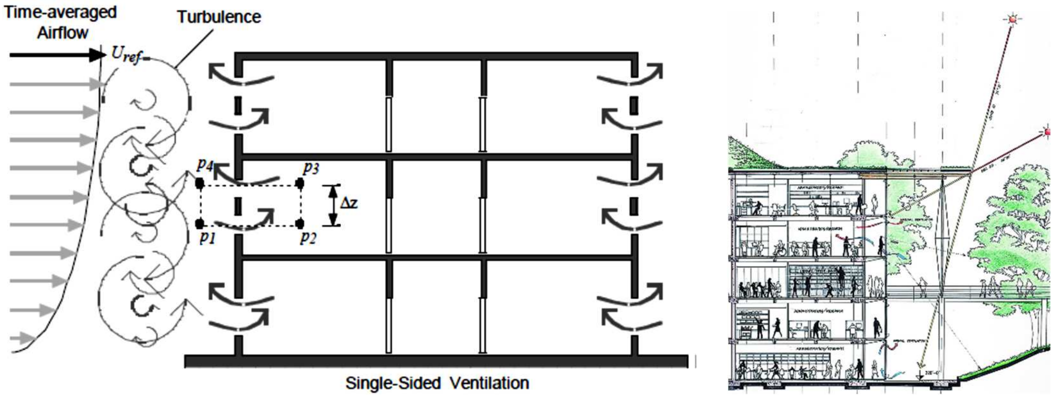

Figure 21. One-sided ventilation (left), Side offices (right)

In an effort to minimize the need for cooling in the open office space, office cooling ventilation design had been done by computational fluid dynamics (CFD) simulations along with a thermal analysis using ROOM – Arup's in-house thermal analysis software – to determine the effect of natural ventilation on occupant thermal comfort in the 30-foot-deep open office space. CFD analysis divulged that only 20 feet of the office width would have been covered by natural side ventilation. As the offices were 30 feet deep, Supplemental mechanical ventilation was required for the inner third of the open office space. In the end, the results of the simulation showed that the temperature inside the space could reach 79°F at certain times of the year, corresponding to 20 percent PPD (Predicted Percentage of Dissatisfied) – an upper limit that was acceptable to the owner. The enclosed office spaces located between the open office and collection areas are mechanically ventilated and cooled (Zelenay et al., 2011).

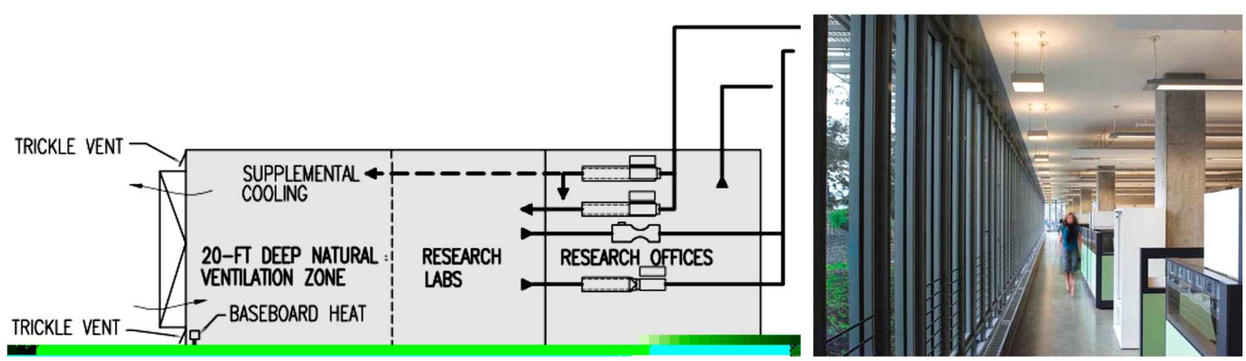

Figure 22. Office ventilation

Mechanical and Natural Ventilation:

Although many spaces in this building including the plaza and the side offices have natural ventilation, still some rooms such as the rain forest or the planetarium room lack natural ventilation probably due to their specific needs. However, although the rain forest space is not naturally ventilated itself, the air is circulated around it and the surrounding spaces are ventilated.

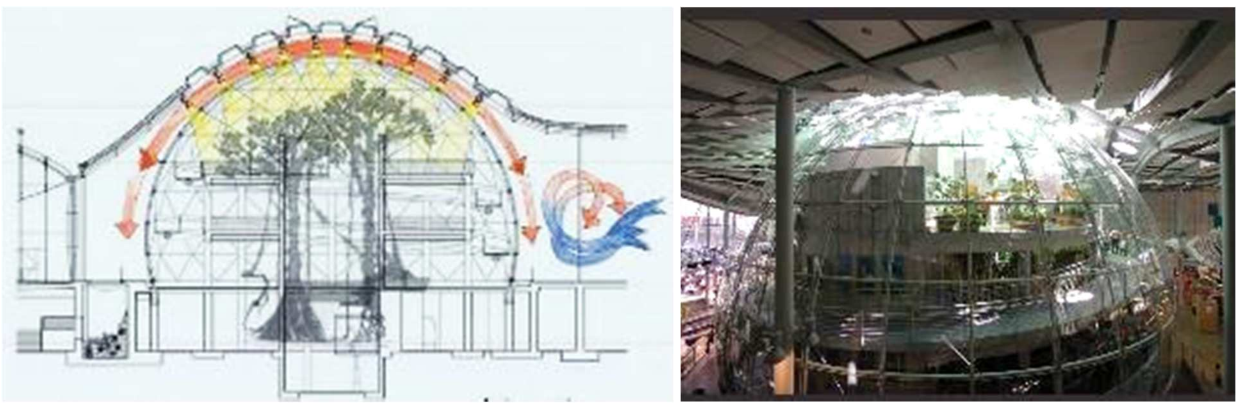

Figure 23. Rain Forest (Left)[30], Right[31]

The HVAC system used in this project is cooling tower with radiant slab hydronic heating and cooling, low pressure ventilation via under-floor air distribution system (Zelenay et al., 2011).

- **Psychrometric chart:**

Let us take a better look at San Francisco weather file and psychrometric chart. Interestingly, it seems that in San Francisco's mild climate, passive solutions could provide the thermal needs almost all over the year. Adding night-ventilated thermal mass, sun shading, and evaporative cooling could highly decrease cooling and ventilation needs in summer. On the other hand, passive solar gain through transparent material could answer to part of heating needs in winter. The California academy of sciences museum covers all these approaches.

[30] https://www.archdaily.com/6810/california-academy-of-sciences-renzo-piano

[31] Photo by Michael Utzinger

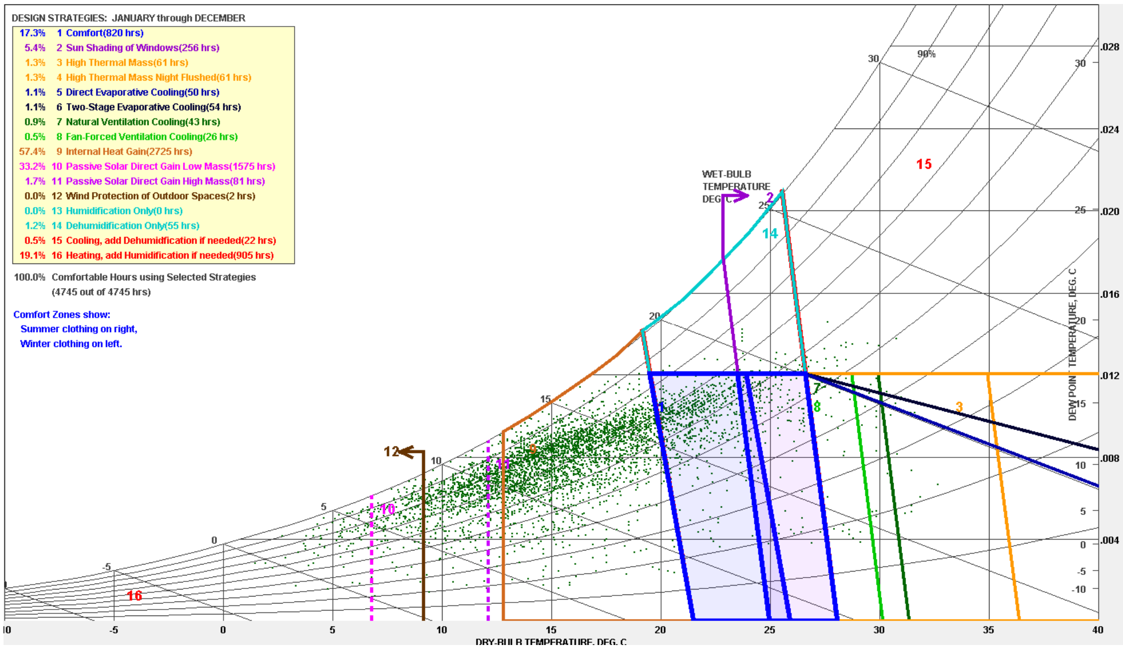

Figure 24. Psychrometric chart, San Francisco, CA – Climate Consultant

It is understandable that there are some spaces with specific thermal and ventilation needs such as the rain forest and planetarium room. Except for these rooms, most of the other parts of the building are naturally cooled and ventilated.

Analysis by the University of California Center for the Built Environment (CBE) suggest that while the predicted EUI was 103 kBtu/ft^2/yr (324.9 kWh/m^2) – which is 12% below ASHRAE 90.1-1999 – the Actual EUI (reported at 2011) was 151.4 kBtu/ft^2/yr (477.6 kWh/m^2) (Zelenay et al., 2011).

What is not mentioned in the CBE report is a suggestion of why the actual energy utilization intensity is 1.5 times that predicted during design. Was that because of not validated simulations? Was that due to extra internal gains from people and equipment? Was that because of changes in constructional plans? Maybe they are going to publish something about it in future.

According to CBE, Window to Wall ratio is greater than 75% (Zelenay et al., 2011). this is for the main public exhibit hall, which is cross shaped in plan and only the end walls of the cross are exterior, so the wall (and therefore glazing) to floor area ratio would be smaller.

4. Aldo Leopold Foundation

Figure 25. Aldo Leopold Foundation

- **Architects:** The Kubala Washatko Architects, Inc.
- **Environmental Consultant:** D. Michael Utzinger
- **Year:** 2007
- **Location:** Baraboo, WI
- **Area:** 1,100 m^2 (11,900 ft^2)

The Aldo Leopold Foundation (ALF) was founded to work on land ethics that was originally developed by Aldo Leopold, the man who said: "*We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect… That land is community is the basic concept of ecology, but that land is to be loved and respected is an extension of ethics.*" (Leopold, 1949)

In 2008 AIA COTE top ten, the Aldo Leopold Foundation was in the spotlight as the first LEED Platinum, carbon neutral building and also recognized with an accolade from the Forest Stewardship Council for using sustainably-harvested timber throughout the structure – 78% of the wood used was FSC-certified and 92% of those materials were locally processed and harvested on site[32].

ALF applies some passive approaches to become close to a net-zero building and decrease energy consumption as much as possible. The Legacy Center was designed to use 70% less energy than a comparable conventional building. A 39.6-kW rooftop photovoltaic array produces more than 85% of the project's annual electricity needs. While the building falls about 15% short of being net zero in operation, on-site carbon sequestration in the managed forests, offsets the greenhouse gas emissions resulting from the organization's[33].

This Building could be in both categories B (a combination of naturally ventilated spaces and mechanically ventilated spaces), and C (Hybrid ventilation control strategy). I decided to put it under this category because the west wing is mechanically ventilated, while the rest of the building is naturally ventilated with the opportunity to switch to mechanical operation.

- **Ventilation strategies:**

The building is not exactly preforming as it was assumed in the design process. The energy consultants of the project had considered a hybrid control strategy for ventilation. The actual building control system was programmed to shut down the HVAC system when the operator switched the building to natural ventilation mode (Utzinger & Bradley, 2009). Moreover, a relatively unconventional system – an earth tube system – is implemented to reduce the thermal loads due to the fresh air. In what follows, I will explain more about both issues and other passive ventilation approaches applied in this project.

[32] https://inhabitat.com/aiacote-top-ten-green-building-projects-of-2008/
[33] Michael Utzinger, personal communication, 2020

Natural Ventilation Mode – Cross ventilation:

The natural mode mainly employs cross ventilation to provide adequate fresh air in swing seasons. The single floor building's occupied core is oriented along an east-west axis. Operable windows are situated both at ground level and in the building's clerestory space along the north and south façades.

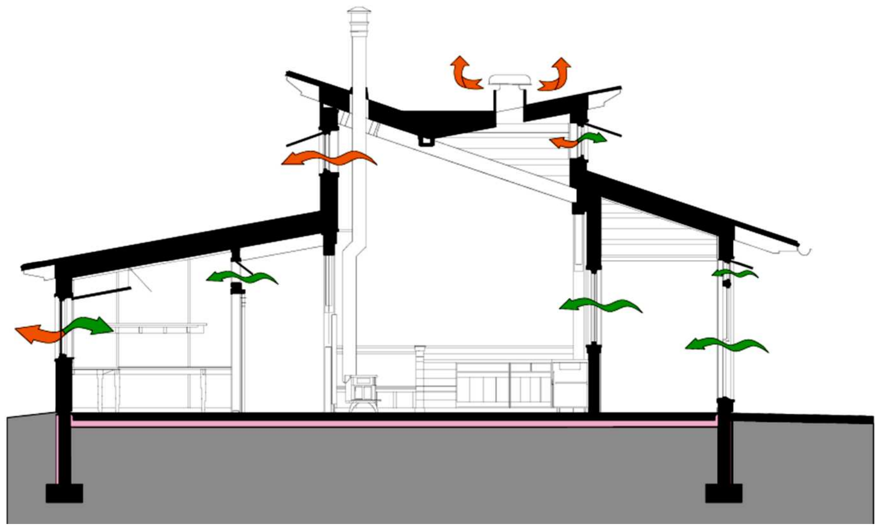

Figure 26. Aldo Leopold Foundation, cross ventilation diagram[34]

An interior wall separates a south facing corridor from the north facing offices but contains a number of large operable doors. In mechanical ventilation mode, the interior partitions are closed to isolate the offices from the south corridor. During natural ventilation mode, the partitions are opened to allow cross flow between the north and south façades (Utzinger).

The longitudinal plan and the central clerestory make the idea of cross ventilation applicable to the working areas. However, simulation revealed that the clerestory windows were not as effective for airflow (Utzinger & Bradley, 2009).

Mechanical Ventilation Mode – radiant slabs, earth tubes:

[34] from The Kubala Washatko Architects' archive

The air-handling unit delivers only required ventilation air, reducing fan sizes by 80% compared with typical systems. Displacement ventilation, VFD fans and demand control ventilation reduce energy demand.[35]

Under mechanical ventilation mode, outside air is drawn through a Horizontal Earth Tube System (HETS) consisting of five buried parallel ducts, each 30 m (100 ft.) long. Hypothetically, HETS reduces both heating and cooling loads of the building due to the relatively constant temperature of the undisturbed soil (Bradley & Utzinger, 2009). Passing through the pipes, air is cooled in summer and heated in winter before any other active conditioning (Peretti, Zarrella, De Carli, & Zecchin, 2013).

Other researchers have used distinct terms to refer to this system such as earth-air tube ventilation system (Yang & Zhang, 2015), earth-to-air heat exchangers, EAHE (Santanouris et al., 1995), earth-to-air heat exchanger (EAHE, EAHX, ETAHE, ATEHE) (Peretti et al., 2013) (Ascione, Bellia, & Minichiello, 2011), ground-coupled heat exchangers (Yang & Zhang, 2015), earth channels (Yang & Zhang, 2015), or simply buried pipes (Santanouris et al., 1995). Mongkon et al. use the term HETS (Horizontal Earth Tube System) (Mongkon, Thepa, Namprakai, & Pratinthong, 2013) (Mongkon, Thepa, Namprakai, & Pratinthong, 2014).

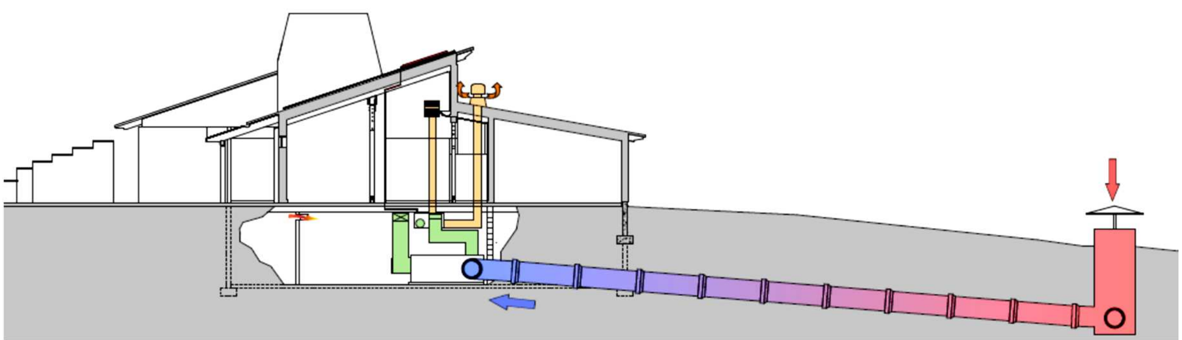

Figure 27. Earth Tube diagram[36]

[35] http://www.aiatopten.org/node/135

[36] from The Kubala Washatko Architects' archive

After passing through the HETS, air is UV filtered and passed through an air handler that contains a changeover coil, (winter heating and summer cooling) (Utzinger).

Figure 28. ALF, Earth Tube Outlet, UV Filter

The ground temperature is low enough during summer to cool and dehumidify air passing through the earth ducts to some extent, additional cooling of the ventilation air is necessary. Next figure illustrates the ambient air temperature and humidity entering and leaving the earth duct system for each hour of the year that the building is occupied (Utzinger).

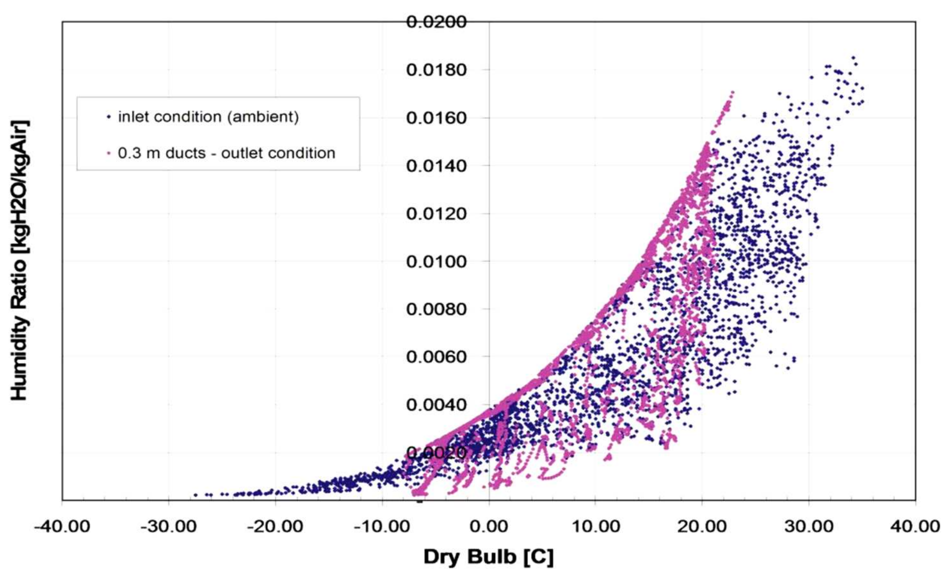

Figure 29. Earth duct inlet and outlet air conditions during building occupancy

The building's non-ventilation loads are met using radiant slabs through which either hot water (winter) or chilled water (summer is pumped (Utzinger). Ground source water-to-water heat pumps maintain a 500-gallon tank at 110°F in winter and 45°F in summer. Water from the tank is pumped to radiant slabs for space heating and cooling and coils to condition ventilation air.[37]

The west wing of the building containing the conference room has a separate ventilation system. Ventilation is provided by an enthalpy ventilator that is only operated when the conference wing is occupied (once per week in the simulation model) (Utzinger & Bradley, 2009).

Figure 30. Earth duct inlet and outlet air[38]

Natural ventilation reduced energy demand by 1,160 kWh per year, 1.9% of the total building energy demand and 4.9% of the total heating and cooling energy requirements. The earth tubes reduced total energy demand by 1,110 kWh per year, 1.8% of the total energy demand and 4.8% of the total heating and cooling requirements (Utzinger & Bradley, 2009).

Despite some discrepancies between the design and post occupancy performance, the project is an excellent case of an integrated design with a mutual collaboration within the architecture and the

[37] http://www.aiatopten.org/node/135
[38] from The Kubala Washatko Architects' archive

environmental consultant teams. In addition, it represents an example of simulation integration into the design process from schematic design to post occupancy evaluation (Utzinger & Bradley, 2009).

- **Psychrometric chart:**

In what follows, I study the psychrometric chart. The closest weather station available to climate consultant is Madison, WI. According to Climate Consultant, although we definitely need non-passive solutions for heating, most of the ventilation load could be provided by appropriate passive design approaches including natural ventilation, evaporative cooling, sun shading, and flushed thermal mass.

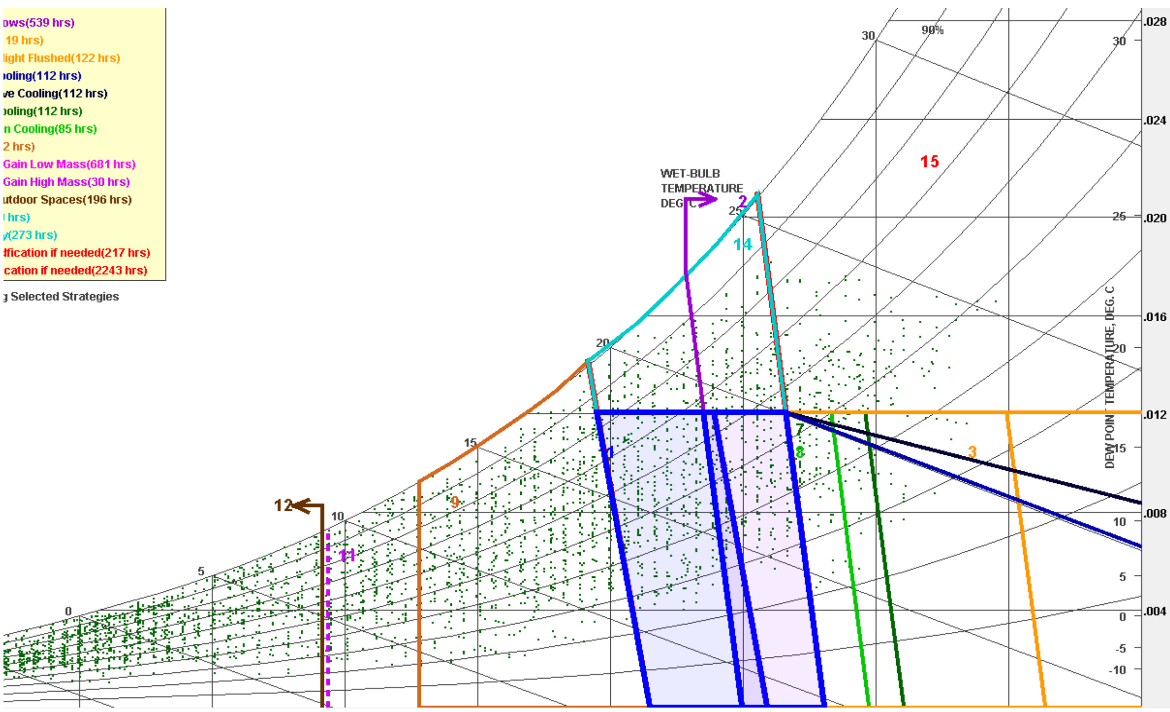

Figure 31. Psychrometric chart, Madison, WI – Climate Consultant

According to the environmental consultant, the window to floor area ratio is 21% all of which are operable (Utzinger). However, it is adequate to guess that this building would probably not face the possible glare problem of the other all-glass façade projects. The opening ratio seems to make sufficient area for ventilation, which is not too much to cause glare either.

Part C: Hybrid ventilation control strategy

5. **Deutsche Messe AG Hannover Administration Building**

Figure 32. Deutsche Messe AG Hannover Administration Building[39]

- **Architects:** Herzog + Partner
- **Engineers for HVAC:** Gerhard Hausladen
- **Year:** 1999
- **Location:** Hanover, Germany
- **Area:** 11,500 m^2 (123,800 ft^2)

"*Hanover's architecture may not be particularly spectacular. It is, however, distinguished by a quality of clarity and moderation.*" This is how Thomas Herzog defines his own work. In fact, the design mainly

[39] http://thomasherzogarchitekten.de/en/en-1999-dmag-hochhaus

revolves around the energy and environmental ideas such as natural ventilation, heating, cooling, and generally thermal comfort with low energy consumption, while harnessing the sun and wind energy. The two missions of the design could be defined as high-quality work places, and innovative exploitation of environmentally friendly forms of energy (Herzog, 2000).

The layout is articulated into a central working area 24 by 24 meters on plan and two access cores. Due to the tight site conditions resulted in a high-rise building. The building is 20 stories in height three of which belong to a recessed entrance hall, and 14 of which contain offices. The other three comprise lobby, boardrooms, and mechanical services. Each floor is capable of having a distinct arrangement including open-plan, individual or combined offices (Herzog, 2000).

- **Ventilation strategies:**

Both active and passive systems have merits and demerits. Passive systems seem to provide greater occupant control, healthier air, as well as save more energy. On the other hand, mechanical systems tend to maintain pressure better, perform more reliably, and provide precise thermal conditions (Axley, 2001). Then it is not far from mind to use hybrid systems with privileges of both natural and mechanical ventilation. In 2000, Phil Jones predicted that: “So, if we look to the future, buildings are more likely to have some form of hybrid ventilation system and there will be less prejudice for choosing either a natural or mechanical solution independent of building and site consideration.” (Jones, 2000). When Jones was talking about using hybrid systems in future, Herzog had already created a building applying hybrid ventilation system in 1999.

Hybrid double-skin façade, thermo-active slab and stack exhaust tower:

The Hannover Administration Building has a double skin façade. The outer skin employs flint glass, and the inner one contains wood-and-glass construction. The peripheral corridor between the two skins form a large-volume air exhaust duct. This space within the skins not only draws the air to the top of the exhaust tower, but also diminishes the wind effect and reduces insolation, which in turn results in less energy consumption.

Each office has individual operable windows to the peripheral duct. The offices have operable windows towards the peripheral duct. As soon as the occupant opens the window, a mechanical device closes the air inlet so that the system can switch between natural and mechanical ventilation (Herzog, 2000).

The exhaust air from all offices find its way to the peripheral exhaust through a central system of conduits beneath the floor slabs. The height of the exhaust tower and strong winds at the top create powerful air suction. A wind tunnel experiment had been implemented on the tower mock-up to fully perceive the system performance in advance. There is a heat-exchange unit at the top of the tower, which recovers 85% of the heating energy before air discharge in winter (Herzog, 2000).

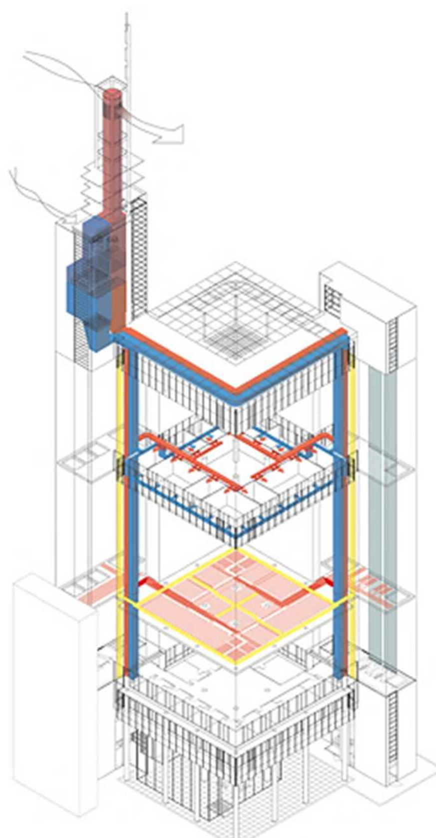

Figure 33. Isometric Diagram

- **Psychrometric chart:**

The closest weather station to Hanover seems to be Bremen[40].

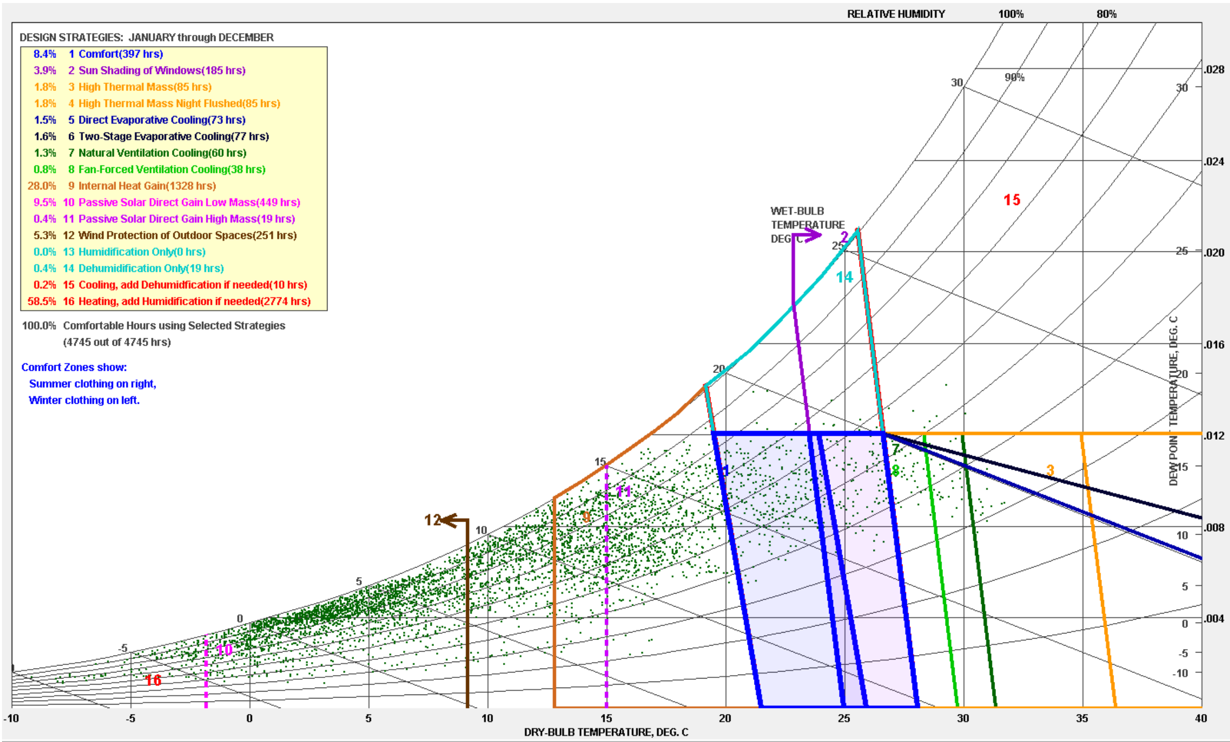

Figure 34. Psychrometric chart, Bremen, Germany – Climate Consultant

In this climate, it seems impossible to provide all heating, cooling and ventilation needs through passive systems, especially the heating needs. Considering this, it seems reasonable to combine mechanical and natural methods. Sun-shading, flushed thermal mass, direct evaporative cooling, natural ventilation cooling, and passive solar and internal heat gain help reduce energy consumption.

I could not find the opening ration even in Herzog's book (Sustainable height), but he does mention that each office has at least one 1.8-meter wide, room-height sliding casement. According to the plan, it seems that there are 14 offices in each floor containing 20 casements. Knowing the fact that the building contains 20 stories, and assuming 3 meters height for each floor, total operable area should be 2160 m^2

[40] https://energyplus.net/weather-location/europe_wmo_region_6/DEU//DEU_Bremen.102240_IWEC

approximately. Considering 11500 m^2 as total floor area, the ratio of operable openings on the inner skin to the floor area should be close to one-fifth or 20%.

An issue not addressed in the literature is whether the corridor width has been sufficient to avoid glare inside offices or not.

6. **Manitoba Hydro Place**

Figure 35. Manitoba Hydro Place[41]

- **Architects:** Smith Carter Architects and Engineers
- **Mech. and Elec. Engineering:** Earth Tech Canada Inc.
- **Year:** 2009
- **Location:** Winnipeg, Manitoba, Canada
- **Area:** 64,800 m^2 (697,500 ft^2)

[41] http://www.skyscrapercenter.com/building/id/9086

Manitoba Hydro Place was among the top winners of AIA Top Ten 2010.[42] Energy efficiency, urban revitalization and a supportive workplace were client[43]'s priorities. A primary goal was to achieve 60% energy reduction below national standards for energy consumption.

Winnipeg is known for its harsh climate, extremely cold in winter, hot and humid in summer. Temperatures vary 70 °C (126 °F) over a year, covering the range of -35 °C (-31 °F) to 35 °C (95 °F). A primary goal was to achieve 60% energy reduction below national standards for energy consumption. Considering the climate, it was an enormous challenge to provide the required energy efficiency. An Integrated Design Process (IDP) was necessary to find appropriate solutions (Lauster & Olsen, 2008). The design was so successful that past the goal and achieved an unprecedented number of 64.9% energy saving. This was possible by harnessing passive solar, wind, and geothermal energy.

- **Ventilation strategies:**

The building works as a hybrid system in which passive and mechanical systems tightly work each other to afford heating, cooling, and ventilation needs in winter, summer, and swing seasons.

Solar assisted stack ventilation:

Eight years after Axley talks about solar assisted stack ventilation to increase buoyancy-driven pressure differences (Axley, 2001), Manitoba Hydro Place was ready for occupancy. The solar chimney is both essential to the passive ventilation strategy and for presenting the building as a new urban icon.[44]

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[42] http://www.aiatopten.org/node/110
[43] Manitoba Hydro
[44] http://www.aiatopten.org/node/110

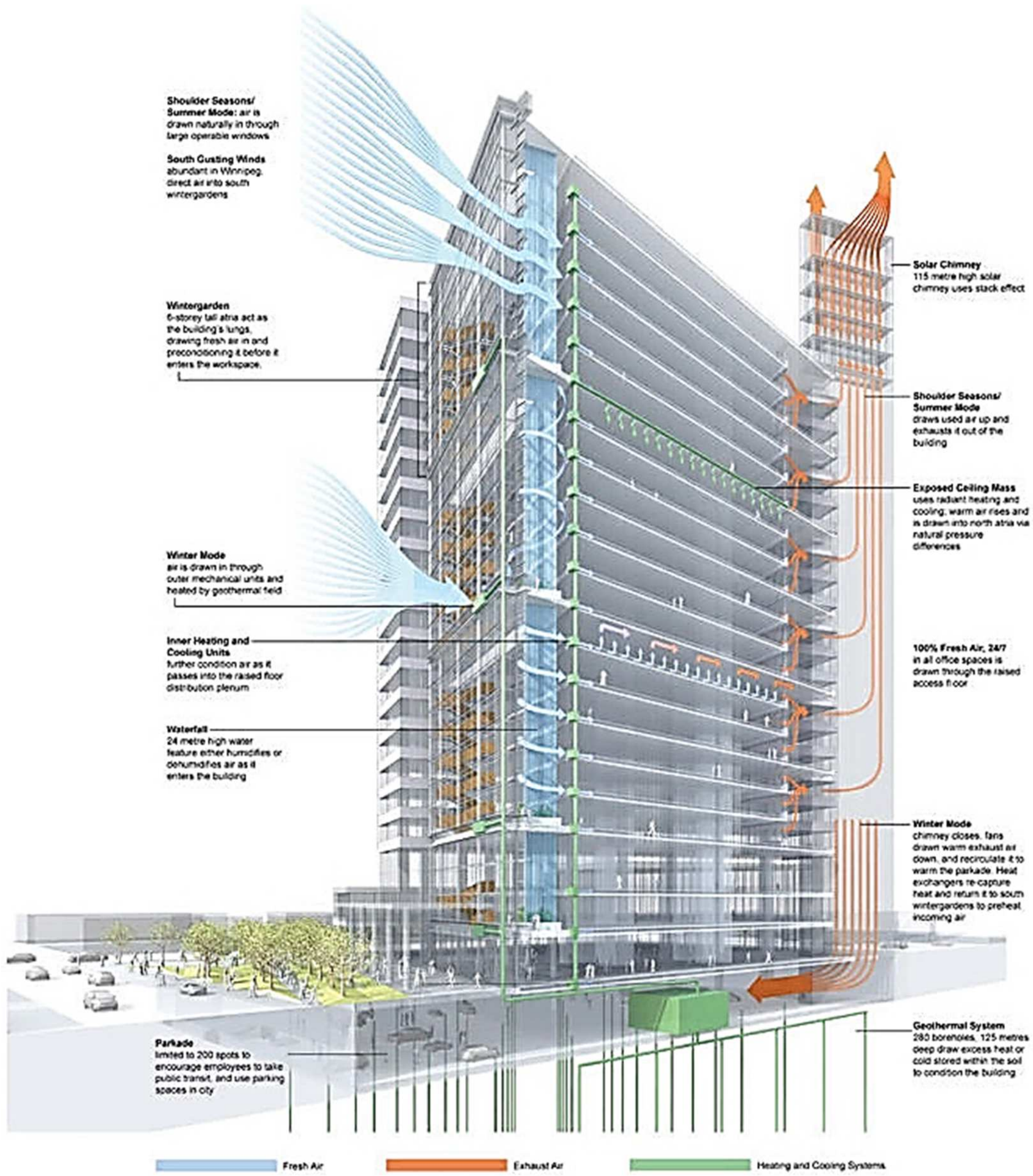


Figure 36. Manitoba Hydro Place, performance diagram[45]

The solar chimney performs as the "lungs" of the building for maximum fresh air delivery. In summer, ventilation is driven through the exhaust chimney completely by solar-augmented thermal buoyancy and wind. In winter, the solar chimney carries the exhaust air from the North atrium to a heat exchanger for heat recovery (Lauster & Olsen, 2008).

[45] http://www.aiatopten.org/node/110

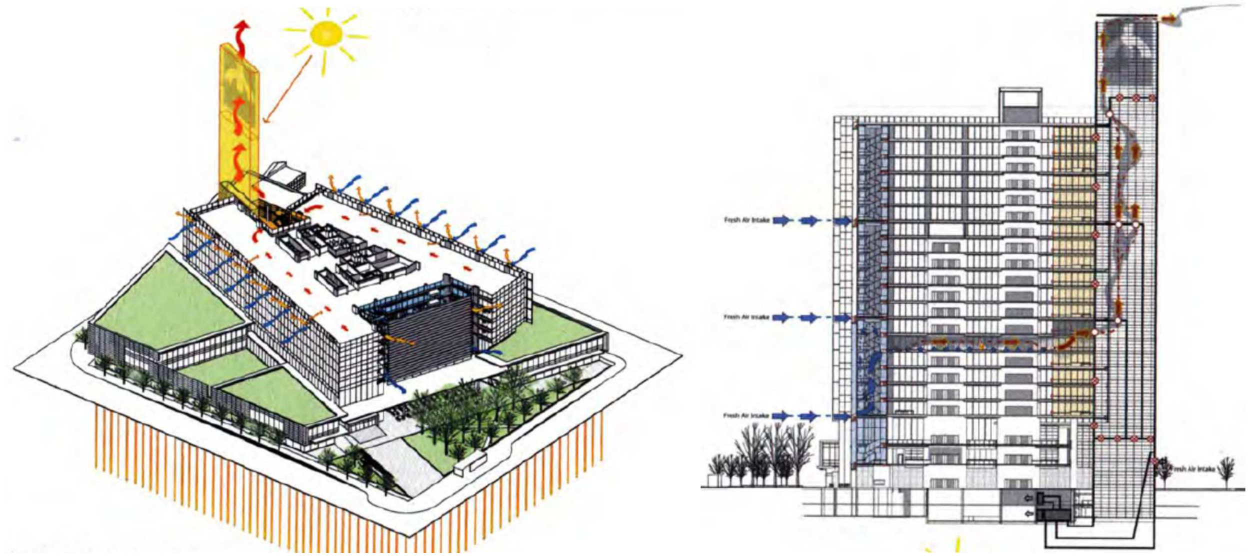


Figure 37. Manitoba Hydro Place, summer performance diagram

Double skin façade:

The building works in three seasonal modes including winter, summer, shoulder. While buffer zones (the space between the two façades) are configured in winter for thermal insulation and fresh air preheating, the configuration changes with season (Lauster & Olsen, 2008). A radiant slab between the double facades maintains minimum temperatures in winter and heat exchange with the geothermal field in summer.[46]

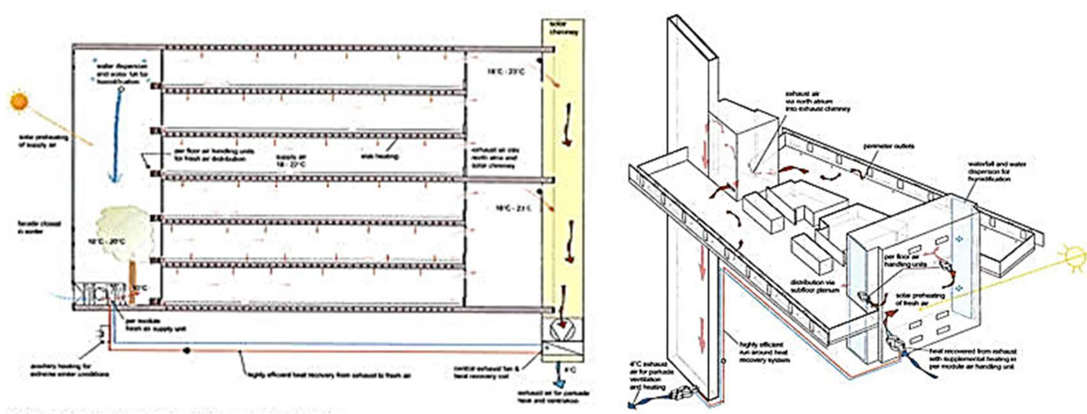


Figure 38. Manitoba Hydro Place, winter performance diagram

[46] http://www.aiatopten.org/node/110

Waterfall humidification/dehumidification:

A 24-meter tall conditioned waterfall humidifies or dehumidifies air as it enters the building. Chilled water dehumidifies the air in summer and warm water humidifies in winter. There are Air Handling Units (AHU) per floor, which further temper fresh air as necessary (Lauster & Olsen, 2008).

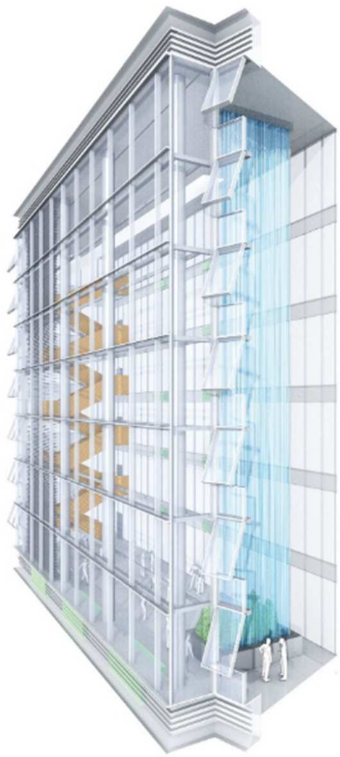


Figure 39. Manitoba Hydro Place, Waterfall[47]

Thermo-active slab attached to geothermal heat exchangers:

The air is further blown into a pressurized subfloor plenum on each level from which it enters the offices at outlets located along the perimeter (Lauster & Olsen, 2008). Thermo-active slab heating and cooling is supported by geothermal heat exchangers.[48]

[47] http://transsolar.com/projects/manitoba-hydro
[48] http://transsolar.com/projects/manitoba-hydro

A sophisticated building management system monitors internal and external environments to optimize lighting, solar shading, and heating and cooling loads while taking advantage of passive energy sources. User control of lighting in the offices, managed through desktop computers, is projected to save an additional 10%–15% in electrical lighting loads.[49]

To reflect the building's minimal active mechanical systems and optimized passive systems, the operations team includes an energy management engineer and a building controls specialist. A comprehensive energy management plan has been incorporated into the daily operations and maintenance processes.[50]

- **Psychrometric chart:**

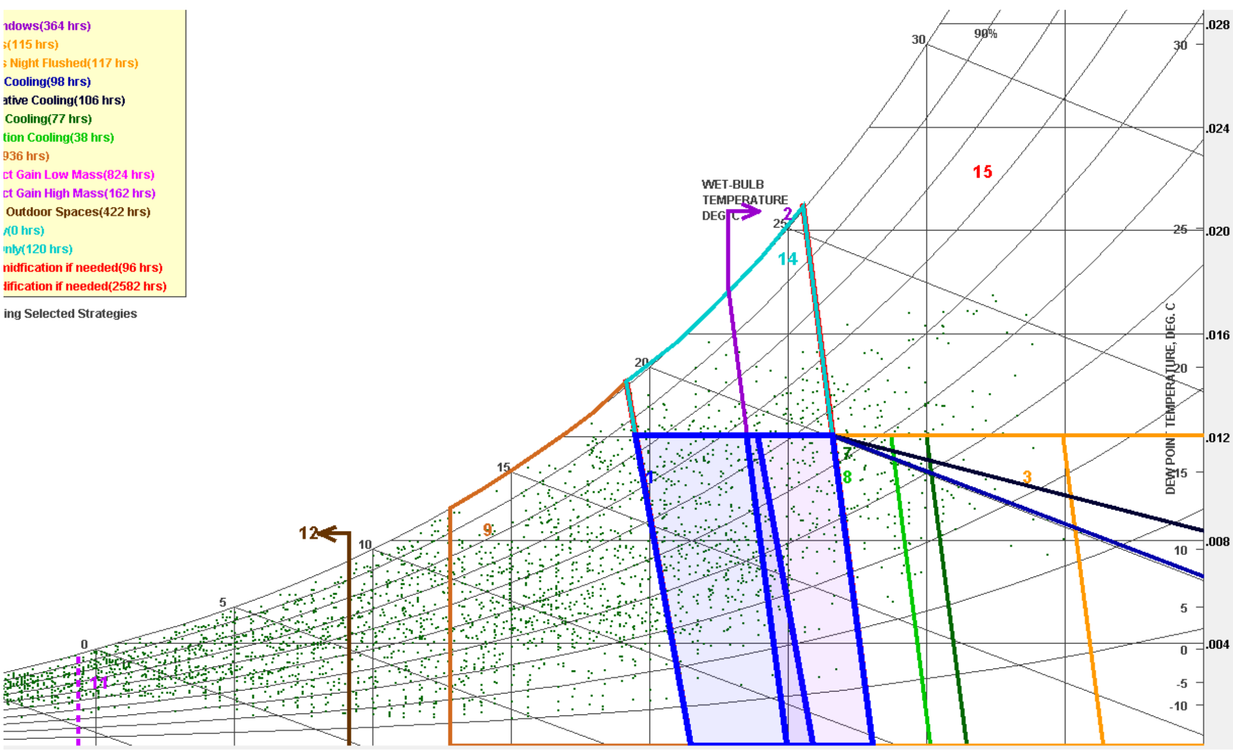


Figure 40. Psychrometric chart, Manitoba, Winnipeg, Canada – Climate Consultant

[49] http://www.aiatopten.org/node/110
[50] http://www.aiatopten.org/node/110

As mentioned in the literature, Manitoba faces severe climatic conditions both on winter and in summer. It is extremely cold in winter, and hot and humid in winter requiring all heating, cooling and ventilation solutions. It is too hard to provide all building needs only through passive approaches in such a geographical location. However, the project proved that even in such a harsh condition, 64% of energy consumption could be reduced.

It is mentioned in the literature that the offices access to operable windows controlled by the occupants. However, there is no clue about the area and percentage of these operable windows. That makes it hard to compare with other cases.

Part D: Natural ventilation with a control strategy

7. **San Francisco Federal Building**

Figure 41. San Francisco Federal Building[51]

- **Architects:** Thom Mayne, Morphosis design
- **Ventilation modelling:** Lawrence Berkeley National Laboratory

[51] Photo by Michael Utzinger

- **MEP engineers:** Ove Arup & Partners
- **Year:** 2007
- **Location:** San Francisco, California
- **Area:** 56,200 m^2 (605,000 ft^2)

"*The San Francisco Federal Building offers a frank, contemporary response to its context, but more importantly, it establishes a benchmark for sustainable design in its use of natural energy sources. During the design process, we learned that the same decisions that maximize energy efficiency could also help create a high-quality workspace that redefines bureaucratic culture. The building physically democratizes the workplace as it enhances health and comfort and empowers its users with a sense of control over their surroundings.*"[52]

Considering sustainability as their mission, Morphosis team were able to design a naturally ventilated office building on the west coast after the advent of air conditioning. The building is not only sustainable and practical, but also a benchmark in San Francisco's skyline.

"*As a result of the tower's narrow profile and strategic integration of structural, mechanical and electrical systems, the building provides natural ventilation to 70% of the work area in lieu of air conditioning and affords natural light and operable windows to 90% of the workstations.*"[53]

There are a couple of fascinating points to observe in this project, revolving around the ventilation ideas, but in a bigger picture. For instance, how the design team, the MEP[54] engineering team, and the ventilation simulation team collaborated in an integrated design approach or how the Lawrence Berkley National Laboratory carried out a Post Occupancy Evaluation (POE) considering various items regarding air quality. I would like to go over them a little bit, but first let us start with the ventilation strategies.

[52] https://www.morphosis.com/architecture/12/
[53] https://www.morphosis.com/architecture/12/
[54] Mechanical, Electrical, Plumbing

- **Ventilation strategies:**

In order to decide about the overall ventilation strategies, the Lawrence Berkley National Lab provided simulation for a few scenarios using DOE[55]'s beta version of EnergyPlus software. The scenarios included wind only, internal stack only, internal and external stack only, internal stack + wind, internal and external stack + wind.

The upper limit design criterion for cooling season was 79-82°F. The simulation team revealed the number of hours when the indoor base temperature was exceeded during the occupied hours during the cooling season.

Simulation divulged that the chimneys (external stacks) not only did not improve the performance of the interior stack and wind driven ventilation, but also had the potential to be counterproductive. Hence, the fund allocated to chimneys could be better used to provide high-performance double-glazed low-E glass on facades (McConahey, Haves, & Christ, 2002). Computational Fluid Dynamics (CFD) analysis were performed later (Levi, 2009) (Figure 42).

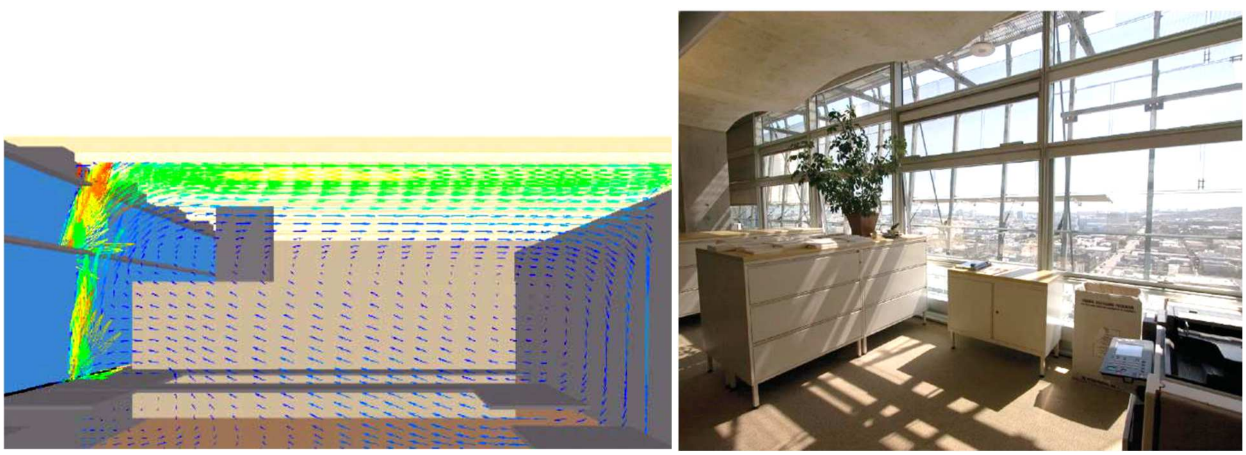


Figure 42. CFD simulations, Automatic and manual windows (left), Inside an office (right)[56]

[55] Department of Energy
[56] Photo by Michael Utzinger

Natural Ventilation System Components – Cross ventilation:

The main natural ventilation strategy used in this project is simply cross ventilation. In what follows, I am going to discuss how the ventilation consultants have made the simple idea of cross-ventilation applicable to such a large-scale project. These are a few tricks to make this system work:

- ✓ Locate windows on South and North facades of the building
- ✓ Use trickle ventilator[57] at floor level on the windward side (which are mechanically opened under automatic control), place corresponding set of relief windows set high on the leeward side open to exhaust the air at the other side of the building
- ✓ Let either façade of the building to be the outdoor air supply depending upon the prevailing winds
- ✓ Provide operable windows on either side of the building for use at the discretion of the occupants
- ✓ Locate the mechanically ventilated and air-conditioned office cabins in the central floor area (with isolated ventilated air due to the occupants need to keep their doors closed) (Apte et al., 2009)

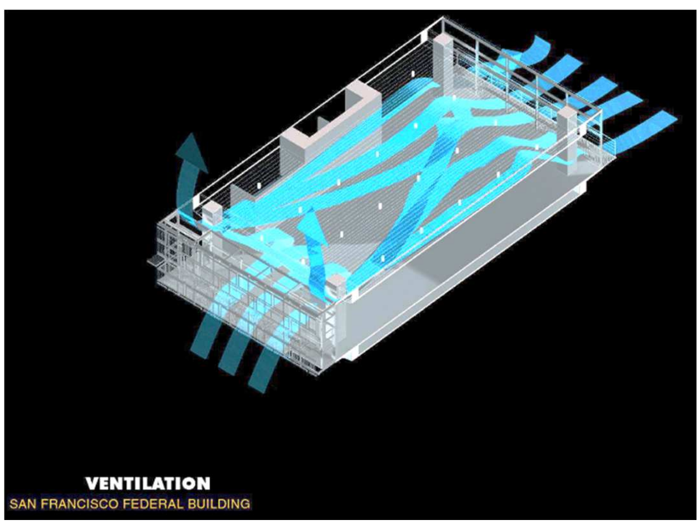


Figure 43. San Francisco Federal Building, Cross ventilation[58]

[57] A trickle vent is a very small opening in a window or other building envelope component to allow small amounts of ventilation in spaces intended to be naturally ventilated when major elements of the design - windows, doors, etc., are otherwise closed.

[58] https://www.morphosis.com/architecture/12/

Indirect Cooling – Night Cooling Strategies:

Most of the cross and stack ventilation strategies consider mainly exposed, or sometimes non-exposed-thermal mass which could be purged at night. Nocturnal ventilation provides the opportunity for the slabs to lose both internal and solar heat gains. McConahey et al. define night purge of structural heat as follows: "*The process by which "freely-cooled" nighttime air is intentionally allowed into the unoccupied building in order to reduce the surface temperature of exposed concrete thermal mass inside*" (McConahey et al., 2002). In the San Francisco Federal building, a combination of underfloor plenum (which is a byproduct of the upstand beam[59]) and motorized windows provide the opportunity for the building to employ nighttime purge.

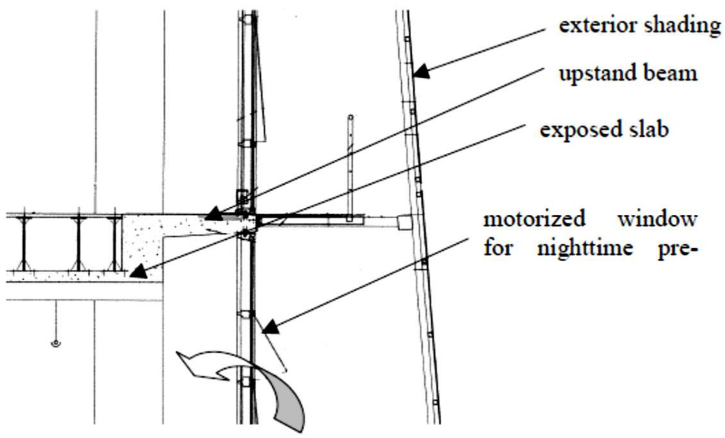


Figure 44. San Francisco Federal Building, Night purge, Shading

Natural Ventilation System Components – Internal stack ventilation:

Based on the EnergyPlus simulation results, the combination of wind-driven and internal stack-driven ventilation produces a modest improvement in performance compared to the wind only case. Adding

[59] A floor beam that projects at its ends above floor level (definition by Oxford Dictionary of Construction, Surveying and Civil Engineering, http://www.oxfordreference.com/view/10.1093/acref/9780199534463.001.0001/acref-9780199534463-e-7738)

internal stack is also very useful if there is significant reduction in wind pressure due to shielding by adjacent buildings (McConahey et al., 2002).

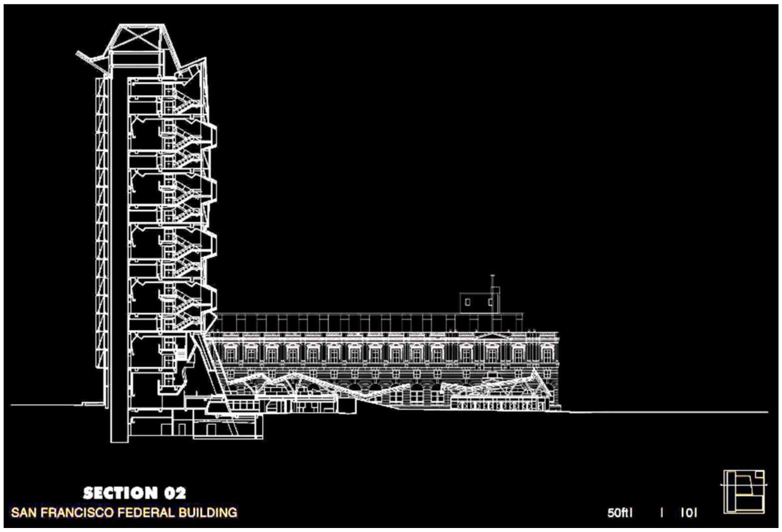


Figure 45. San Francisco Federal Building section[60]

- **Climate Consultant:**

The psychrometric chart for San Francisco is already illustrated. The chart clarifies that passive systems can provide almost all the natural and cooling needs of a building in San Francisco, which is not surprising considering San Francisco's moderate climate. The annual wind velocity is about 4 m/s, which should be enough for natural ventilation if not blocked by adjacent buildings.

- **Indoor Air Quality, POE:**

Lawrence Berkley National Lab has performed some Indoor Air Quality (IAQ) measurements as a Post Occupancy Evaluation (POE). What is remarkable is both the way they have done the ventilation measurements, and the number of elements they have considered for IAQ evaluation. For ventilation evaluation, they used the sulfur hexafluoride (SF_6) tracer gas decay method. They had injected the tracer

[60] https://www.morphosis.com/architecture/12/

gas through the lecture hall and monitored the SF_6 concentration by three portable Miran SapphIRE instruments[61]. The whole-space air exchange rate is calculated by means of the decay data. For IAQ evaluation, they had applied the following instruments:

- Fuji ZPF9 infrared for CO_2,
- Met-One™ 6-size-bin for counting particle,
- VOC sampling pump for Volatile organic compounds,
- Aldehyde sampling pump,
- Hobo™ temperature (T) logger, for air temperature,
- Hobo™ relative humidity (RH) logger, for air Relative Humidity,
- Aethalometer™ to measure black carbon particulate matter,
- TSI Qtrak™ to measure CO, CO_2, T and RH (Apte et al., 2009).

The measurements revealed that:

- ✓ The occupancy density in some spaces were much lower than expected.
- ✓ The spaces are highly over-ventilated relative to standards.
- ✓ The thermal condition is within ASHRAE 55 standard for thermal comfort: 72-81°F, 30- 60% RH.
- ✓ Indoor CO2 level is extremely low, due to high per-person ventilation rates.
- ✓ The measured particle concentrations indicated very low concentrations.
- ✓ Indoor VOC and aldehyde concentrations were low reflecting an absence of significant sources.
- ✓ IAQ is quite good. However, ventilation rates were high relative to minimum requirements and potentially wasteful of energy. If the ventilation rates were lowered, indoor pollutant concentrations would increase due to less dilution (Apte et al., 2009).

- **Integrated Design:**

[61] https://tools.thermofisher.com/content/sfs/brochures/D00876~.pdf

One of the reasons this building has been so successful in providing natural ventilation in a large-scale office building seems to be the perfect collaboration between different parties involved with the building design including the architects, the structural/MEP engineers (Ove Arup & Partners), the ventilation modelers (Lawrence Berkley National Lab), lighting engineers (Horton Lees Brogden Lighting Design, Inc.), etc. The teams highly cooperated to provide three main purposes including drastic reduction in energy consumption, creation of a healthy productive office environment, and redefinition of vertical circulation. McConahey et al. state that they answered the need to embed the architectural language of the building within the mechanical and structural engineering concepts through an integrated design process (McConahey et al., 2002).

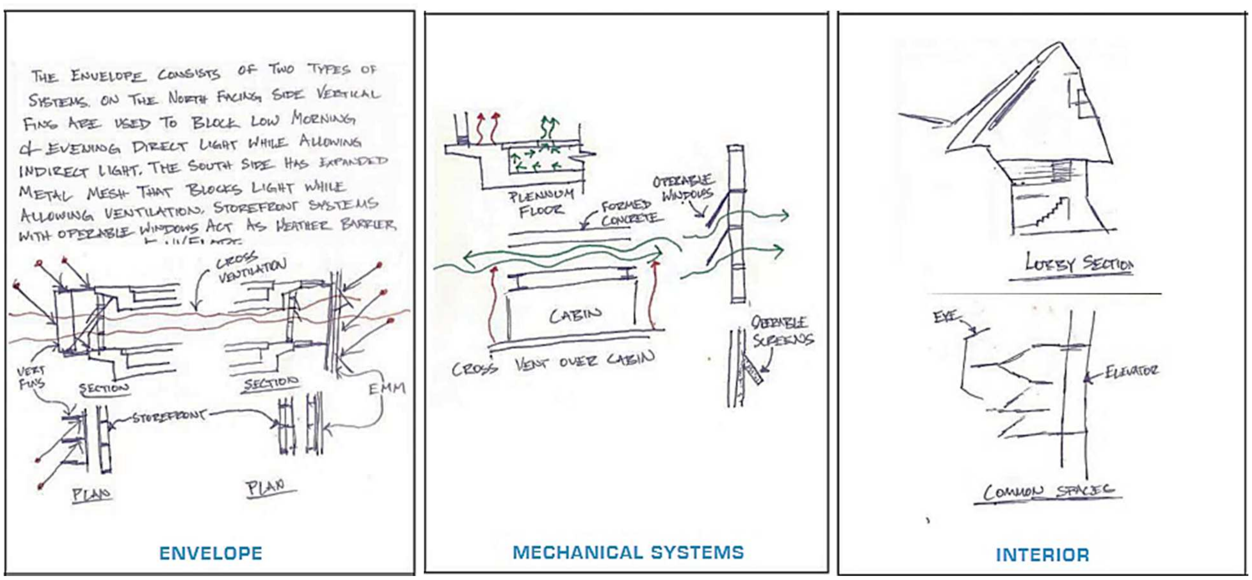


Figure 46. San Francisco Federal Building, Sketches reflecting early strategies[62]

- **Opening ratio:**

Thom Mayne indicates in an interview (by Melanie McGraw and Andrew Blum) that the porous screen in front of the facades acts like clothing protecting the building[63]. The computer-controlled screen opens up

[62] https://issuu.com/christineatienza/docs/sf-federal-building-tectonics
[63] https://vimeo.com/304541#

to 50%. Lower amount would block ventilation and view. Higher amount is not feasible since the material would begin to deform during the punching process (Lerum, 2008).

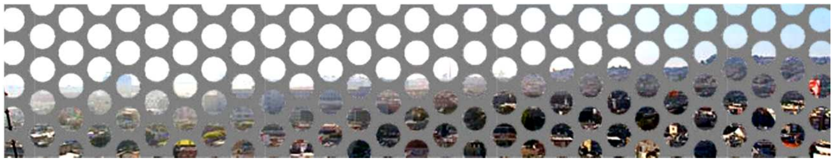


Figure 47. San Francisco Federal Building, Sunscreen

8. The Confederation of Indian Industries TQM Centre

Figure 48. Confederation of Indian Industries TQM Centre[64]

- **Architects:** Karan Grover Associates
- **Year:** 2003
- **Location:** Bangalore, India
- **Area:** 2,500 m² (27,000 ft²)

Bangalore is located in the Southern India, away ocean, and has a population of over 10 million people. Hot arid climate of Bangalore has provided the opportunity for passive evaporative cooling combined with

[64] Photo by Brian Ford

thermally massive structures to be the main characteristic of numerous buildings for over the past 500 years. In fact, this solution has resulted in perfect thermal comfort conditions in such a harsh climate.

The Adalaj step well, the well house at Mehmadabad, The kupagar of the Akbari Mahal, the Shish Mahal Agra, The Ghusal Khana Agra, and the Rai Pravina Mahal Orchha are only a few samples of Indian magnificent architecture providing thermal comfort along with highly elaborate and appealing spaces (Ford & Hewitt, 1996).

The Confederation of Indian Industries TQM Centre is located at the Western periphery of the city, away from congestion and pollution. The building includes a 200-seat auditorium, break rooms, a library, canteen and administrative offices within a garden landscape.

Energy efficiency was the main mission of the design. The main sponsor had requested that the building should only use passive systems. That is why Passive Downdraught Evaporative Cooling (PDEC) was adopted as the main cooling ventilation strategy (Ford et al., 2010).

- **Ventilation strategies:**

Passive Downdraught Evaporative Cooling (PDEC):

PDEC is based on ancient Middle Eastern and Eastern Asian strategies, which add evaporative cooling to the supply stack of a top-down or balanced stack ventilation system (Axley, 2001). In the more recent developments of this approach, water is injected high into the supply air stream as a fine spray cooling the air stream via evaporation and simultaneously increasing the supply air density; thereby, increasing the buoyancy induced pressure differences that drive airflow (Bowman, Eppel, Lomas, Robinson, & Cook, 2000).

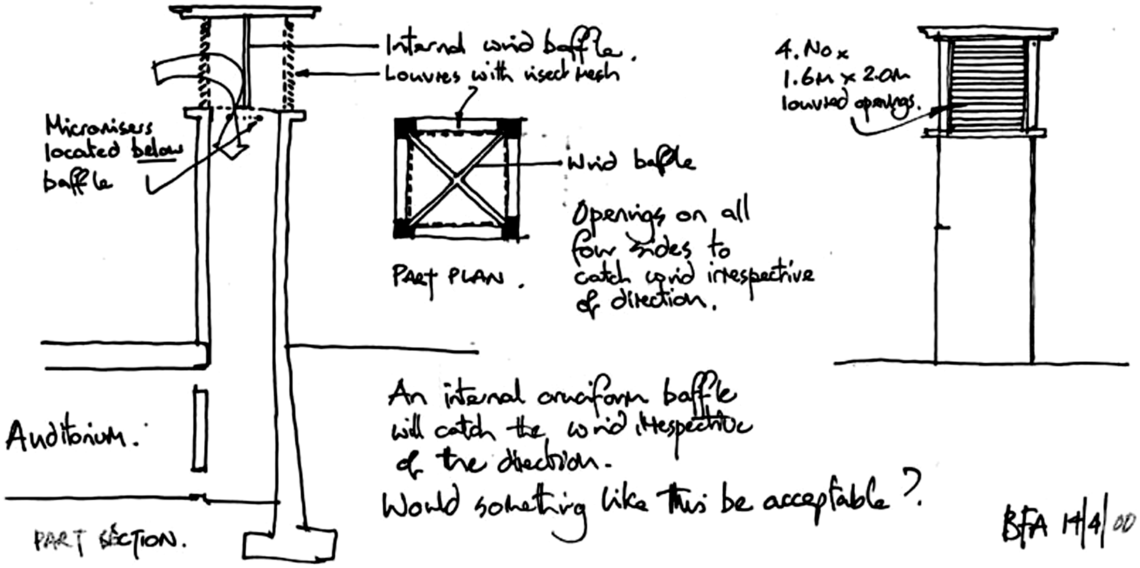


Figure 49. PDEC sketch

The auditorium accommodating 200 people is the largest space of the building. It is cooled down by three towers. Brian Ford Associates have performed a Computational Fluid Dynamics (CFD) analysis on the auditorium connected to the towers (Ford et al., 2010).

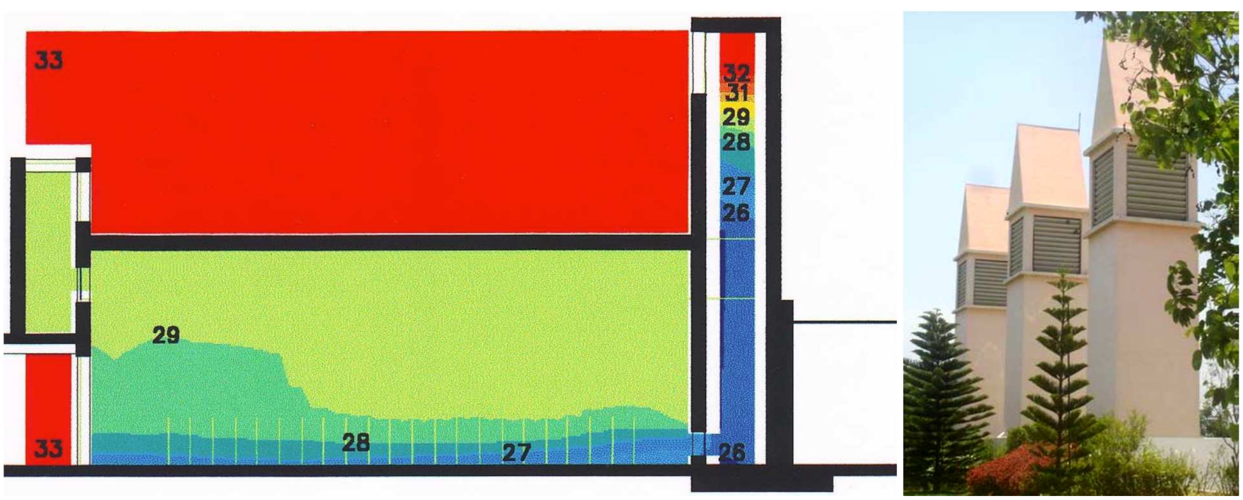


Figure 50. TQM Centre, Auditorium CFD analysis

The CFD analysis reveals that even when the air temperature is 33 °C, the temperature of the inside air is about 27 to 28 °C, without any mechanical ventilation.

During the hot dry summer period, fresh air is drawn in through the towers by openings at a low level; exhaust air goes out through openings at a higher level. At night in summer, and during the monsoon, the direction of the flow of air is reversed, being supplied at low level and exhausted at high level, driven by either natural buoyancy or a combination of buoyancy and wind (Ford et al., 2010).

PDEC electric control:

The PDEC system uses water-misting nozzles, located at high level within misting towers. The operation of the nozzles in each zone was designed to be controlled via an electrical panel linked to sensors measuring temperature and relative humidity in each zone. However, the system is currently manually controlled, relying on the judgement of staff as to when cooling is required (Ford et al., 2010).

Figure 51. PDEC misting towers

A survey was carried on to qualitatively investigate occupants' thermal satisfaction in May 2008. The survey divulged that overall, the general perception of the building has been favorable for about 99%. However, the results show that there have been some levels of inconvenience during summer. Nonetheless, air movement and air quality have been generally satisfactory (Ford et al., 2010).

Moreover, there has been a significant perception of diurnal temperature variation. This is not far from mind considering that the system is being controlled manually instead of electrically as supposed to. While automatic control is activated as soon as temperature or relative humidity pass certain limits, manual control might happen by delay which could result in sensible air movement and thermal dissatisfaction.

The idea of performing a qualitative Post Occupancy Evaluation (POE) aligned with quantitative ones seems to be highly useful since the thermal perception could be distinct for people with different race, gender, age, etc.

- **Psychrometric chart:**

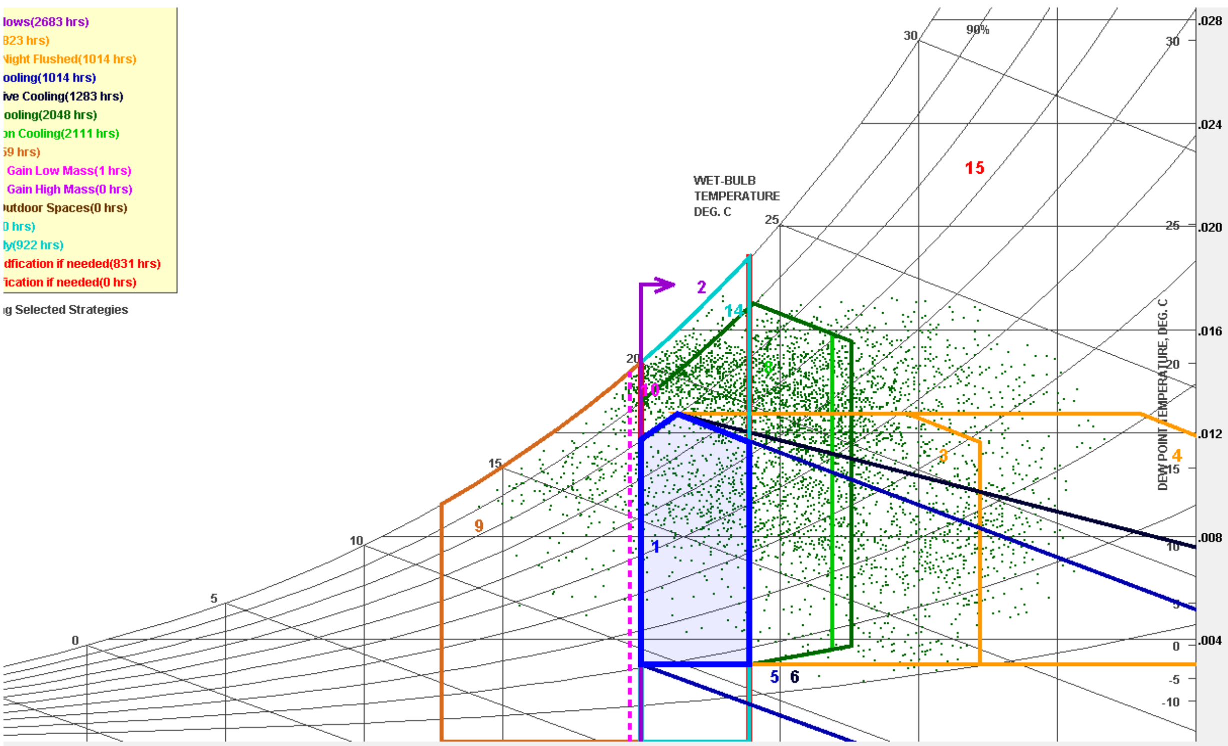


Figure 52. Psychrometric chart, Bangalore, India – Climate Consultant

Bangalore's psychrometric chart is much different from other case studies. For non-residential purposes, the heating load is almost zero. Evaporative and natural ventilation combined with sun shading and night ventilation can cover almost all cooling and ventilation needs. Having a fan to accelerate the process of convection and evaporation should answer to all needs without further mechanical equipment. This is why all thermal and ventilation needs can be provided by passive solutions in Bangalore:

- Due to high temperature fluctuations, night-purged thermally massive mass works perfectly.
- Due to high solar radiation, shading would simply decrease cooling loads tremendously.
- Due to low relative humidity, evaporative cooling is the best strategy.
- Due to the site location - far from the dense part of the city – favorable wind for natural ventilation is available.

There are many questions not answered by the literature review of this building. For instance, it does not mention why the building is not working as supposed to. Was there any problem with the electronic sensors? Does it cost more to control it manually or electronically? Do they have a plan to fix it and switch back to sensors?

Additionally, I could not find a definite number as a ratio of opening to the floor area. I believe this is very interesting building providing cool air for an auditorium only through a simple evaporative procedure. However, the building seems not to be very well documented, or at least not in English.

Precedent Studies, Final Analysis:

Here is a summary of the eight studies buildings. Although they all seem different, there might be some similarities if we look more carefully into the table. In what follows, I am going to discuss a few points, which sounded interesting to me:

1. Naturally ventilating the building has nothing to do with the size. There are buildings in the macro scale that have been almost completely naturally ventilated, and there are some buildings in the micro scale that has not been able to provide natural ventilation for all spaces.
2. In some climates, such as San Francisco, the weather makes it easier to provide natural ventilation due to the moderate temperature and favorable winds (if not blocked by adjacent buildings). However, even in the most severe climates such as Manitoba, Canada, designers have been able to reduce energy consumption by 64% in with a 65,000-m^2 area.

3. Similar approaches have been used in cities with similar climatic conditions. For instance, evaporative downdraught cooling has been applied as the main strategy in both Yazd and Bangalore, both of which have hot arid conditions.
4. The two skyscrapers have both used a hybrid control strategy. Both use a large exhaust stack, with offices the windows of which opens to the stack. The stack is employed to naturally draw the exhaust air out, while the supply air is conditioned through active systems. This reveals that although not all the ventilation cycle may be provided naturally in a high-rise building, combined solutions could still help reduce energy usage hugely.
5. Two out of eight projects use downdraught cooling, both of which are somehow evaporative, albeit in different ways. In the Confederation of Indian Industries TQM Centre, the misting nozzles are located at the top of the tower and humidify the air at the inlet. However, the ponds are at the bottom of the wind catcher at Dolat Abad garden. The air is humidified at the outlet of the wind catcher.

   Considering the heights of the two towers relative to the building height, the first approach – humidifying air at the source – seems to be more efficient. While the height of the misting tower in the Confederation of Indian Industries building is almost twice the height of the building, this ratio is about 4 in the case of Dolat Abad Garden.
6. Now, let us compare the stack ratios in four buildings applying stack towers:

- The Queens building: only a couple feet above the roof level (almost the same height as building),
- Hanover administration building: the height of the stack is almost 1.5 times the building height,
- Manitoba Hydro Place: the solar assisted stack tower is almost 1.25 times the building height,
- San Francisco Federal Building: the tower has almost the same height as the building.

Logically, the higher the stack height, the more wind it can draw in. I expected the ratio of stack height to building height to be at least 2 maybe. Nonetheless, it seems that in favorable wind conditions, stacks that are slightly higher than the building work with no problem.

7. In case of thermal masses supposed to be nightly flushed, they are usually exposed to be able to cool down through radiative and convective heat transfer.

   The material is brick, tile and concrete in the Queens building; brick in Dolat Abad garden and Confederation of Indian Industries TQM Centre; and exposed concrete in California Academy of Sciences museum and San Francisco Federal building. No matter what the material is, the process is the same.

8. Various ventilation systems have been calculated through different methods, the most favorite one seems to be Computational Fluid Dynamics (CFD). Other projects have also used TRNSYS, ENERGYPLUS, ROOM, or simply manual calculations.

9. Unfortunately, not all buildings have mentioned the ratio of openings to the floor area. Others have explained this number as a ratio to wall, rather than floor. Considering only the operable area, let us study the ones that have provided this number:

o Queens building	10%	Window to floor,	5% inlet, 5% outlet
o California Academy of Sciences	75%	Window to wall	
o Aldo Leopold Foundation	20%	Window to floor	
o Hanover administration building	20%	Window to floor	
o San Francisco Federal building	up to 50%	Window to wall	

The numbers vary tremendously. The operable window to floor area range within 10 – 20 %. The operable window to wall area covers a range of 20 to 75%.

What is important to have in mind is that the amount of opening should be judged based on the ventilation system.

- For instance, in case of California Academy of sciences, this number is too high simply because it only uses one-sided ventilation, which is much less efficient than cross ventilation.
- In San Francisco Federal Building, some sensors control the amount of facade opening; however, it is not allowed to exceed 50%; otherwise, the façade structure would be deformed.
- Considering the ratio of operable window to floor area, 10 to 20% seems reasonable for the purpose of cross ventilation.

10. While some strategies such as cross ventilation, stack ventilation or nightly flushed thermal mass are pretty commonplace, some systems including the green roof and Earth Tube system are very rare. It does not necessarily mean that these systems are not practical or useful, but it means not enough studies might have been done for these systems.
11. Some systems seem to be archaic. This does not mean that they cannot evolve to be a modern plausible system. The Passive Evaporative Downdraught Cooling is one of the developed systems, which is simply based upon the wind catcher idea. This system seems to be practical and some architects, especially from UK, have been studying and using them a lot in the past two decades.
12. Five out of the eight samples apply mechanical ventilation systems or electrically controlling sensors. Both the mechanical and electrical appliances need some kind of programming so that the building could switch between natural and mechanical ventilation (Aldo Leopold Foundation, Hannover Administration Building, Manitoba Hydro Place), or to turn on misting nozzles (in the Confederation of Indian Industries TQM Centre), or to change the size of the façade openings (San Francisco Federal Building).

    Nonetheless, two of these control systems are not working as supposed to, and the occupants have developed a manual switch system instead. In the Aldo Leopold Foundation, switching between natural and mechanical ventilation is not happening automatically. In the Confederation of Indian Industries TQM Centre, the nozzles were supposed to respond to some temperature and relative humidity sensors, but they are not. Two out of five – 40% - is a large number for building malfunction. It brings the question into mind that how many of the High-Performance Buildings actually perform as they assumed in the design process. What is the reason that some portion of them are not working appropriately? Is there any within the design, construction, occupancy, and post-occupancy cycles?

13. All eight samples are successful samples in terms of ventilation. A common point between all of them is an integrated design approach and tight collaboration between designers and engineers. In some of them (The Dolat Abad garden, and probably the Queens building), the architect and the engineering were the same person. Same person designed the building and suggested the ventilation system. It is not practical anymore for one person or team doing both jobs in more elaborate multi-functional buildings, such as the San Francisco Federal Building or California Academy of Sciences. However, a mutual collaboration between the architects and the engineers resulted into a high-performance building. How this collaboration is developed is an interesting subject.

Table 1. Summary of Ventilation Case Studies

	Building	Location	Area (m^2)	Natural Ventilation									Mech. Ventilation	Elec. sensors	Calc. Method
				Cross ventilation	Single-sided	Stack effect	Double skin facade	Evaporation	Down draught	Night-flushed thermal mass	Green roof	Earth Tubes			
A1	Queens Building at De Montfort University	Leicester, UK	10,050 (medium)	Window to Floor: 10%											Manual Calc.
A2	Dolata Abad Garden	Yazd, Iran	1,000 (small)	-				Pond	Wind catcher						-
B1	California Academy of Sciences museum	San Francisco, California	37,000 (large)		Window to Wall: 75%										CFD, ROOM 1
B2	Aldo Leopold Foundation	Baraboo, WI	1,100 (small)	Window to wall: 20%								30 m long			TRNSYS
C1	Deutsche Messe AG Hannover Administration Building	Hanover, Germany	11,500 (medium)		Window to Floor: 20%										Wind tunnel (structural?)
C2	Manitoba Hydro Place	Manitoba, Canada	65,000 (large)			Solar assisted		Water fall							CFD
D1	San Francisco Federal Building	San Francisco, California	56,000 (large)	Window to Wall: 50%											CFD, Energy Plus
D2	Confederation of Indian Industries TQM Centre	Bangalore, India	2,500 (small)					Misting nozzle							CFD

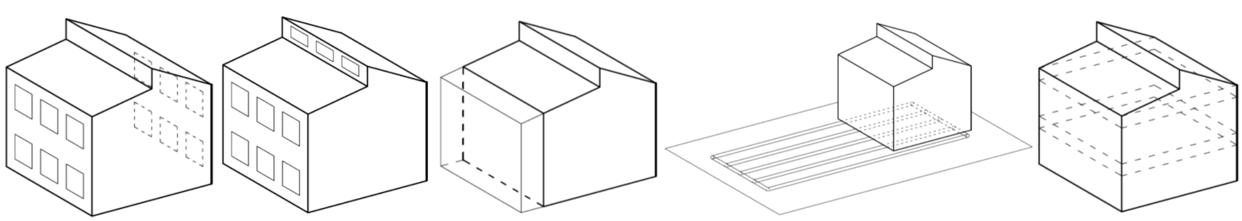
2.4. The Matrix of Ventilation and Design

Based on the case studies, a set of ventilation matrixes have been developed which relate some popular natural and hybrid ventilation strategies to architectural design elements. Moving within the rows of the matrixes demonstrates the design features affected by the ventilation method.

Table 2. Ventilation and Design Matrix

	Plan & Section	**Room Height**	**Form**	**Orientation**	**Enclosure**	**Structure**	**Footprint**	**Foundation**
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

The most popular strategies seem to be cross ventilation, stack ventilation, Double Skin Façade (DSF), earth tubes, and hybrid ventilation approaches with mechanical ventilation embedded in the plenums. First, I am going to study the effects of each approach separately, and then together.



Cross ventilation, Stack Ventilation, Double Skin Façade, Earth Tubes, Hybrid Ventilation

Figure 53. Ventilation Strategies Schematic Concepts

Cross Ventilation

Cross ventilation mainly affects the plan and section, form, orientation and enclosure.

Table 3. Cross Ventilation and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

Stack Ventilation

Stack ventilation mainly affects the plan and section, room height form, orientation, enclosure and the structure (due to the weight of the stack or chimney).

Table 4. Stack Ventilation and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

Double Skin Façade

Double Skin Façade almost affects all design features.

Table 5. Double Skin Facade and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

Earth Tubes

Earth Tubes have influence on the orientation, footprint and the foundation of the building – in terms of having no conflict with the foundation.

Table 6. Earth Tube Ventilation and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

Hybrid Ventilation

The hybrid ventilation with embedded plenums for the mechanical parts affect the plan and section, room height, and the structure because of the additional space and accordingly greater room height required to place the plenums.

Table 7. Hybrid Ventilation and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation								
Stack Ventilation								
Double Skin Facade								
Earth Tubes								
Hybrid Ventilation								

Ventilation Systems Combination

We might not use all these systems at the same time; however, we might combine a few of them together in which case, we should be aware of any possible conflicts.

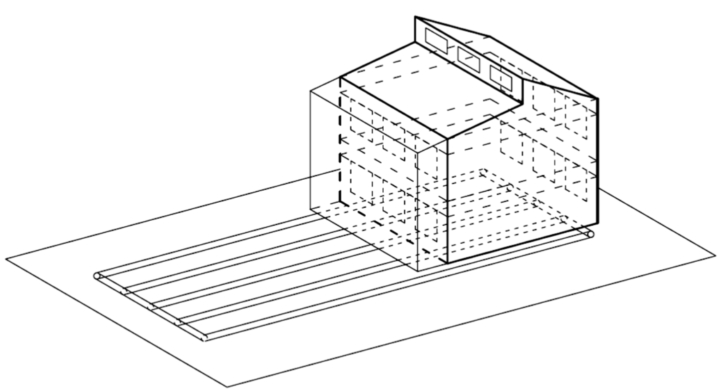


Figure 54. Ventilation Systems Combination Schematic Concepts

Now, let us put all mentioned systems in one matrix.

Table 8. Ventilation Systems Combination and Design Matrix

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Footprint	Foundation
Cross Ventilation	■		■	■	■			
Stack Ventilation	■	■	■	■	■	■		
Double Skin Facade	■	■	■		■	■	■	■
Earth Tubes				■			■	■
Hybrid Ventilation	■	■	■	■	■	■	■	■

When using more than one system, not only the horizontal rows, but also the vertical columns of the matrix should be studied. That is, the effect of different systems on one aspect of the design, such as room height, orientation, etc., should be investigated to avoid potential conflicts. Usually, a combination of different ventilation systems is used. Let us see how this matrix works for the ventilation case studies.

Table 9. Ventilation and Design Matrix in Ventilation Case Studies

	Plan & Section	Room Height	Form	Orientation	Enclosure	Structure	Foot print	Foundation
Queens Building Cross+ Stack Ventilation	■	■	■	■	■	■		
Dolat Abad Pavilion Cross+ Stack Ventilation + Downdraught Cooling	■	■	■	■	■	■	■	■
California Academy of Sciences museum Cross+ Stack Ventilation Single-Sided Ventilation	■	■	■	■	■	■		
Aldo Leopold Foundation Hybrid Ventilation: Cross Ventilation + Earth Tube Ventilation	■	■	■	■	■	■	■	■

Hannover Building Hybrid Ventilation: Double Skin Façade + Stack Exhaust Tower								
Manitoba Hydro Place Hybrid Ventilation: Double Skin Façade + Solar Stack Ventilation + Waterfall Humidification/ Dehumidification								
San Francisco Federal Building Cross+ Stack Ventilation								
Confederation of Indian Industries TQM Centre Downdraught Cooling								

2.5. Soil-Based Ventilation System Examples

In this section, I am going to look into some examples of ventilation systems based on air-to-soil relation. They all follow a very basic rule. The soil tends to be warmer than air in winter and cooler in summer. Why not use this feature of soil to naturally cool the air in summer and warm it up in winter in addition to provide the required outdoor fresh air?

1. Earth Rangers Centre, ON, Canada

Figure 55. Earth Rangers Centre

- **Architect:** John Buttner & Bautech Developments
- **Energy Consultant:** Transsolar Klimaengineering
- **Year:** 2004
- **Location:** Woodbridge, ON, Canada
- **Area:** 5,800 m^2 (60,000 ft^2)[65]

Earth Ranger Centre (ERC) is a Canadian kids' conservation organization. The center is committed to instill environmental knowledge, positivity, and the confidence to act in every child in Canada to show them that the things we do today will matter tomorrow.[66]

The building itself attempts to be an environmentally friendly one. One of the approaches to achieve this goal is using Earth Tubes, a passive technology that enables the transfer of ground source energy to heat or cool ventilation air. There are 9 pre-fabricated concrete tubes, buried 3 meters below the ground level, with the length and diameter of 20 and 0.9 meters respectively, at the East wing of the building.[67]

Figure 56. Earth Rangers Centre, Earth Tubes[68]

[65] http://www.tboake.com/sustain_casestudies/edited/Earth-Rangers-Centre.pdf
[66] http://www.earthrangers.org/about/
[67] http://www.ercshowcase.com/hvac/earth-tubes/
[68] http://www.ercshowcase.com/hvac/earth-tubes/

"Earth Tubes are probably the most-effective energy-saving feature of the ERC. They also allow us to use 100% fresh air within the building, without incurring large energy costs as a result."[69]

Fresh air enters the tubes through the inlet, passes through the tubes, then goes into a wall plenum, a UV light filter (to irradiate mold), a humidity controller, another UV light filter, and finally an Air Handling Unit before going into the air distribution channel. Moreover, the system applies high-efficient filters to remove airborne particulate matter such as dust to keep indoor air quality high. The intake plenum is estimated to provide a minimum of 2,100 L/S of air. There is an enthalpy-wheel, which captures heat and moisture from the exhaust air and releases it to the incoming fresh air. The wheel recovers up to 75% of exhaust energy.

Fresh air enters each zone at a low flow rate at floor level, then rises up due to the stack effect and exits from the top of the room.

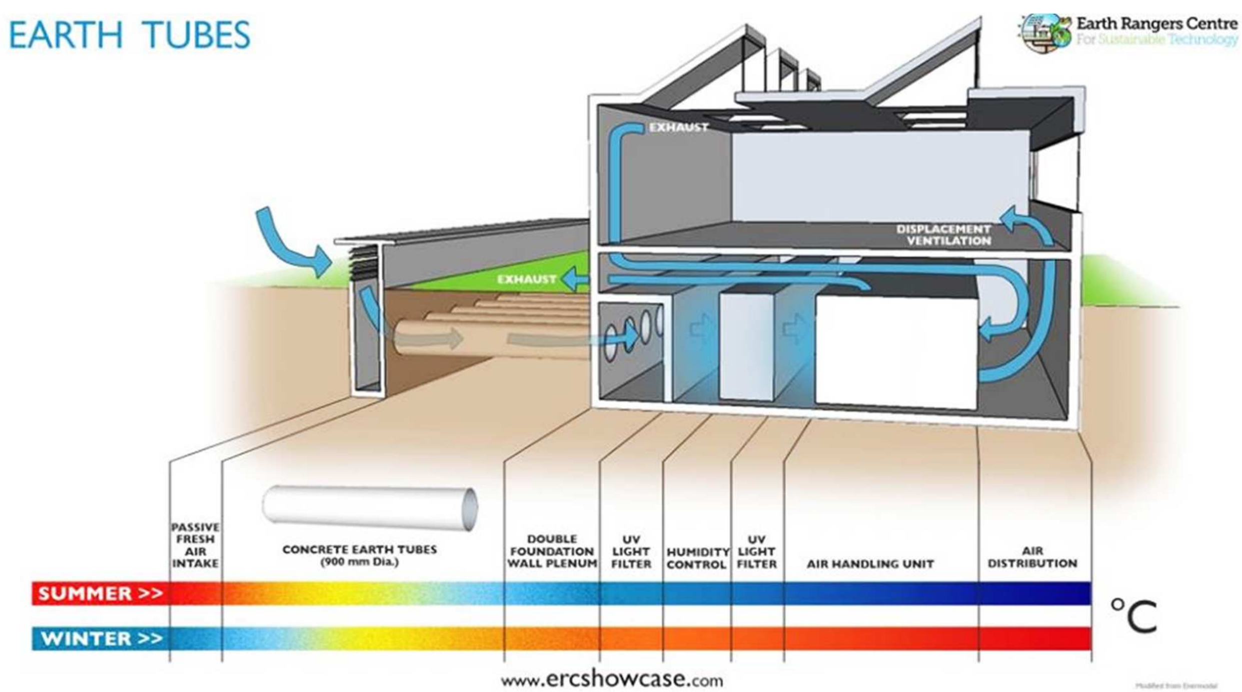


Figure 57. Earth Rangers Centre, Ventilation System Schematic Diagram

[69] http://www.ercshowcase.com/hvac/earth-tubes/

"The addition of earth tubes to a building's temperature control system could significantly reduce the need for certain kinds of ventilation air heating and cooling," says Michel Tardif, research engineer and project leader with Canmet Energy, a branch of Natural Resources Canada. In fact, results from a recent field study conducted in Toronto, Ont. indicated that earth tubes can warm winter air by as much as 14.3°C and cool summer air by about 6.8°C.[70] Fresh air enters each zone at a low flow rate at floor level, then rises up due to the stack effect and exits from the top of the room.[71]

2. Avasara Academy, Lavale, India

Figure 58. Avasara Academy

- **Architect:** case design[72]
- **Energy Consultant:** Transsolar Klimaengineering
- **Year:** 2016
- **Location:** Lavale, Maharashtra, India
- **Area:** 11,148 m^2 (120,000 ft^2)

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[70] https://www.energy-manager.ca/news/all-about-earth-tubes-an-energy-efficient-way-to-heat-cool-buildings-2770
[71] http://www.tboake.com/sustain_casestudies/edited/Earth-Rangers-Centre.pdf
[72] http://casedesign.in

Avasara Academy is a newly-opened school aiming to be the leader of education and educate young Indian women. The school is entirely built from recycled and local sourced materials collected from surrounding of the campus.

In this project, Transsolar Klimaengineering developed a particular passive climate strategies to achieve net-zero energy for the school with a modest budget.[73] One of these strategies is using earth ducts as part of the ventilation system. The internal earth tube cuts throughout the building to provide cool air.

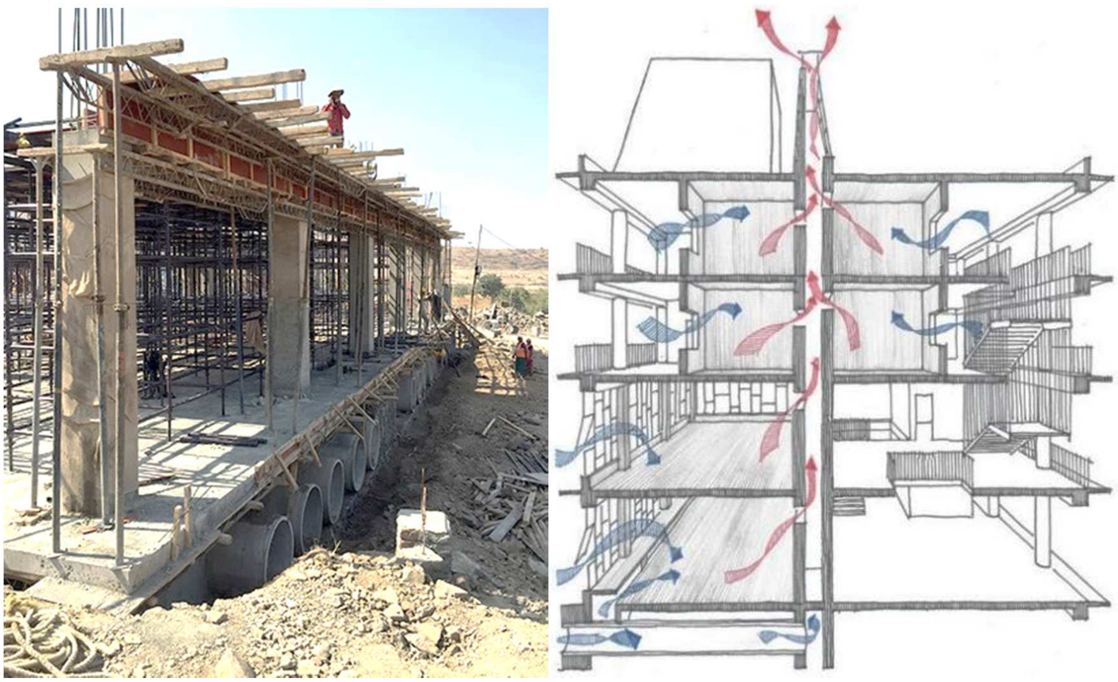

Figure 59. Avasara Academy, Earth Tubes

This strategy not only pre-cools the supply air, but also allows natural ventilation while eliminating any outside noise transmission (from the school campus) into classrooms. The air from all classrooms and living spaces passively transfers in three separate centrally located "exhaust cavities" which are integrated in the structural core of the building and eventually extends out as solar chimneys above roof level. These

73 https://worldarchitecture.org/articles/cvezc/avasara_academy_resembling_an_unfinished_structure_educates_young_women_in_the_moorland_of_pune.html

chimneys, using solar heat from the sun, are designed to passively drive the entire air flow, and provide cooling, throughout the building.

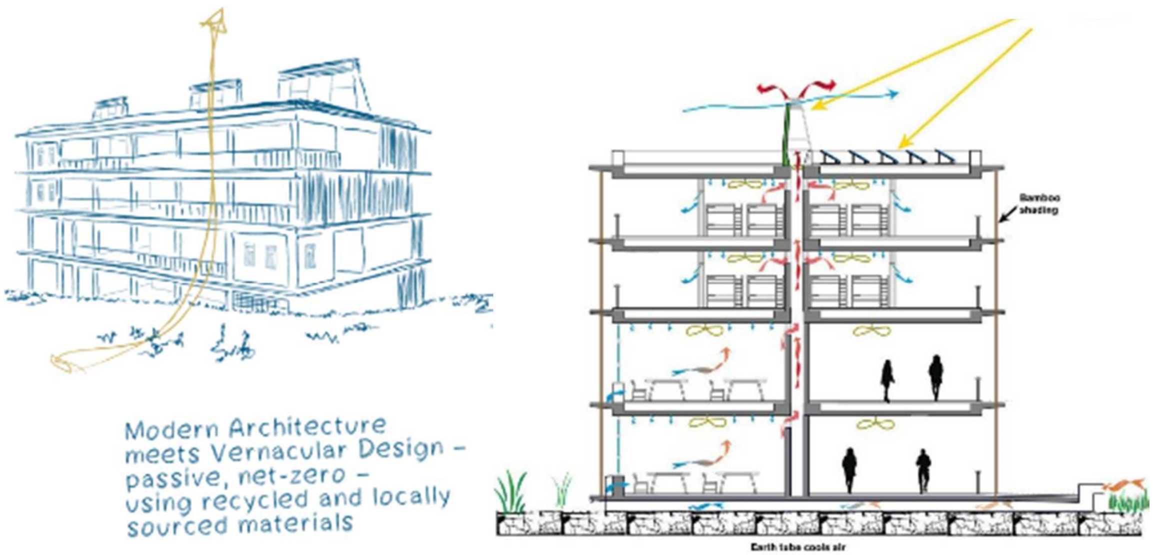

Figure 60. Avasara Academy, Ventilation Strategies

The proposed design reduced initial construction cost by approximately 7% through elimination of mechanical systems and reduced annual energy cost by 80% due to a completely passive design.[74]

3. UTSC, Environmental Science and Chemistry Building, ON, Canada

Figure 61. UTSC, Environmental Science and Chemistry Building[75]

[74] https://transsolar.com/projects/avasara-academy
[75] https://utsc.utoronto.ca/news-events/pictures/environmental-science-and-chemistry-building

- **Architect:** Diamond Schmitt Architects[76]
- **Energy Consultant:** Smith + Anderson[77]
- **Year:** 2015
- **Location:** Scarborough, ON, Canada
- **Area:** 10,200 m^2 (110,000 ft^2)

The Environmental Science and Chemistry Building on the University of Toronto's Scarborough Campus is a LEED Gold project designed by Diamond Schmitt Architects. The Smith + Andersen, a Canadian consulting engineering firm received the OCEA (Ontario Consulting Engineering Awards) 2017 Award for this project. Elaine Guenette, Associate at Smith + Andersen, mentions that "measured results by the University for 2016 are showing that the building is using about 50% of the energy of other, similar laboratory buildings on the campus."[78]

Under the landscape adjacent to the building, there are 6 stainless steel Earth Tubes which draw fresh air below ground where it naturally warms or cools in the earth's embrace before entering the HVAC system. "This pre-treatment tempers the air and significantly reduces the energy costs associated with heating and cooling. The Environmental Sciences and Chemistry Building requires up to 12 complete air changes per hour to meet fresh air demands. As part of an integrated learning component, one of the earth tubes has a translucent portion that passes under the entrance vestibule where an information kiosk explains the technology. A glass screen and floor opening permit students to see the earth tube in action. Wind deflectors and colored light emitting diodes (LEDs) are integrated to illustrate the air movement within the tube and emphasize the free heating/cooling these tubes extract from the latent energy of the soil."[79]

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[76] https://dsai.ca/
[77] http://smithandandersen.com/about
[78] http://smithandandersen.com/smith-andersen-receives-2017-ontario-consulting-engineering-award-merit
[79] https://dsai.ca/utsc-environmental-science-and-chemistry-building/

Figure 62. UTSC, Earth Tube Construction[80]

"The tubes emerge via a basement corridor, resembling tunnels out of a science fiction movie. They are tucked behind the main mechanical room, where other geothermal pipes run deep underneath the basement instead of being placed beside the building. The purified, temperate air is then circulated around the building, eventually being vented out via the labs."[81]

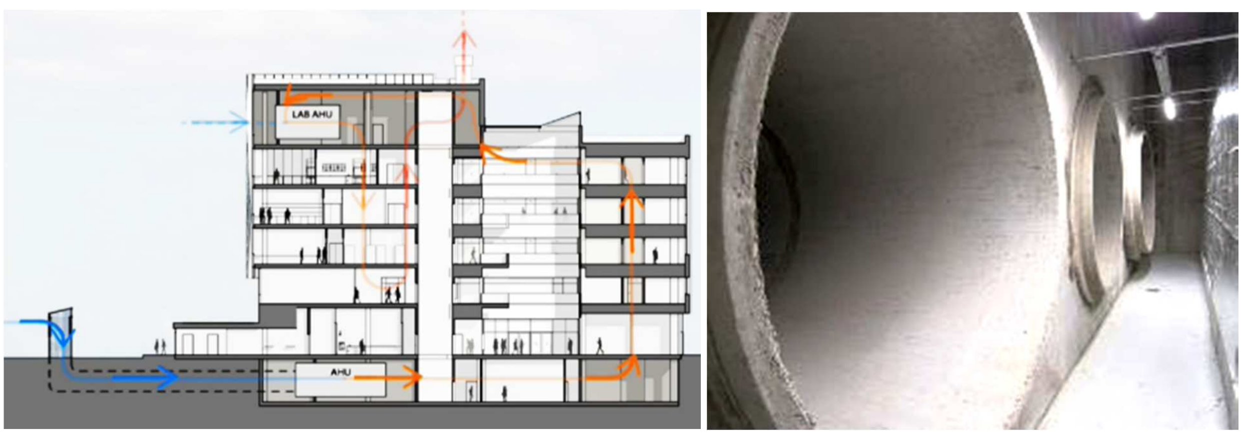

Figure 63. UTSC, Ventilation Diagram[82] (left), Basement Corridor[83] (right)

[80] https://dsai.ca/utsc-environmental-science-and-chemistry-building/
[81] https://torontoist.com/2016/01/introducing-utscs-environmental-science-chemistry-building/
[82] https://dsai.ca/utsc-environmental-science-and-chemistry-building/
[83] https://torontoist.com/2016/01/introducing-utscs-environmental-science-chemistry-building/

4. Lycée Charles de Gaulle Damascus, Syria

Figure 64. School in Damascus, Syria[84]

- **Architect:** Dagher, Hanna & Partners architects sarl, Beirut, Lebanon
- **Energy Consultant:** Transsolar Klimaengineering[85]
- **Year:** 2008
- **Location:** Damascus, Syria
- **Area:** 5,600 m^2 (60,2 78ft^2)

The school is a complex of small low-rise buildings, each with two stacked classrooms, connected via small courtyards. As a modern interpretation of the traditional architecture , the design aims to use combine Syrian architectural elements, the wind-catchers, with Earth ducts. Considering the Syria's climate, this seems to be a very appropriate approach. "Syria has a dry desert climate with hot days and cold nights. Wind-assisted solar chimneys are used to drive natural cross-ventilation through the classrooms. The chimneys are faced with a polycarbonate sheet to trap solar radiation and enhance the stack effect. During the day, outdoor intake air comes either directly from the shaded microclimate of the

[84] https://facadeworld.com/2013/10/29/lycee-charles-de-gaulle-damascus-syria/
[85] https://transsolar.com/projects/filter:chronological

courtyards or is pre-cooled using miniature earth ducts made up of pipes embedded in the ground floor slab. Operable louvers at the air intake and exhaust provide ventilation control."[86]

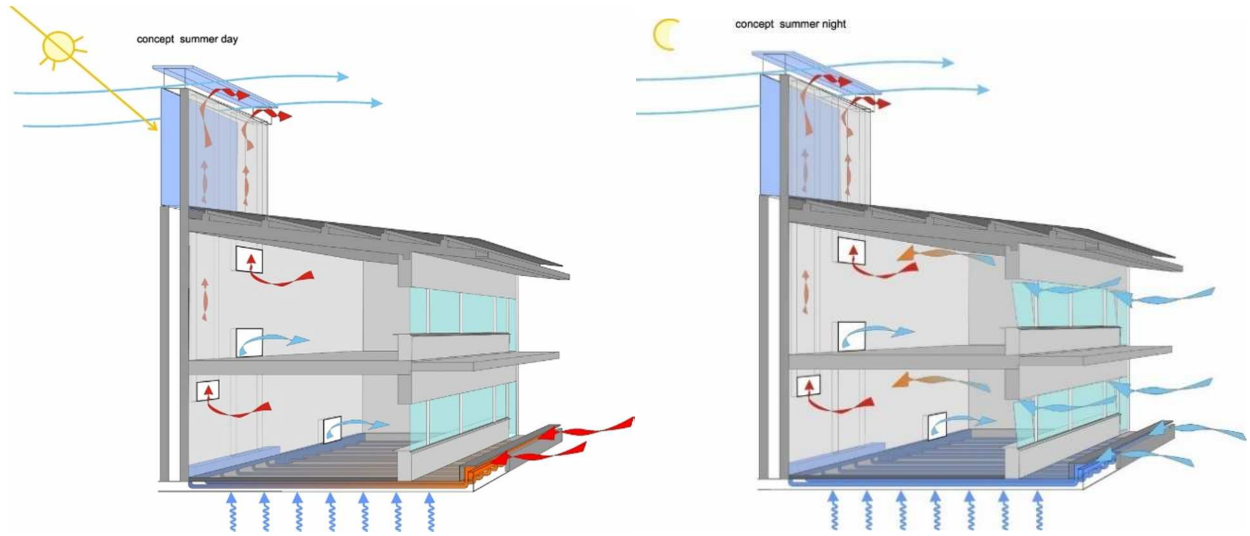

Figure 65. Damascus Schools, Ventilation Diagram, Summer Day (left), Summer Night (right)[87]

"During nighttime, the thermal mass of the chimney releases heat stored during the day and continues to draw air through the open windows and the earth ducts. Cool night air flushes the classrooms, cooling down the thermal mass and providing comfort for the following day."[88] The strategy is not only useful for pre-cooling the air in summer, but also for pre-heating the air in winter.

"This ventilation strategy is very similar to that found in traditional Iranian architecture where an outlet wind tower was used to pull warm air from a house, and where fresh air was pre-cooled by bringing it through underground chambers where it comes in contact with the earth and a *qanat* , or an underground water canal, before it reaches the indoor spaces it is meant to ventilate and cool."[89]

[86] https://www.german-architects.com/en/transsolar-klimaengineering-stuttgart/project/lycee-charles-de-gaulle
[87] https://www.german-architects.com/en/transsolar-klimaengineering-stuttgart/project/lycee-charles-de-gaulle
[88] https://www.german-architects.com/en/transsolar-klimaengineering-stuttgart/project/lycee-charles-de-gaulle
[89] http://www.carboun.com/sustainable-design/a-damascus-school-revives-traditional-cooling-techniques/

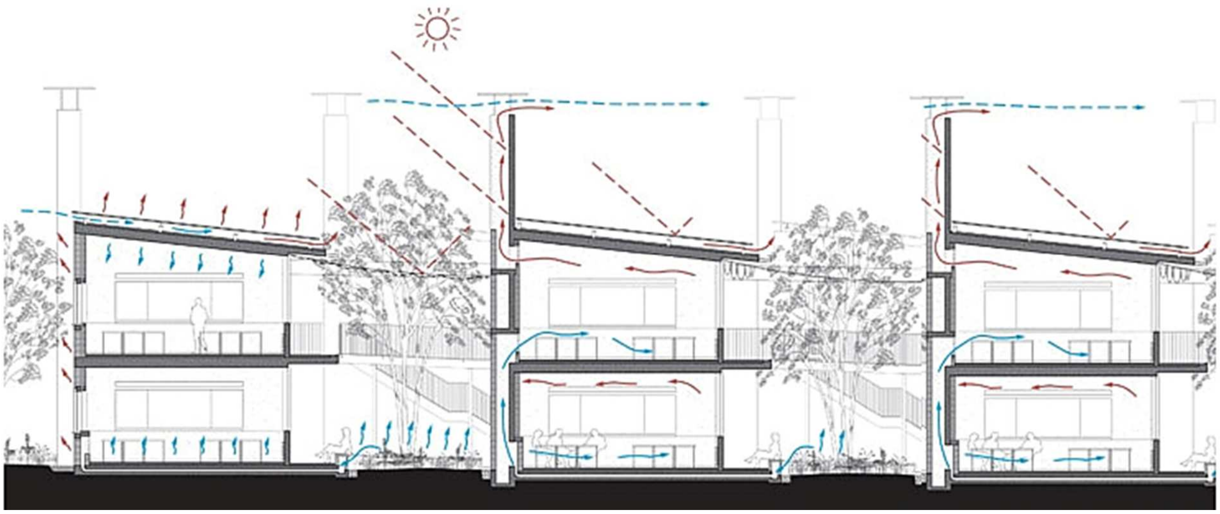

Figure 66. Diagram of integrated cooling and ventilation strategies[90]

The strategy is not only useful for pre-cooling the air in summer, but also for pre-heating the air in winter. ‘During the winter the earth ducts reverse their role, warming cool winter air as it comes into contact with earth’s steady temperature.”[91]

5. Bellevue Youth Theater, WA, USA

Figure 67. Bellevue Youth Theater, WA, USA[92]

[90] Copyrights: Ateliers Lion
[91] http://www.carboun.com/sustainable-design/a-damascus-school-revives-traditional-cooling-techniques/
[92] https://www.commercialarchitecturemagazine.com/youth-theatre-an-engineering-challenge/

- **Architect:** Becker Architects
- **Energy Consultant:** Ecotope[93]
- **Year: 2015**
- **Location:** Bellevue, Washington, USA
- **Area:** 1,100 m^2 (12,000 ft^2)

The Bellevue Youth Theater is a LEED-Gold certified building. Being located in a park, a green roof covers the building so that it does not cause any conflicts with the Crossroads Park landscape. A geothermal heating/cooling system has been considered by means of The BlueDuct® underground pre-insulated duct system, which is installed around the inside perimeter of the Bellevue Youth Theatre.[94]

Figure 68. Bellevue Youth Theater, BlueDuct® System[95]

"Ground source heat pumps were chosen as the mechanical system to harmonize with the below ground nature of the building and eliminate all noise and mechanical equipment presence outside in the park. The result is an extremely quiet energy efficient building that provides an important community function while integrating with and augmenting a public open space."[96]

Let us see how the Earth tube system has affected the soil-based ventilation system case studies.

[93] http://ecotope.com/project/bellevue-youth-theater/
[94] https://www.aqcind.com/cubeportfolio/bellevue-youth-theater-washington/
[95] https://www.txap.com/wp-content/uploads/2017/01/Bellevue-Youth-Theater.pdf
[96] https://pugetsoundashrae.org/congratulate-our-technology-award-winners/

Table 10. Ventilation and Design Matrix in Earth Tube Case Studies

	Plan & Section	**Room Height**	**Form**	**Orientation**	**Enclosure**	**Structure**	**Foot print**	**Foundation**
Earth Rangers Centre Earth Tube+ Stack Effect								
Avasara Academy Earth Tube+ Stack Effect								
UTSC, Environmental Science & Chemistry Building Earth Tube+ Stack Effect								
Lycée Charles de Gaulle Damascus Earth Tube+ Stack Effect								
Bellevue Youth Theater Earth Tube								

In four out of the five cases, the Earth Tube has been used in combination with stack ventilation. The integration of the two has influenced almost all aspects of the building design.

3. Parametric Ventilation Design and Validation

The trend of parametric performance evaluation, starting from early design process is currently developing. The merits of this approach include simultaneous form and performance developing, timesaving, and having a holistic view during the design process. Unfeasibility of ideas will be figured out early in the design process and conflicts between different elements will show up faster. More importantly, it is within the same architectural software using the parametric architectural language. Developing building analysis tools prevents the need to going back and forth within different software. In parametric performative approach, visualization happens in the same virtual architectural environment.

Pulling components from Grasshopper for means of performance analysis is getting more common rather than a large standalone simulation model. This chapter looks at validating components for inclusion in ventilation simulation modeling. Validation happens through measured data from Schlitz Audubon Nature Center (SANC) in Bayside, Wisconsin. A natural ventilation model of the meeting room at SANC was created using off-the-shelf components for TMY climate data and natural ventilation from Ladybug and Honeybee. Moreover, this chapter investigates integration the self-written Earth Tube component into a full building simulation model using available components from Ladybug and Honeybee. The airflow volume from simulation is compared with the airflow rate obtained based on CO_2 concentrations.

This chapter also illustrates the use of 3D design optimization tool which includes performative outcomes based on geometric design variables. It also provides a full exploration of the methodology of creating a three-dimensional model and performing simulation and optimization from off-the-shelf components in Grasshopper.

3.1. Parametric Ventilation Design

To create and analyze the ventilation systems parametrically, we do not have to start from scratch. There are already some plugins in Grasshopper which allow you study the natural and mechanical ventilation modes separately. One of the most commonplace ventilation plugins available within Grasshopper is Ladybugs tools (Sadeghipour Roudsari and Park 2013). Ladybugs tools is a collection of applications including a variety of components such as TMY climate data, natural ventilation, psychrometric chart, 3D chart display, program and occupancy schedules and so on.

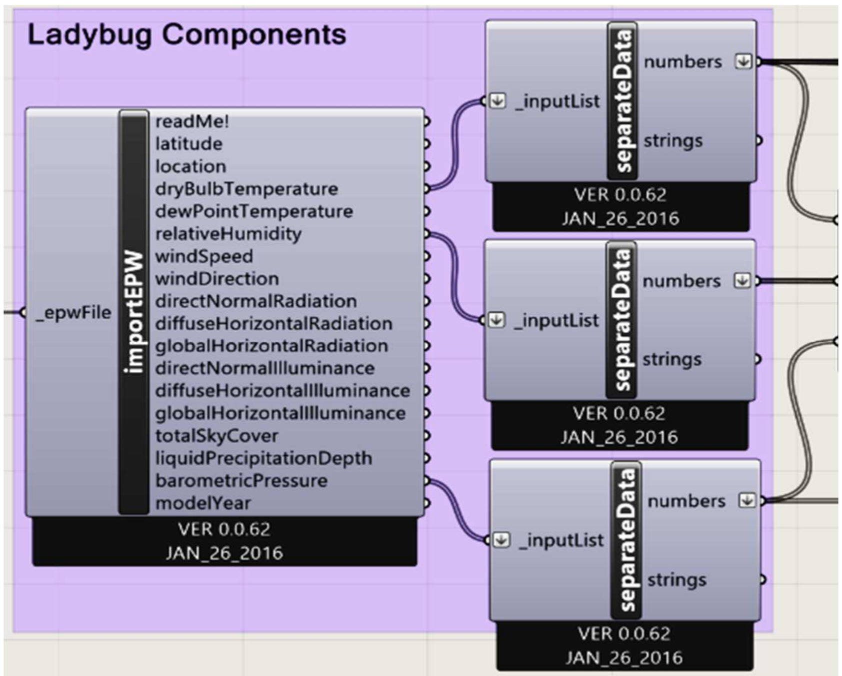

Figure 69. Grasshopper Components, Ladybug Climate Data Tools

The first step in the ventilation analysis is to determine the required ventilation rate. Minimum ventilation rates in breathing zones are listed in the ASHRAE Standard 62.1-2013 for various occupancy categories (ASHRAE 62.1, 2013). Equation 1 determines the minimum airflow value as a function of number of occupants and the floor area.

$$V_{bz} = R_p \times P_z + R_a \times A_z \qquad (1)$$

- V_{bz} = Outdoor airflow of the breathing zone, L/s
- R_p = Outdoor airflow rate per person, L/s-person
- P_z = Zone population

- R_a = Outdoor airflow rate per unit area, L/s-m^2
- A_z = Zone floor area, m^2

Two main types of natural ventilation are cross ventilation and stack ventilation. The Ladybug components use the EnergyPlus engine, which is aligned with the ASHRAE Fundamentals (EnergyPlus 8.9.0 Engineering Reference, 2018; ASHRAE Fundamentals, 2013). Equation 2 is the basis of cross ventilation calculations.

$$Q = C_v\, A\, U \qquad (2)$$

- Q = Airflow rate, m^3/s
- C_v = Effectiveness of openings
- A = Free area of inlet opening, m^2
- U = Wind speed, m/s

Equation 3 is the basis of stack effect calculations.

$$Q = C_D\, A \sqrt{2\, g\, \Delta H_{NPL} (T_i - T_o)/T_i} \qquad (3)$$

- Q = Airflow rate, m^3/s
- C_D = Discharge Coefficient for opening
- A = Free area of inlet opening, m^2
- g = acceleration of gravity, m/s^2
- ΔH_{NPL} = Height from midpoint of lower opening to NPL (Neutral Pressure Level), m
- T_i = indoor temperature, K
- T_o = Outdoor temperature, K

The total airflow rate should satisfy the ASHRAE breathing requirements. Total airflow could be provided by means of natural, mechanical, or hybrid ventilation. In the hybrid mode, the ventilation switches between the natural ventilation, when possible, and mechanical ventilation, when required. As previously explained in the literature review, by defining the right control system, one can perform a hybrid ventilation. In this case, existing components to evaluate natural and mechanical modes can be used.

What would be ideal is to keep all the simulation pieces in the same place that the 3D modeling happens. One can design, visualize, evaluate, and even optimize the system in only one platform needless to switch between numerous software.

As a case in point, the ventilation of the auditorium of the Schlitz Audubon Nature Center (SANC) has been studied. A natural ventilation model of the auditorium at SANC is created using off-the-shelf components for Typical Meteorological Year (TMY) climate data and natural ventilation tools from Ladybug. This chapter further includes the results of attaching a hypothetical Earth Tube heat exchanger to room, adding mechanical ventilation and looking to keep thermal comfort in the desired range.

3.2. Schlitz Audubon Nature Center

The Schlitz Audubon Nature Center (SANC) building is located at Bayside, WI, next to Lake Michigan. The hill on the east side connects the building to the water edge. SANC is about 30 m above the lake level.

The auditorium of SANC, which is shown by the red color in the following image, is located at the North side of the building. It is designed to benefit from natural ventilation through six operable windows in the breathing zone, three at the east and three at the west side, promoting cross ventilation. It also has operable windows on both the east and west sides of a clerestory space above the breathing zone.

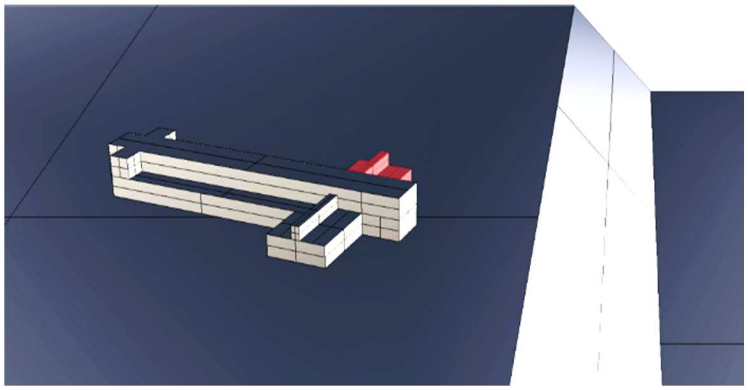

Figure 70. SANC Building

On October 16th, 2005, David Bradley and Michael Utzinger performed Carbon dioxide (CO_2) measurement experiments on the auditorium. They measured CO_2 level in the auditorium as well as the outdoor CO_2 level, temperature, relative humidity, wind speed and wind direction. A gas cylinder was then used to add CO_2 to the space at a rate of 0.566 m^3/hr. In Experiment 1, only a single leeward and a single windward window were open. In Experiment 2, all six auditorium windows were open (Bradley and Utzinger, 2006).

Based on Appendix C of ASHRAE Standard 62.1-2013, the required outdoor airflow rate per person is related to the difference between the CO_2 level in the space and in the outdoor air (ASHRAE 62.1, 2013). Knowing the amount of initial and final CO_2 level in a space as well as the outdoor CO_2 level during a certain amount of time, we can calculate the actual natural ventilation rate. The actual ventilation rate could be compared to the ASHRAE required amount of ventilation to see whether the natural ventilation is sufficient in the auditorium of the SANC building or not. Whenever the ventilation target is not hit, mechanical ventilation would be required. This could lead us to the basics of the control system of a hybrid ventilation approach in terms of switching between the natural and mechanical modes.

Simulation of Natural Ventilation

Natural ventilation simulation happens in two steps. Step 1 studies the SANC building and the auditorium room in the larger context. Step 2 focuses only on the auditorium.

In step 1, a Computational Fluid Dynamics (CFD) model is developed in Autodesk Simulation CFD. This model helps us comprehend the air flow around the auditorium. Air velocity, pressure coefficients and effectiveness of openings can be estimated based on the CFD results. The inputs of the CFD model are based on the 2005 experimental data. The wind speed is 1 m/s. The wind direction is 66 degrees or East North-East direction; that is, the wind is coming from the lake, heading up the hill and almost perpendicular to the east windows. The CFD simulation includes the lake breeze effect.

In step 2, the natural ventilation in the auditorium is simulated with both two and six windows open by means of Ladybug tools in Grasshopper.

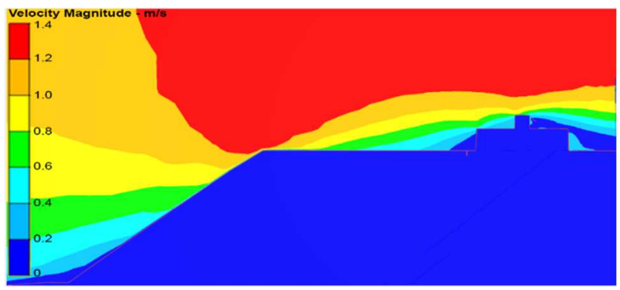

Figure 71. SANC Building CFD Model, Section

Simulation of Mechanical Ventilation

Should two conditions be satisfied, a control element of a hybrid system activates the natural ventilation mode. First, the natural ventilation system should be able to provide the minimum airflow rate. Second, the outdoor weather temperature and relative humidity should be in the thermal comfort range. The first condition depends on climatic specifications such as air temperature, wind speed and direction, as well as the design parameters such as the area of the openings and their arrangement. The second condition only relies on the outdoor weather situation.

In case the air velocity is not sufficient for natural ventilation, or the outdoor air is too hot, humid or cold, mechanical ventilation takes over. Hence, to study the mechanical ventilation mode, thermal comfort and the psychrometric chart will be investigated first. While there are different tools for studying thermal comfort, I am going to employ Ladybug components to remain consistent and carry out all the simulations in Rhinoceros and Grasshopper. Mechanical ventilation is simulated using Honeybee components in Grasshopper (Roudsari, Mackey, Yezioro, Harriman, Chopson, Ahuja, 2014).

A simple fan coil unit with available hot water is modeled to meet the heating requirements from November 1st through April 30th. The days during which the room could be operated in natural ventilation mode with either one or three windows open on either side are determined by analyzing ambient temperature, relative humidity and comfort conditions from May through October.

Simulation of a Hypothetical Earth Tube System

Next, a scenario is considered in which a theoretical Earth Tube (ET) system is added to the auditorium to assist with the mechanical ventilation. The system will not only provide the airflow requirement, but also (ideally) save energy due to its pre-heating and pre-cooling features. The same schedules are used in Earth Tube simulation as well as in prior simulations. While the Earth Tube system (which includes a fan) provides the required airflow rate, we will observe the amount of energy that could have been saved due to the passive pre-heating and pre-cooling. The simulation has been carried out using Python-based components in Grasshopper which will be thoroughly explained.

Thermal Comfort and Psychrometric Chart

In this section, temperature, relative humidity and comfort conditions are studied to determine which days the auditorium could be operated in natural ventilation mode with either one or three windows open on either side. There are different tools and apps available to study thermal comfort. Ladybug has a set of components to draw psychrometric charts. To keep the whole study in one software, thermal comfort is studied through the Ladybug tools.

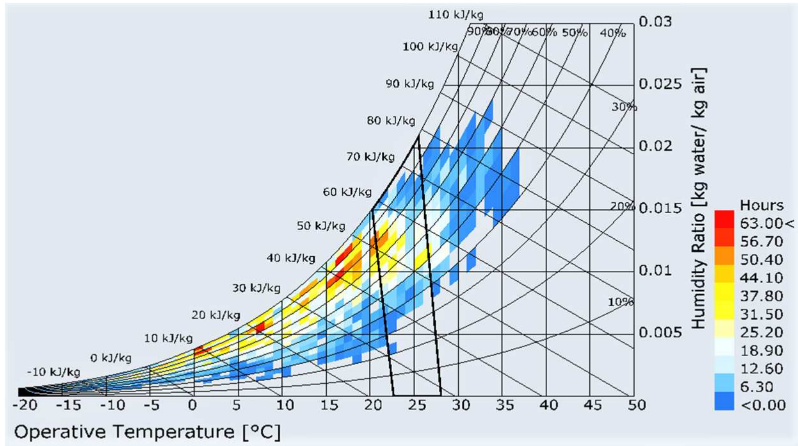

Figure 72. Psychrometric Chart, Bayside, WI

According to the psychrometric chart, the outdoor air conditions are conducive to natural ventilation mode only 10% of the year. The number of hours that the temperature is below 22 °C is dominant, whereas the number of hours when the temperature exceeds 28 °C is minimal. As a result, the role of natural ventilation would be limited to the swing and cooling season.

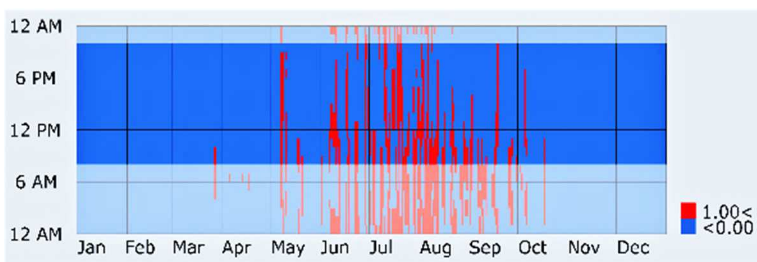

Figure 73. Total Comfort Chart, Bayside, WI

This image illustrates the comfortable hours more vividly. The time of the year with no occupancy is covered with a transparent white layer. The red and blue colors depict comfortable and uncomfortable hours respectively. There are only a few comfortable hours during November through April.

Hybrid Ventilation in Heating Season

The outdoor conditions are not typically comfortable during the heating season. Natural ventilation would only increase levels of discomfort. Hence, ventilation will be in mechanical mode during November through April.

Hybrid Ventilation in Cooling Season

For May through October, we should consider two issues: thermal comfort and adequacy of natural airflow. The natural ventilation mode will be activated if and only if both conditions are satisfied. In this section, I will first study the thermal comfort in the cooling season. Then, I investigate if the natural airflow is sufficient in the comfortable hours.

Next figure displays the comfort hours based on the outdoor weather data. However, the real comfort hours inside the auditorium might change considering the material, construction, occupancy, internal gain schedules, lighting schedule and so on. The image displays the simulation of the room with respect to the mentioned items without additional mechanical ventilation.

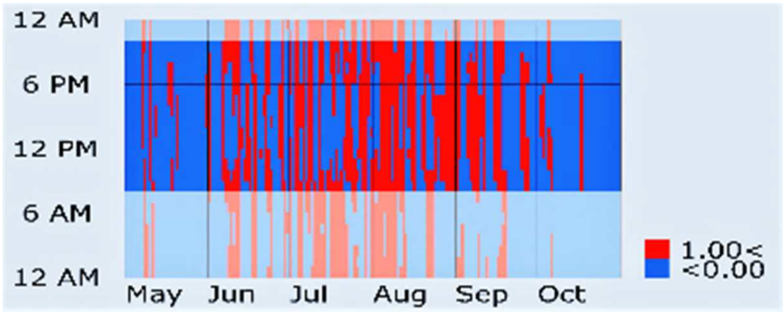

Figure 74. Comfort Chart, Cooling Season

During the cooling season, 5, 11, 14, 18, 14 and 3 days are thermally comfortable in May, June, July, August, September and October respectively. In these 65 days, there are only two days in which the required natural ventilation rate does not meet the target with two windows being open, May 12th and September 8th. Unlike September 8th, on May 12th, opening six windows would not help.

To sum up, there are 64 days during the May through October period when natural ventilation mode could be activated. For the remaining 120 days, we are going to need mechanical cooling. Otherwise, the natural ventilation would only increase the possibility of discomfort.

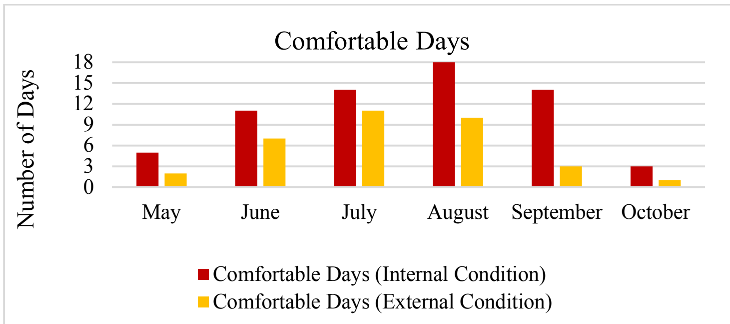

Figure 75. Number of Comfortable Days, Cooling Season

Program, Occupancy and Schedule

The auditorium is a multi-use space. Occupancy schedule follows seven days per week, 9 am to 5 pm Sunday through Thursday and 9 am to 10 pm Friday and Saturday. There are typically 15 people in the room from 9 am to 5 pm every day and 80 people from 5 pm to 10 pm Friday and Saturday (typical wedding reception days in summer).

Based on Equation 1, the minimum airflow, V_{bz}, for the auditorium is 107 L/s when 15 people are in the room and 354 L/s when there are 80 people in the room. The rates have been considered in the schedule. The Ladybug and Honeybee tools have some predefined schedules as well as some components that allow you write your own schedules. The schedule is written for the whole year containing 8760 items.

The occupancy schedule is a multiplication of two schedules. One considers the occupancy hours (which do not change from summer to winter). The second one considers the use of natural ventilation mode during 64 days of summer. The days in which natural ventilation is possible are given a value of zero, and the rest are assigned a value of 1. When this schedule is combined with the first, it causes the fan to turn off whenever the outdoor conditions are suitable to leave the windows open.

Heating Loads Simulation

In this section, I look into the mechanical system used to provide the heating requirement in winter. Then, the possibility of saving some energy by means of an alternative hybrid solution will be studied.

A fan coil unit is modeled using Honeybee components from November 1st through April 30th. The construction, occupancy and schedule are already assigned.

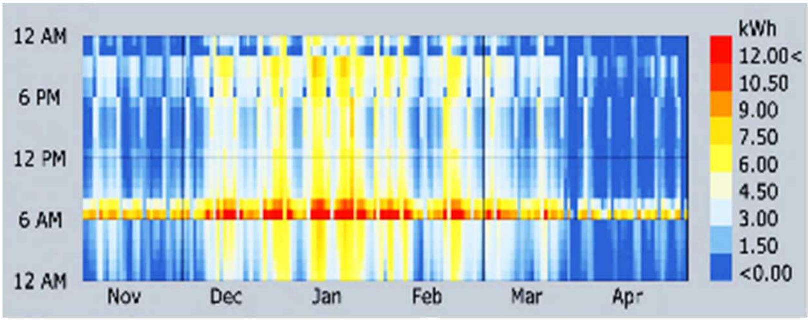

Figure 76. Hourly Heating Load (kWh)

This image illustrates the hourly heating load for the auditorium. The peak hourly heating load is about 12 kW. The annual total heating load of fan coil is 10,170 kWh. This includes both heating and fan loads.

Cooling Loads Simulation

As the cooling season in Bayside, WI, is relatively short, the total cooling load is 2280 kWh during May through October. Using a fan coil unit, this number considers both the cooling and the fan loads. The peak hourly cooling load hardly ever exceeds 9 kW.

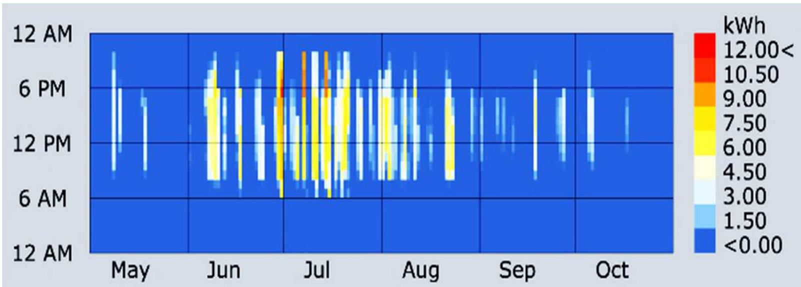

Figure 77. Hourly Cooling Load (kWh)

3.3. Validation of the Ventilation Simulation

This section focuses on the validation of the natural ventilation component of the Ladybug tools. First, I calculate the airflow rate in the auditorium in two scenarios matching with Experiment 1 and 2 using Equation 2. Then, this number is used as the basis to verify both the equation and the simulation results.

In Experiment 1, the auditorium was brought from its natural CO_2 concentration up to 1000 ppm. Then, two out of six windows (one leeward and one windward) were opened. The CO_2 level was seen to drop to 800 ppm in 15 minutes. The outdoor CO_2 level was approximately constant at 384 ppm (Bradley and Utzinger, 2006). The room volume is 714 m^3. Accordingly, the natural ventilation rate is 258 L/s assuming that the zone was well mixed and that the measured CO_2 concentration was representative of the entire air volume. While this approach provides a convenient way to estimate the airflow rate, it is somehow limited since I am assuming homogeneous indoor air properties by considering only one air node representative of the indoor conditions. However, this simplified method is also available in airflow modeling software such as CONTAM (Dols, 2002). It is worth noting that the height of SANC auditorium is only one third of its width; that is, it is not very tall as compared to its width. In the case of this room, one node seems a reasonable assumption.

In Experiment 2, the same room was brought to 1250 ppm. All six windows (three leeward and three windward) were then opened. The CO_2 level dropped to 670 ppm. During Experiment 2, the outdoor CO_2 level was 385 ppm (Bradley and Utzinger, 2006). The ventilation rate is then 532 L/s. Due to the wind direction, during the experiment and the building orientation, the wind hit the auditorium at an almost perpendicular angle during the experiments.

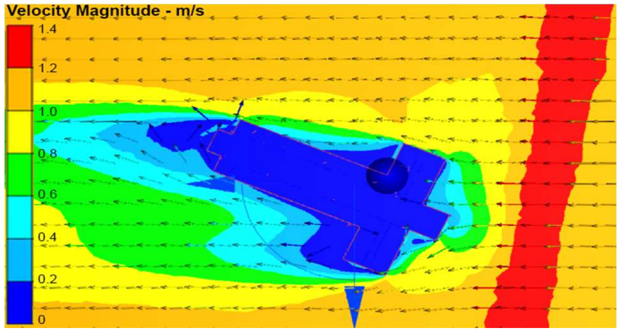

Figure 78. SANC Building CFD Model, Plan

A CFD analysis was used to compute wind pressure coefficients for the facades. After importing the geometry from Rhino, adding a volume of air, assigning boundary conditions – including the wind speed on the windward side, zero pressure on the leeward side, and slip-symmetry on the other sides – and creating a dense set of mesh, I solved the CFD model in a steady state mode. The solution converged after 393 iterations. The pressure coefficients were obtained as part of the result quantities.

Because of the wind direction, we could insert the lower range of opening effectiveness for perpendicular winds, which is 0.5, into Equation 2. C_v is typically between 0.5 to 0.6 for perpendicular winds (ASHRAE Fundamentals, 2013).

Based on Equation 2, the airflow rate for the conditions in Experiments 1 and 2 would be 186 L/s and 557 L/s respectively. These numbers are comparable with the experiment.

The measured data was limited to the duration of the experiment. For the validation of the simulation, I directly used the measured data through replacing the numbers in the Typical Meteorological Year (TMY) file by the measured numbers for the day of the experiment.

I was interested to extend the simulation to the whole year. For this means, I compared the TMY data with the measured quantities. While the temperature and relative humidity were close to the experiment, the wind speed reported in the data file was higher than the number measured at the site. It might be because of the fact that the meteorological station is located outside of the dense urban area; accordingly, wind speed would be much higher. By comparing the TMY wind speed and the measured wind speed, I came up with the factor to be multiplied by the TMY wind speed so that the wind speed would be adjusted to the site conditions.

The simulation shows 236 L/s and 575 L/s of airflow for Experiments 1 and 2 respectively. The simulation numbers are comparable to the experiments, within 8% of uncertainty, which validates the Honeybee natural ventilation component.

3.4. Ventilation System Optimization

There are a few items which tremendously affect Earth Tube performance including the depth at which the tubes are buried, the length, number and diameter of the tubes, the fan volume flow rate, the soil conditions, the outdoor weather, etc. Some of these items are out of our control such as the weather data. Some of them, we can control to some extent. For instance, excavation up to 3 m should be convenient. While the deeper the soil, the higher the potential energy saving would be, similar papers consider 2 m to 3 m as an optimum (Peretti, Zarrella, De Carli, Zecchin, 2013).

Some of them might have common sense estimation. As a case in point, we might consider the diameter of the tubes to be 0.6 m so that a person could crawl into them if need be. Volume flow rate depends on the estimated number of occupants as already discussed.

So far, some of our variables allocate some fixed numbers to themselves. Let us consider Bayside, WI, weather condition, a depth of 3 m for the soil and a diameter of 0.6 m for the tubes. Now, the influential parameters would only be the number of the tubes and the length of them. These two items give us the total length of the tubes.

Theoretically, there should be a limitation to the amount of saved energy in an Earth Tube system. This limitation is determined by the outlet temperature which in turn follows the soil temperature. In fact, the temperature of the outlet of the tubes can never be lower than the soil temperature in summer and warmer in winter. The heat flows from warmer object to the colder one until they come to a temperature equilibrium. That is, the direction of the heat is from soil to air in winter and from air to soil in summer. Ultimately, the outlet temperature would ideally be the same as the soil temperature although in practice this cannot happen unless the earth tube is infinitely long, and the soil is highly conductive. In this case, the soil temperature determines the total length of the tubes which in our case is 125 m. There is no use of considering a longer set of tubes since the outlet temperature stays the same – which equals the soil temperature in each moment.

Table 9 studies the total heating and cooling energy saved due to the Earth Tube system in a year as a function of the number of the tubes and the length of them.

Table 11. Total Saved Energy, ET (kWh)

	10 m	**12 m**	**14 m**	**16 m**	**18 m**	**20 m**
# 3	5370	5820	6175	6432	6653	6846
# 4	6038	6363	6640	6879	7074	7212
# 5	6425	6743	7000	7185	7292	7358

Next Image displays the Total amount of saved energy as a function of total tubes length. As one can observe, the points represent a non-linear relationship between the total tubes' length and the annual saved energy. Instead they show diminishing returns as the tube length is extended.

As the total tubes' length approaches 125 m, the curve tends to converge. In this case, total tubes length greater than 125 m does not result in higher level of saved energy with the made assumptions.

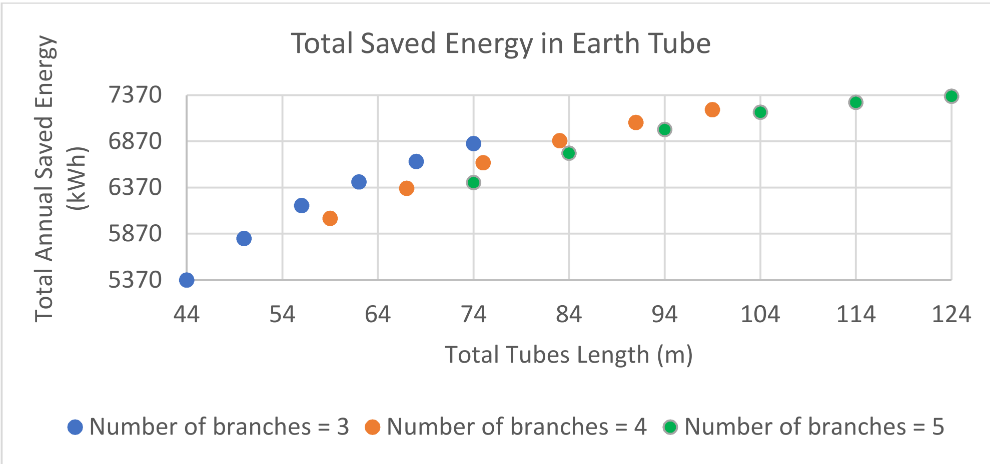

Figure 79. Total Saved Energy, ET (kWh)

To provide 125 m of tube, a configuration of 5 branches are considered to fit properly on the footprint. Figure 86 displays the tubes arrangement regarding to the auditorium.

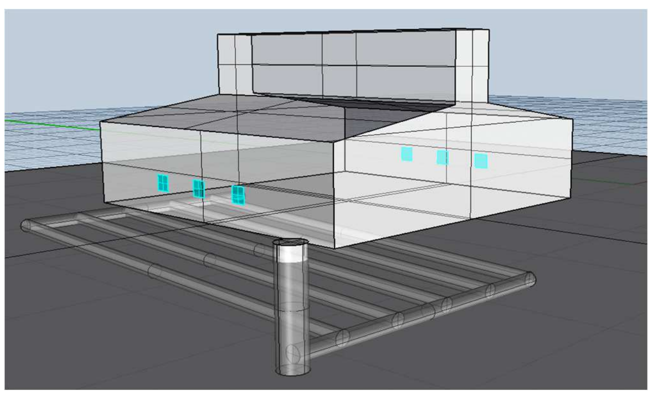

Figure 80. Optimized Earth Tube Arrangement

Earth Tube Energy Saving

By attaching the outcome of the Earth Tube components to the Ladybug 3D Chart component, we can present the heating and cooling loads in the same way as the EnergyPlus results are presented. Had we added this Earth tube system to the auditorium, the total amount of heating energy that could have been saved is 4535 kWh in a year. This is about 46% of the total fan and heating load of the fan coil during winter. We still need energy to run the Earth Tube fan, but the heating load would have highly decreased.

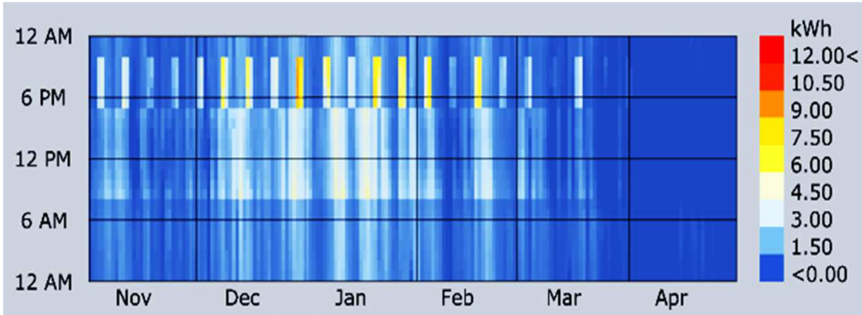

Figure 81. Hourly Saved Heating Energy, ET (kWh)

Next image displays the hourly cooling energy which could have been saved thanks to the Earth Tube system. Hypothetically, all the required cooling energy for the SANC auditorium could have been provided during the cooling season by means of an Earth Tube system. We would still need to run the Earth Tube fan during the 120 days of the cooling season. Overall, 55% of annual energy (6848 kWh) would have been saved by adding an earth tube system.

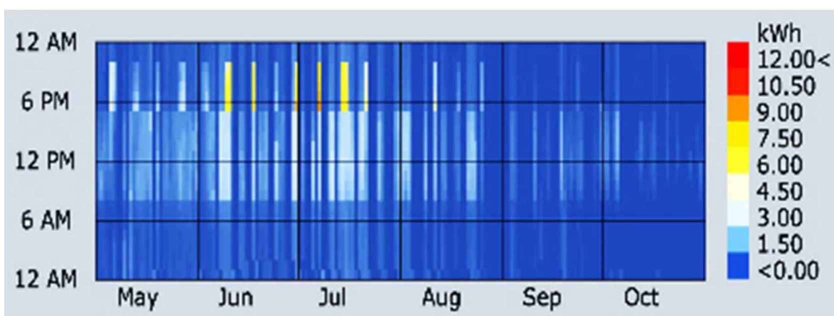

Figure 82. Hourly Saved Cooling Energy, ET (kWh)

3.5. Hybrid Ventilation Analysis Methodology

Passive ventilation approaches seem to provide greater occupant control, healthier air, and save more energy. On the other hand, mechanical systems tend to maintain pressure more steadily, perform more reliably, and provide thermal comfort more precisely (Axley, 2001). Hybrid systems benefit from both natural and mechanical ventilation.

While there are some components to simulate natural and mechanical ventilation systems separately, there are not adequate tools to simulate both as part of a hybrid system. This study explains the control strategy to switch between the two modes and puts forward a model which integrates not only the natural and mechanical components, but the control system as well.

The idea behind this research is to keep all the simulation pieces in the same place that the 3D modeling happens, the Rhinoceros. One can design, visualize, evaluate, and even optimize the system in only one platform needless to switch between numerous software.

The simulation provides a visualization of the system as well so potential conflicts between the building and the ventilation system components would show up early in the design and can be solved more conveniently.

The research does not suffice to only presenting the model but validates it as well through measured data from Schlitz Audubon Nature Center (SANC) in Bayside, Wisconsin.

The methodology used in this study in terms of creation of Python-based simulation components in the design software (Rhino), validation and finally optimization of the system is a process which can be extended to other aspects of Performative Based Design (PBD).

Figure 83. Parametric Ventilation Analysis Methodology

4. Earth Tube Ventilation

4.1. Aldo Leopold Foundation Experiment

The Aldo Leopold Foundation (ALF), located in Baraboo, WI, is designed by the Kubala Washatko Architects, and Professor Mike Utzinger was the Energy Consultant of the project. ALF was built in 2007 and it is now more than 10 years old.

In 2008 American Institute of Architects Committee on the Environment (AIA COTE) top ten, ALF was the first building to receive a Leadership in Energy and Environmental Design (LEED) innovation point for carbon neutral operation and was also recognized with an accolade from the Forest Stewardship Council for using sustainably-harvested timber throughout the structure.[97] Moreover, ALF applies some passive approaches to become close to a net-zero building.

Figure 84. Aldo Leopold Foundation, the Kubala Washatko Architects

Earth Tube System

One of the passive methods used in ALF is a Horizontal Earth Tube System (HETS). Hypothetically, it reduces both heating and cooling loads of the building due to the relatively constant temperature of the undisturbed soil (Bradley and Utzinger, 2009).

[97] https://inhabitat.com/aiacote-top-ten-green-building-projects-of-2008/

Other researchers have used distinct terms to refer to this system such as earth-air tube ventilation system (Yang and Zhang, 2015), earth-to-air heat exchangers, EAHE (Santanouris et al., 1995), earth-to-air heat exchanger (EAHE, EAHX, ETAHE, ATEHE) (Peretti, Zarrella, De Carli, & Zecchin, 2013) (Ascione, Bellia, & Minichiello, 2011), ground-coupled heat exchangers (Yang and Zhang, 2015), earth channels (Yang and Zhang, 2015), ground source heat pump, GSHP (Peretti, et al., 2013), or simply buried pipes (Santanouris, et al., 1995). Mongkon et al. use the term HETS (Horizontal Earth Tube System) (Mongkon, Thepa, Namprakai, & Pratinthong, 2013) (Mongkon, Thepa, Namprakai, & Pratinthong, 2014).

In this system, ground works as a heat sink in summer and heat source in winter. Basically, the temperature of the undisturbed soil deep in the ground is lower than the outside air temperature in summer and higher in winter. Passing through the pipes, air is cooled in summer and heated in winter before any other active conditioning (Peretti, et al., 2013).

The simulation during the design level for ALF indicated that HETS would perform better than an enthalpy-heat-recovery system precooling and dehumidifying the air, but not quite as well preheating the air in winter. The earth tube model which was used in the design simulation had not been validated. This research focuses on setting up a data collection system to measure the amount of precooling and preheating.

A subtle point is that the HETS should perform differently in summer and winter. In winter, HETS affects the dry bulb temperature; therefore, the sensible heating. In summer, not only it affects the dry bulb temperature, but also the moisture content as well; therefore, the latent cooling. Cooling down the air in summer may cause the air to reach the dew point. As soon as it hits the dew point, both temperature and the amount of moisture in the air decrease, so both sensible and latent cooling are subjects of study during summer.

The earth tubes are located on the Northern part of the main building which is illustrated by the red rectangle in the following image.

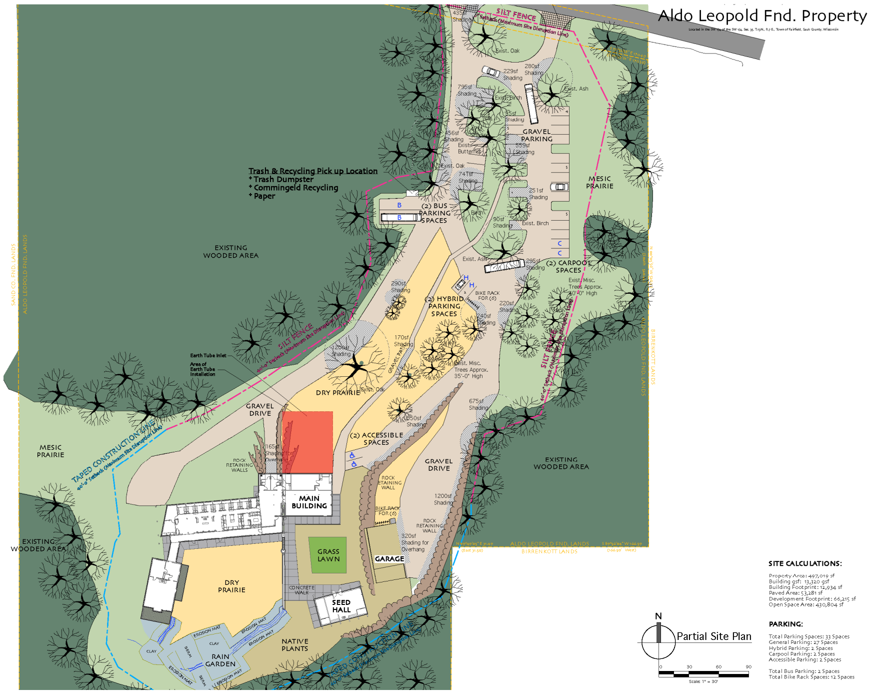

Figure 85. Location of the earth tubes (Site Plan by: Kubala Washatko Architects Inc.)

Although the Kubala Washatko's plans indicate 6 lines of tubes, only 5 lines are implemented.

Figure 86. Horizontal Earth Tube System (HETS)

There are 5 earth tubes with an Inner Diameter (ID) of 2 feet (0.6 m). According to the picture, there are 12 straight sections of concrete pipes in each line in addition to two 2 feet stubs at the two ends of Tee pipes. The length of each piece is about 8 feet (2.44 meters) which makes the total length 104 feet which is about 32 meters. Total length of the pipes is about 598 feet or 182 meters. The pipes are sloped by 4°.

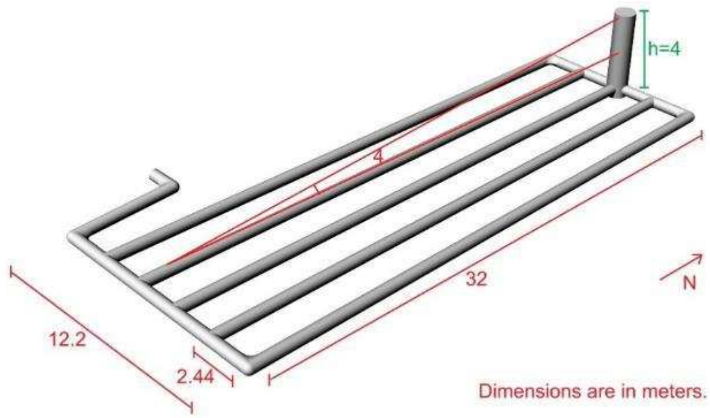

Figure 87. Earth Tube Rhino model

There is a manhole at the entrance of the earth tubes which makes it accessible. The manhole has an Inlet Diameter (ID) of 4 feet (1.2 m). It has a metal cap to prevent the entrance of animals, water and sand into the manhole which can be removed whenever needed.

Figure 88. Inside the Manhole, Manhole and the cap

Data Collection

Trip May 22nd, 2017

First set of sensors were installed on 22nd of May 2017, although not all of them are used in the models. I installed totally 18 sensors: 9 sensors in the tubes, 2 sensors in the Air Handling Unit (AHU) right before entering the chiller, and 7 sensors inside the rooms on the ground floor:

- 12 Onset Hobo U12-012[98] (for Temperature and Relative Humidity),
- 3 Hobo U20-001-01[99] (for Pressure and Temperature),
- 2 MX1102[100] (for CO2 level, Temperature and Relative Humidity) – Bluetooth smart,
- 1 MX1101[101] (for Temperature and Relative Humidity) – Bluetooth smart.

U12-012, U20-001-01, MX1102, MX1101

Figure 89. Sensors (Photos from: ONSET website[102])

Table 10 indicates the technical specifications of these sensors.

Table 12. Sensors technical specifications, extracted from ONSET website[103]

Name	Temperature		RH		CO2		Pressure	
	Range	Accuracy	Range	Accuracy	Range	Accuracy	Range	Accuracy

98 http://www.onsetcomp.com/products/data-loggers/u12-012
99 http://www.onsetcomp.com/products/data-loggers/u20-001-01
100 http://www.onsetcomp.com/products/data-loggers/mx1102
101 http://www.onsetcomp.com/products/data-loggers/mx1101
102 http://www.onsetcomp.com/products/data-loggers
103 http://www.onsetcomp.com/products/data-loggers

1	U12-012	-20 to 70 °C	±0.35 °C From 0 to 50 °C	5-95 %	±2.5 % From 10 to 90 %, to a max of ±3.5% ±5.0 % Below 10% Above 90%				
2	MX1101	-20 to 70 °C	±0.21 °C From 0 to 50 °C	1-90 %, non-condensing	±2.0 % From 20 to 80 %, to a max of ±4.5% ±6.0 % Below 20% Above 80%				
3	MX1102	0 to 50 °C	±0.21 °C From 0 to 50 °C	1-70 %, CO2 enabled 1-90 %, CO2 disabled	±2.0 % From 20 to 80 %, to a max of ±4.5% ±6.0 % Below 20% Above 80%	0 to 5000 PPM	±50 PPM ±5 %, At 25 °C, Less than 70% RH & 1013 mbar		
4	U20-001-01	-20 to 50 °C	±0.44 °C From 0 to 50 °C					0 - 207 kPa	Typ: ±0.21 kPa Max: ±0.62 kPa

Next two figures demonstrate the location of the sensors in the tubes and the Air Handling Unit before the chiller entrance, and in the rooms of the ground floor respectively.

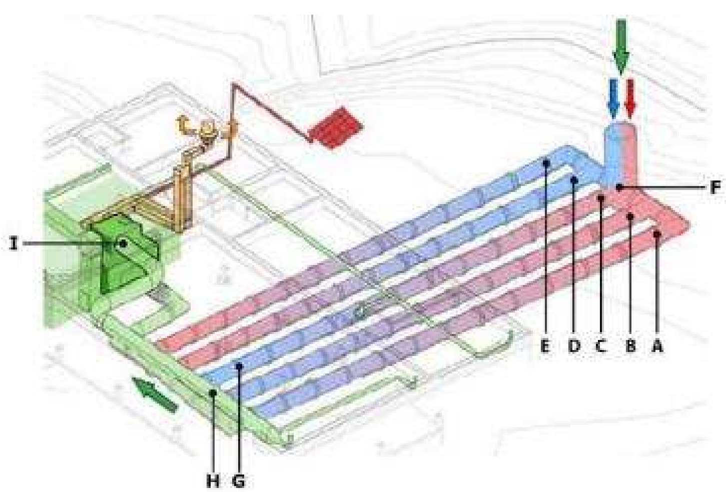

Figure 90. Location of the sensors – Earth tubes and AHU

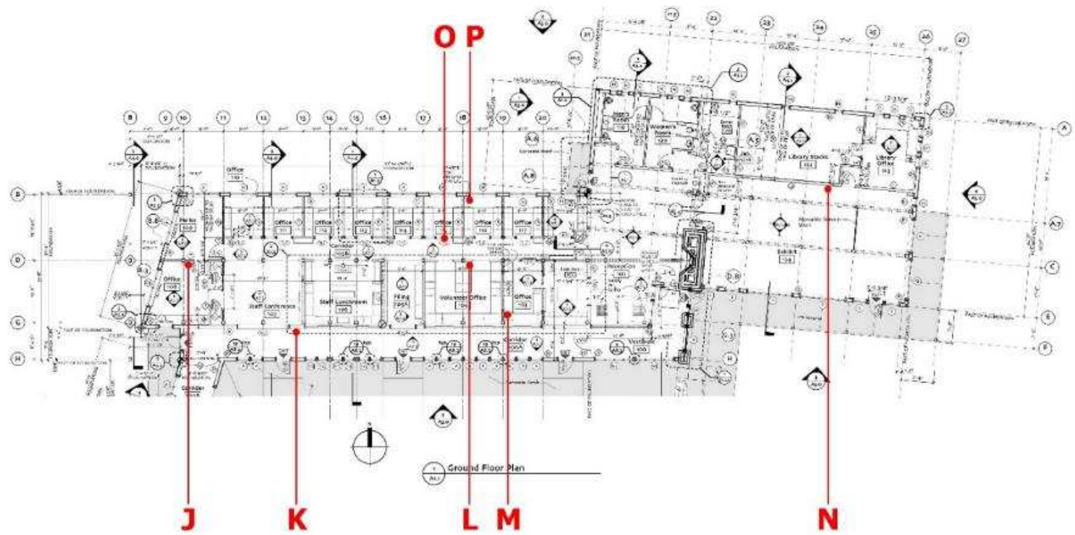

Figure 91. Location of the sensors – ground floor (Plan by: Kubala Washatko Architects Inc.)

Table 13. Name, type and location of the sensors

	Name	Location	Type	Temp	RH	Pres	CO2	Bluetooth	Explanation
1	19	A	U12-012						Pipe
2	SARUP 3436	B	U12-012						Pipe
3	SARUP 3440	C	U12-012						Pipe
4	10743983	C	MX1101						Pipe
5	SARUP 3439	D	U12-012						Pipe
6	SARUP 3442	E	U12-012						Pipe
7	10151230	F	U20-001-01						Manhole
8	SARUP 3443	G	U12-012						Pipe
9	SARUP 3438	H	U12-012						Pipe
10	10151231	I	U20-001-01						AHU
11	20045799	I	MX1102						AHU
12	10	J	U12-012						Buddy's office
13	18	K	U12-012						Corridor (South)
14	17	L	U12-012						Interns' office
15	29959508	M	MX1102						Gift store
16	SARUP 3437	N	U12-012						Exhibit area
17	10151229	O	U20-001-01						Corridor (North)
18	20	P	U12-012						Office 116

For installing the sensors inside the earth tubes (locations: A-E, G and H), I attached the sensors to a stick the length of which was a little bit (1/16") longer than the inner diameter of the pipe so that they could stuck in the tube and remain stable. The sensors are set to record the data every 15 minutes. They can keep the data between 3 months (for the MX1101 sensor) till 7.5 months (for U12-012 sensors).

19 – Location A   SARUP 3436 – Location B   SARUP 3439 – Location D   SARUP 3442 – Location E

Figure 92. Sensor installation inside the tubes

Trip August 4th, 2017

Second round of sensor installation was carried out on 4th of August 2017. I set up a weather station including a Hobo U30 NRC (No Remote Communication) datalogger with a solar battery and 3 sensors.

U-30 NRC[104]   1.2 Watt Solar Panel[105]   Rain Gauge Sensor[106]   12-bit Temp/RH[107]   Si Pyranometer[108]

Figure 93. Sensors (Photos from: ONSET website[109])

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[104] http://www.onsetcomp.com/products/data-loggers/u30-nrc
[105] http://www.onsetcomp.com/products/power/solar-12w
[106] http://www.onsetcomp.com/products/data-loggers/rg3-m
[107] http://www.onsetcomp.com/products/sensors/s-thb-m002
[108] http://www.onsetcomp.com/products/sensors/s-lib-m003
[109] http://www.onsetcomp.com/products/data-loggers

Table 14. Name and type of the data logger and sensors in the weather station

	Name	Type	Temp	RH	Rain	Solar radiation	Explanation
1	10171716	U30 NRC					Data logger
2	10160293	0.01” RainGauge					
3	10164305	12-bit Temp/RH					
4	20052380	Si Pyranometer					

Table 15. Sensors technical specifications, extracted from ONSET website[110]

	Name	Temperature		RH		Rain Gauge		Solar Radiation	
		Range	Accuracy	Range	Accuracy	Range	Accuracy	Range	Accuracy
1	S-THB-M002	-40°C to 75°C	±0.21°C from 0° to 50°C	0-100% RH at -40° to 75°C, below -20°C or above 95% RH may increase the maximum RH sensor error by an additional 1%	±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%				
2	RG3-M					0-12.7cm 0 - 5” per hour	±1.0% at up to 20 mm/hr		
3	S-LIB-M003							0-1280 W/m^2	10 W/m^2 or ± 5%, whichever is greater in sunlight

The assembly is in the open area on the South side of the building. The spot was selected based on the availability of solar radiation for the solar battery and not blocking the visitors view. Table 3 Indicates the serial numbers of the sensors and the data logger. I set 15 minutes as the logging interval and 5 seconds as the sampling interval. Logging started at 3 PM on August 4th, 2017. It should save log data for 2.7 years.

110 http://www.onsetcomp.com/products/data-loggers

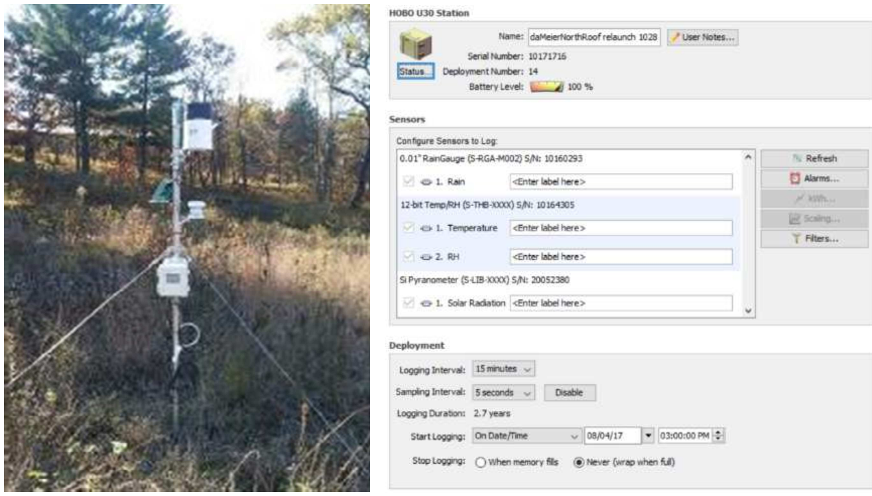


Figure 94. Weather station, Hobo U30 NRC, sensors and data logger

I also set a micro station data logger to save the soil specifications as well. 2 soil moisture and 2 soil temperature sensors are attached to the micro station. The data logger is attached to the manhole wall.

Figure 95. Micro station attached to the manhole wall

12-Bit Temperature Smart Sensor[111]   Soil Moisture Smart Sensors[112]

Figure 96. Soil Sensors

[111] http://www.onsetcomp.com/products/sensors/s-tmb-m002
[112] http://www.onsetcomp.com/products/sensors/s-smc-m005

Table 16. Sensors technical specifications, extracted from ONSET website[113]

	Name	Temperature		Water Content	
		Range	Accuracy	Range	Accuracy
1	S-TMB-M0XX	-40° to +100°C	< ±0.2°C from 0° to +50°C		
2	S-SMC-M005			0 to 0.55 m^3/m^3	±0.031 m^3/m^3 (±3.1%) typical 0 to 50°C

I dug two holes with depth of 2' and 3'-8". One soil moisture and one soil temperature are buried in each hole. Table 4 demonstrates the micro station assembly specifications. It should be able to save log data for 2.5 years.

Table 17. Name and type of the data logger and sensors in the soil station

	Name	Type	Temp	Soil Water content	Explanation
1	10152623	Hobo micro station			Data logger with Alkaline battery
2	20186021	12-bit Temp			
3	20186022	12-bit Temp			
4	20191889	Soil probe 10HS			
5	20191889	Soil probe 10HS			

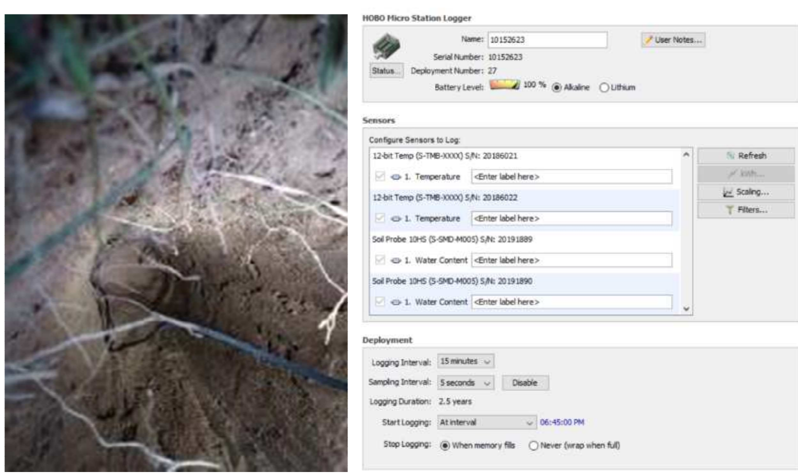


Figure 97. Hole dug for soil sensors, Micro station, sensors and data logger

113 http://www.onsetcomp.com/products/data-loggers

Trip May 23rd, 2018

I could not extract data from Hobo U30 data logger. Professor Utzinger sent it back to see if they could. So far, I had no data regarded to the amount of rain and solar radiation. On May 23rd, 2018, we replaced the U30 weather station logger with a H21 micro station logger.[114]

Trip June 6th, 2018

Professor Utzinger and I set up two more micro loggers on June 6th, 2018. One of them is set inside the Air Handing Unit. The reason we set it there was that we bought a new temperature and relative humidity sensor[115], which is new and calibrated. It had to be attached to a logger.

The second micro logger supports two new sensors located 8' deep in the ground to measure soil temperature and water content somewhere closer to the pipes. We were not able to dig an 8' hole previously; hence, we tried a whole new plan (suggested by David Bradley) this time.

So far, we had used a 4' hole-digger. One cannot exceed digging a hole deeper than 3'-8" to 4' with this device.

Figure 98. Hole Digger, Conduit

[114] http://www.onsetcomp.com/products/data-loggers/h21-usb
[115] http://www.onsetcomp.com/products/sensors/s-thb-m002

First, we dug the 4’ hole with this hole digger. Then we dug a narrower hole for the next 4’ using an 8’. We hammered the conduit into the ground, pull it out and tapped the head of the conduit till all the soil came out. The following images shows the thin hole inside dug at the end of the 4’ hole.

Figure 99. Conduit hole within the hole

Trip June 20th, 2018

On this trip, we added 5 air and surface temperature and relative humidity U-12 sensors attached inside the middle tube.[116] The purpose is to observe the temperature gradient within the length of one tube.

Our visit on June 20th, 2018 was right after a set of heavy rains. Inside the tubes were highly wet and humid; however, it was not clear whether the moisture was due to saturation or just water penetrating from the outside surface of the concrete tube. Still, I did not observe any molds in any of the tubes check.

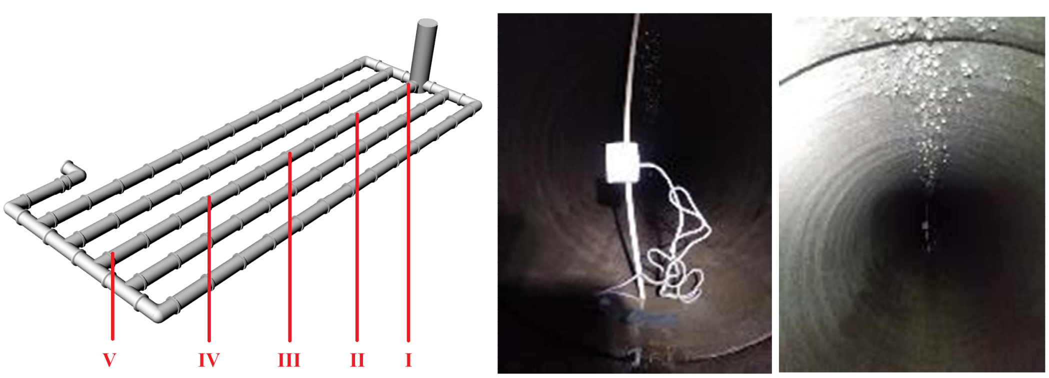


Figure 100. U-12 sensors inside the central tube

[116] http://www.onsetcomp.com/products/data-loggers/u12-012

On this trip, we also located a long-term alpha track Radon detector[117] in one the interior office areas to see if the Radon level is higher than expected during summer. Another test long-term detector will be installed for heating season.

Figure 101. Long-term alpha track Radon detector

4.2. Earth Tube System, Material and Energy Equations

First Law of Thermodynamics

First law of thermodynamics discusses the conservation of energy. Simply, any thermal analysis has roots in the first law of thermodynamics. It is based on the fact that total energy of a system is conserved within the boundaries. Should the amount of energy in a system change, it shows that energy has crossed the boundaries, which in turn happens only through two methods: heat transfer through the boundaries (Q) and work done on or by the system (w). ΔE_{st} represents the change in the total energy stored in the system.

[117] https://www.radonzone.com/product/long-term-radon-test-kit.html

$$\Delta E_{st} = Q - W \qquad (4)$$

In order to employ this equation, we need to define the system and the boundaries. The following picture schematically does so. Two terms will be used so often in this text, Manhole and Air Handling Unit (AHU). Manhole is where the fresh outdoor air enters. AHU is where more advanced conditioning happens on the pre-conditioned air before entering the building. The materials we deal with are air, soil, and concrete pipes. As the concrete pipes and soil will eventually come to an equilibrium, it is mainly air and soil that matters, both of which has been extensively discussed in the material section.

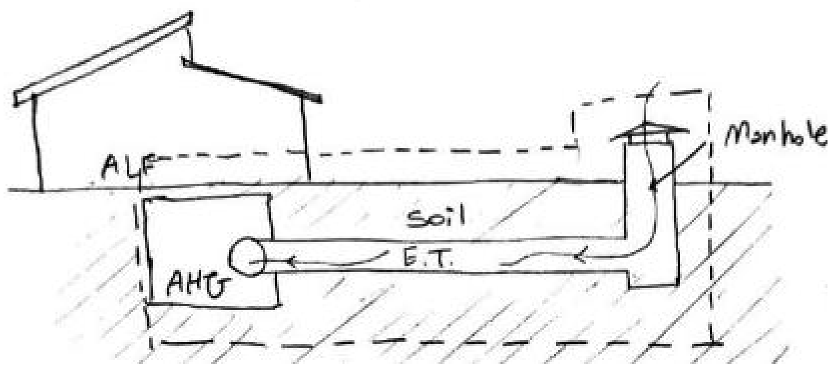


Figure 102. System Boundaries

The first law could be developed into the following format.

$$\Delta E_{st} = E_{in} - E_{out} + E_g \qquad (5)$$

I have set the equipment to measure data every 15 minutes. Should I assume that each time step has steady-state conditions, I deal with a semi-steady-state situation. Hence, the ΔE_{st} in each time step will be zero, as well as E_g.

$$E_{in} = E_{out} \qquad (6)$$

This could be broken down into thermal, kinetic and potential energies.

$$\dot{q}_i + \dot{w}_i + \dot{m}_i(h_i + \frac{\dot{V}_i}{2} + g_{z_i}) = \dot{q}_o + \dot{w}_o + \dot{m}_o(h_o + \frac{\dot{V}_o}{2} + g_{z_o}) \qquad (7)$$

If we assume that velocity and mass flow rate of the air would be the same at the inlet and the outlet, and potential energy would be zero, we could cancel out some of the items.

$$\dot{q}_i + \cancel{\dot{w}_i} + \dot{m}_a(h_i + \cancel{\frac{\dot{V}_i}{2}} + \cancel{gz_i}) = \dot{q}_o + \cancel{\dot{w}_o} + \dot{m}_a(h_o + \cancel{\frac{\dot{V}_o}{2}} + \cancel{gz_o}) \quad (8)$$

$$\dot{q}_i - \dot{q}_o = \dot{m}_a(h_o - h_i) \quad (9)$$

Considering the enthalpy change, the following equation will be obtained.

$$\dot{q}_i - \dot{q}_o = \dot{m}_a C_P(T_o - T_i) \quad (10)$$

To develop the left side of the equation further, I need to study modes of heat transfer more deeply.

Modes of Heat and Mass Transfer

To investigate the thermal performance of the earth tubes, first I need to figure out what types of heat and mass transfer is happening throughout the system. Let us assume the system includes the tubes, the manhole, the soil, and the air entering the manhole, moving through the pipes, ending in the Air Handling Unit. The following image depicts this procedure.

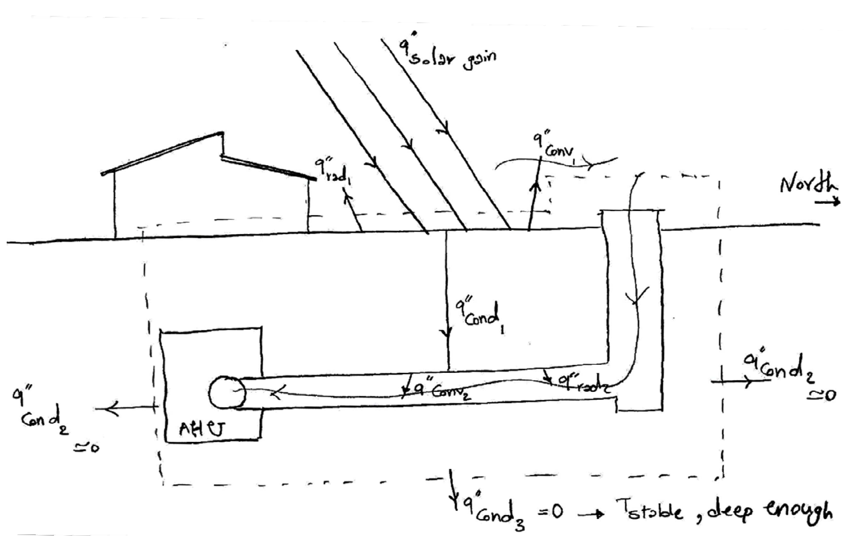


Figure 103. Heat Transfer in the System

$$\dot{q}_{Cond_1} + \dot{q}_{Cond_2} + \dot{q}_{Cond_3} + \dot{q}_{Conv_1} + \dot{q}_{Conv_2} + \dot{q}_{Rad_1} + \dot{q}_{Rad_2} + \dot{q}_{Solar\ gain} = \dot{m}C_P(T_o - T_i) \quad (11)$$

Next figure illustrates the heat and mass transfer in a schematic isometric section.

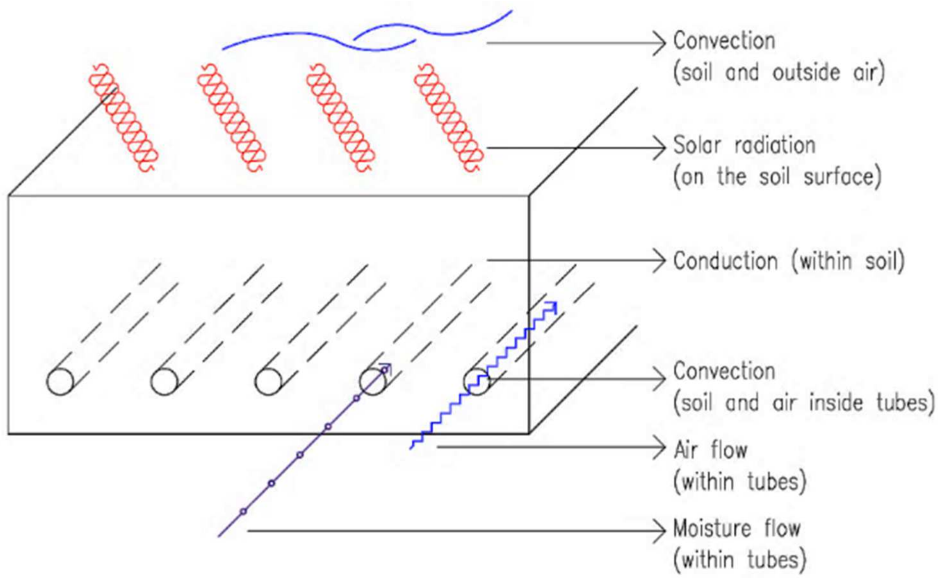


Figure 104. Heat and mass transfer schematic isometric section

Some of the previous papers have assumed all items except for the air convection negligible and have simplified the above equation into the following one.

$$\cancel{\dot{q}_{Cond_1} + \dot{q}_{Cond_2} + \dot{q}_{Cond_3} + \dot{q}_{Conv_1}} + \dot{q}_{Conv_2} \cancel{+ \dot{q}_{Rad_1} + \dot{q}_{Rad_2} + \dot{q}_{Solar\ gain}} = \dot{m}_a C_P (T_o - T_i) \qquad (12)$$

However, it seems that soil conduction plays a role as significant as convection. Therefore, I am going to consider the following equation as the basis of the bulk-flow model.

$$\dot{q}_{Cond_1} \cancel{+ \dot{q}_{Cond_2} + \dot{q}_{Cond_3} + \dot{q}_{Conv_1}} + \dot{q}_{Conv_2} \cancel{+ \dot{q}_{Rad_1} + \dot{q}_{Rad_2} + \dot{q}_{Solar\ gain}} = \dot{m}_a C_P (T_o - T_i) \qquad (13)$$

$$\dot{q}_{Cond_1} + \dot{q}_{Conv_2} = \dot{m}_a C_P (T_o - T_i) \qquad (14)$$

This final equation will be developed into the bulk flow model. However, before doing so, I need to figure out the material (including soil and air) specifications as well as the air flow pattern. Accordingly, the next two sections discuss material and the Computational Fluid Dynamics (CFD) model respectively. Then, on the section following that, the bulk flow model will be elaborated.

Material

Air Specifications[118]

Considering that air specification changes with temperature, relative humidity, and pressure; one could define various air features as functions of these three items. These features include viscosity, humidity ratio, density, specific heat, conductivity, and Prandtl number.

Air Viscosity[119] **(μ)**

Viscosity is a function of temperature. Viscosity of air as a gas increases with temperature. Power law has been used to calculate air viscosity (White, 2009).

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{0.7} \qquad (15)$$

μ_0 is viscosity at a known absolute temperature. With T_0 = 273 °K, μ_0 = 1.71 E-5 kg/(m.s)

Humidity ratio of moist air at saturation[120] **(ω_s)**

Humidity ratio is also a function of temperature. The humidity ratio of the saturated moist air ω_s between 0 and 100 °F (-17.8 and 37.8 °C) can be calculated by the following polynomial. Using this equation, the error should be less than 0.000043 lb/lb (kg/kg) (Wang, 2000).

$$\omega_s = \alpha_1 + \alpha_2 T_s + \alpha_3 T_s^2 + \alpha_4 T_s^3 + \alpha_5 T_s^4 \qquad (16)$$

- T_s = Saturated temperature of moist air (°F)
- α_1 = 0.00080264
- α_2 = 0.000024525

[118] Python code for each variable is provided in the footnote. Each variable is part of a *function* in a *class*.

[119]
```
Mo=0.0000171*math.pow((self.T+273.15),0.7)/math.pow(273.15,0.7)
```

[120]
```
w_s=0.00080264+0.000024525*T_k+0.000002542*math.pow(T_k,2)-
0.000000025855*math.pow(T_k,3)+0.0000000004038*math.pow(T_k,4)
```

- α_3 = 2.542 × 10^{-6} = 0.000002542
- α_4 = -2.5855 × 10^{-8} = -0.000000025855
- α_5 = 4.038 × 10^{-10} = 0.0000000004038

Water vapor pressure of moist air at saturation[121] (P_{ω_s})

Humidity ratio is the ratio of the mass of water vapor (m_ω) to the mass of dry air (m_a) in lb/lb or kg/kg[122].

$$\omega = \frac{m_\omega}{m_a} \qquad (17)$$

By developing the humidity ratio, using ideal gas equation and Dalton's law, one could relate water vapor pressure and humidity ratio (Wang, 2000).

$$\omega = \frac{m_\omega}{m_a} = \frac{P_\omega V R_a T_R}{P_a V R_\omega T_R} = \frac{R_a}{R_w}\frac{P_\omega}{P_a - P_\omega} = 0.62198\,\frac{P_\omega}{P_a - P_\omega} \qquad (18)$$

Or I could rearrange the equation in the following format.

$$P_\omega = \frac{P_a \omega}{\omega + 0.62198} \qquad (19)$$

Similarly, water vapor pressure of moist air at saturation will be calculated by the following equation.

$$P_{\omega_s} = \frac{P_a \omega_s}{\omega_s + 0.62198} \qquad (20)$$

Water vapor pressure of moist air is a function of atmospheric pressure and humidity ratio. Humidity ratio is a function of air temperature. So, water vapor pressure is a function of air pressure and temperature.

Water vapor pressure of moist air[123] (P_ω)

Interestingly, relative humidity is the item that relates water vapor pressure of moist air (P_ω) and water vapor pressure of moist air at saturation (P_{ω_s}) (Wang, 2000).

---

121 `P_ws=self.P*w_s/(w_s+0.62198)`
122 `w=0.62198*P_w/(self.P-P_w)`
123 `P_w=self.RH*P_ws/100`

$$\Phi = \frac{P_\omega}{P_{\omega_s}} \qquad (21)$$

If I have already calculated P_{ω_s}, I can get the P_ω using the relative humidity.

$$P_\omega = \phi P_{\omega_s} \qquad (22)$$

Volume of moist air[124] (v)

The volume of moist air (v) is defined as the volume of the mixture (m^3/kg) of the dry air and water vapor (V) when the mass of the dry air (m_a) is exactly equal to 1 kg. This definition can be developed further by applying the ideal gas law (Wang, 2000). Accordingly, volume of moist air is a function of temperature, atmospheric pressure, and relative humidity of air.

$$N = \frac{V}{m_a} = \frac{R_a T_R}{P_a - P_\omega} \qquad (23)$$

Air Density[125] (ρ)

Should we define air density as the ratio of the mass of dry air (m_a) to the total volume of the mixture, the following equation is applicable (Wang, 2000). Following the equations, one can realize that air density is a function of all three items: temperature, atmospheric pressure, and relative humidity of air.

$$\rho = \frac{m_a}{V} = \frac{1}{v} \qquad (24)$$

Air Specific heat[126] (C_P)

The specific heat of moist air at constant pressure (C_P) is defined as the heat required to raise its temperature 1 °C at constant pressure. The sensible heat of moist air is represented by the following equation (Wang, 2000).

[124] `v=287*(self.T+273.15)/(self.P-P_w)`
[125] `rho=1/v`
[126] `C_p=1005+1859*w`

$$q_{sen} = \dot{m}_a(C_d + \omega C_s)T = \dot{m}_a C_P T \qquad (25)$$

C_d and C_s, which represent specific heat of dry air and water vapor at constant pressure respectively, are both functions of temperature; therefore, C_P is also a function of temperature as well as a function of humidity ratio (Wang, 2000).

$$C_P = C_d + \omega C_s \qquad (26)$$

For a temperature range of 0 to 100 °F (-17.8 to 37.8 °C), C_d and C_s are 1005 and 1859 (J/kg.K) respectively.

$$C_P = 1005 + 1859\omega \qquad (27)$$

Air Conductivity[127] (K)

Air conductivity equation is obtained from the kinetic theory of gases. Ultimately, it will be determined by the following equation (Bergman, 2011).

$$K = \frac{9\gamma - 5}{4}\frac{C_V}{\pi d^2}\sqrt{\frac{\mathcal{M} k_B T}{\aleph \pi}} \qquad (28)$$

- $\gamma = \frac{C_P}{C_V}$
- $d = 3.72 \times 10^{-10}$ (Molecular diameter)
- $\mathcal{M} = 0.02897$ (Molecular weight)
- $k_B = 1.381 \times 10^{-23}$ (Boltzmann's constant, J/K)
- $\aleph = 6.022 \times 10^{23}$ (Avogadro's number)

Air Prandtl number[128] (P_r)

---

[127] `K=(9*gamma-5)/4*C_v/math.pi/math.pow(0.372e-9,2)*math.sqrt(0.02897*1.381e-23*(self.T+273.15)/6.022e23/math.pi)`

[128] `Pr=Mo*C_p/K`

Prandtl number is a dimensionless parameter obtained from the following parameters. It is a fluid property which provides a measure of the relative effectiveness of momentum and energy transport by diffusion in the velocity and thermal boundary layers, respectively (Bergman, 2011).

$$P_r = \frac{C_P \mu}{K} \qquad (29)$$

In the model, all air properties have been defined as functions of only air temperature, relative humidity and atmospheric pressure. Relating these features to the basic air properties answers to the fluctuations of air specification as a result of varying climatic conditions.

The following figure summarizes the air features and how they are calculated.

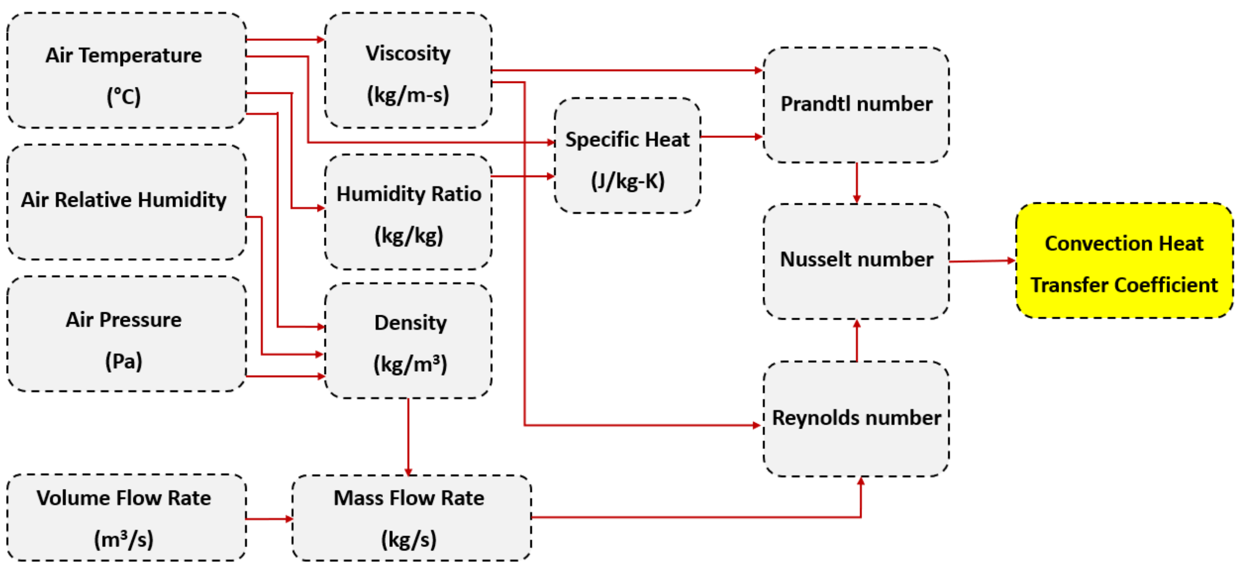


Figure 105. Air Specification

Soil Specifications

Soil characteristics play an important role in our calculations. The features we need to know are soil thermal conductivity, density and specific heat, which lead to thermal diffusivity (α). Thermal diffusivity as well as outdoor climatic conditions affect soil temperature. Soil properties differ in dry and moist soil. That is why we also need to know soil moisture content. Basic soil features such as density or porosity can be measured by simple laboratory facilities. As we were not equipped for more advanced measurements such as soil thermal conductivity and specific heat, I used experimental data from similar papers.

Soil Density

To calculate the dry soil density, I dried out the soil in an oven with temperature of 280 °F, for 48 hours.

Figure 106. Soil sample from the field

As I had only five 50-ml beakers available, the experiment was done twice to have 10 samples overall. First, the mass of the 5 empty beakers are measured. The scale measures up to 0.001 grams accurately. The box around it prevents the air movement and does not let it affect the mass.

Figure 107. Beakers and Scale

Next, the beakers are filled with dried soil up to 40 millimeters level, and the mass of beaker and soil is measured. I have already measured mass of each beaker. So, I can calculate the mass of dry soil in each beaker. Knowing the sample volume, I can calculate dry soil density. It is 1373 kg/m^3.

Figure 108. Beakers filled with dry soil in 40 ml samples

Soil Porosity

Next, the samples are saturated with water (keeping the 40-ml volume), and the mass of beaker, soil including water is measured. I note down the saturation water volume in this step. Now, I can calculate the mass of water required for saturation. Knowing the porosity helps us make sure about the type of soil by comparing it to other papers measurements.

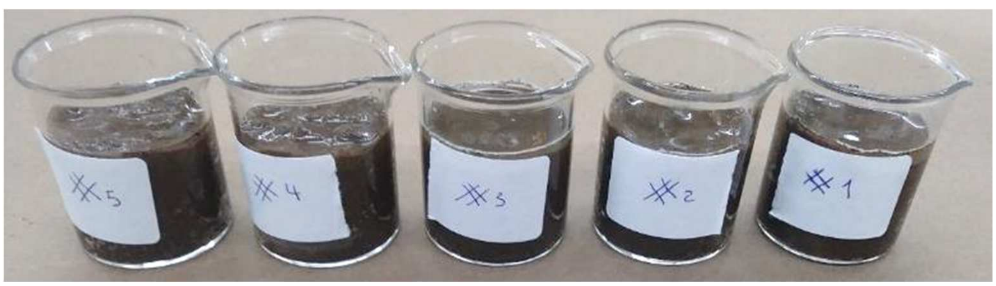


Figure 109. Beakers filled with soil, saturated with water, in 40 ml samples

Table 18. Soil density measurements

Sample No.	Beaker mass (#1)	Beaker + dry soil mass	Dry Soil mass (3) = (-#1)	Beaker + moist soil mass	Water mass = (-#2) =	Saturation water volume	Sample Volume	Soil density = /
	gr	gr	gr	gr	gr			kg/m^3
Volume		40	40	40				
		ml	ml	ml		ml	ml	
1	27.870	83.325	55.455	100.701	17.376	17.5	40	1386
2	27.869	84.274	56.405	100.110	15.836	16.2	40	1410
3	27.909	83.141	55.232	99.812	16.671	16.7	40	1381

4	27.960	83.719	55.759	99.505	15.786	16.0	40	1394
5	29.360	85.360	56.000	102.145	16.785	17.0	40	1400
6	27.870	83.982	56.112	100.271	16.289	16.5	40	1403
7	27.869	79.987	52.118	96.094	16.107	16.2	40	1303
8	27.909	79.217	51.308	95.275	16.058	16.0	40	1283
9	27.960	82.761	54.801	100.060	17.299	17.3	40	1370
10	29.360	85.492	56.132	102.592	17.100	17.3	40	1403
Ave	28.194	83.126	54.932	99.657	16.531	16.7	40	1373

The porosity of our soil seems to be 42%. Now I can compare soil porosity, n, in $\frac{\mathrm{m}^3}{\mathrm{m}^3}$ with quantities from a previous paper (Trząski and Zawada, 2011). I was told that the soil is a sandy loam type of soil; however, it seems that it is closer to the loam type rather than sandy type.

Table 19. Predicted Porosity for different soil types (Trząski and Zawada, 2011)

No.	Soil type	Symbol	Sand (%)	Silt (%)	Clay (%)	Quartz content (%)	Porosity (%)
1	Detached sand	ds	95	3	2	85	35.7
2	Sand	s	90	5	5	81	36.5
3	Loamy sand	ls	80	15	5	77	37.5
4	Sandy loam	sl	65	30	5	69	39.0
5	Light loam	ll	58	27	15	63	40.7
6	Loam	l	42	40	18	54	42.6
7	Sandy clay loam	scl	60	27	13	64	40.3
8	Clay loam	cl	33	35	32	45	44.9
9	Silty clay loam	sicl	10	55	35	33	47.5
10	Sandy silt	ssi	29	65	6	52	42.7
11	Silt	si	10	85	5	43	44.5
12	Silt loam	sil	19	60	21	42	45.2
13	Sandy clay	sc	55	5	40	52	43.5
14	Silty clay	sic	10	45	45	29	48.5
15	Clay	c	23	27	50	34	47.7
16	Heavy clay	hc	20	10	70	25	50.0

Soil Water Content

For the next step, let us first look at soil data and the measured water content as I need it to look up the conductivity and specific heat of the soil. The MicroStation gives us the soil temperature and moisture content, 2 feet (0.6 meters), and 3’-8” (1.1 meters) below the ground surface. The tubes are about 8’ (2.5

meters) below the surface ground. The MicroStation started logging from August 4th, 2017 till present. Let us consider the data from August 5th, 2017 to May 22nd, 2018.

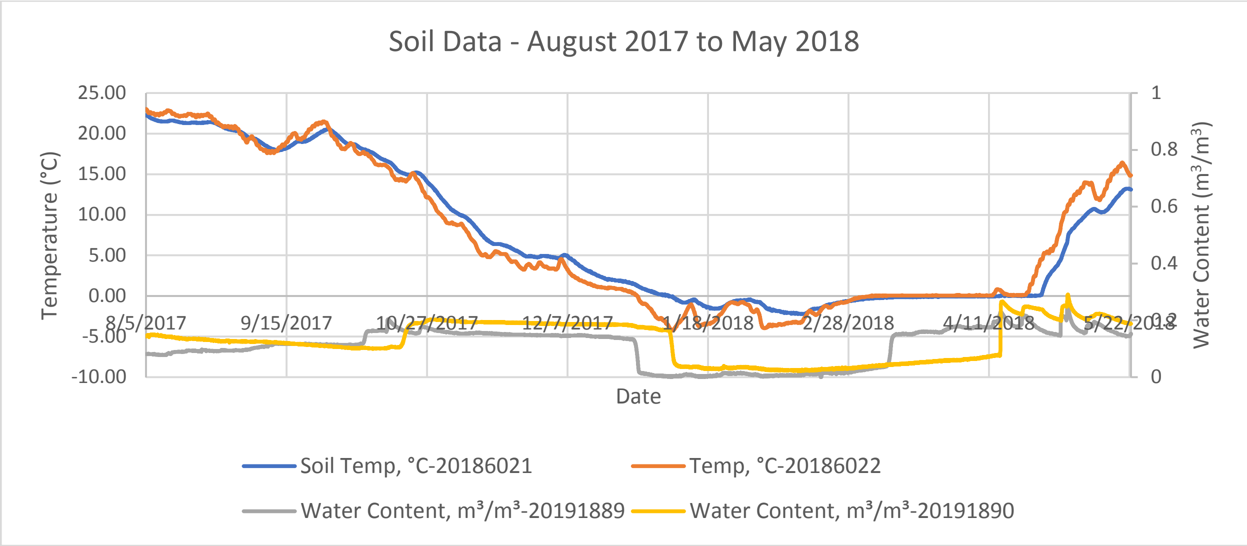


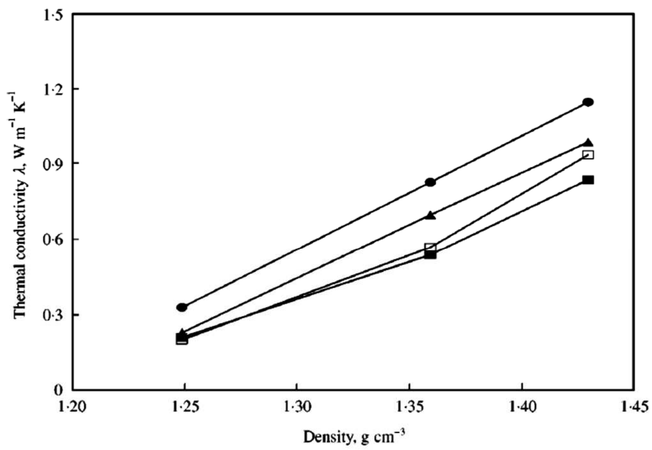
Figure 110. Soil Data - August 2017 to May 2018

Table 20. Soil Temperature and Water Content

	Temp-20186021-°C	Temp-20186022-°C	Water content-20191889-m³/m³	Water content-20191890-m³/m³
AVE	7.28	7.04	0.11	0.13
Min	-2.25	-4.26	0.00	0.02
Max	22.30	23.04	0.25	0.29

Soil Conductivity and Specific Heat

The conductivity (k) of a sandy loam soil with a density of 1.37 g/cm^3 and about 10% moisture content is about 0.5 W/m.K (Abu-Hamdeh, 2001). The specific heat (C_P) of this soil is about 1300 J/kg.K (Alnefaie and Abu-Hamdeh, 2013).



Thermal conductivity as a function of soil density for sandy loam using the dual probe method at four moisture contents: ■, *7·2%;* □, *9·7%;* ▲, *12·6%;* ●, *17·1%*

Figure 111. Soil Thermal Conductivity

Soil Thermal Diffusivity

Next, I can calculate soil thermal diffusivity (α) in m^2/day by the following equation. In this case, it is 0.0242 m^2/day.

$$\alpha = \frac{k}{\rho C_P} \times 86400 \qquad (30)$$

Soil Temperature[129]

Having the thermal diffusivity, I can plug it into Kusuda equation and get soil temperature as a function of depth and time of the year (Kusuda and Achenbach, 1965) (Solar Energy Laboratory, 2007).

$$T = T_{mean} - T_{amp} e^{\left(-d\left(\frac{\pi}{365\alpha}\right)^{0.5}\right)} \cos\left(\frac{2\pi}{365}\left(t_{now} - t_{shift} - \frac{d}{2}\left(\frac{365}{\pi\alpha}\right)^{0.5}\right)\right) \qquad (31)$$

- T = Temperature (°C)
- T_{mean} = Average air temperature (°C)

---

[129]
```
T_s=[]
c=T_amp*math.exp(-self.Depth*pow((math.pi/365/self.alpha),0.5))
for i in range(365):
      a=T_mean-c*math.cos(2*math.pi/365*(i-
      (self.Depth/2*math.pow((365/math.pi/self.alpha),0.5))))
      T_s.append(a)
```

- T_{amp} = Amplitude of surface temperature (°C)
- d = Soil depth (m)
- α = Soil thermal diffusivity (m^2/day)
- t_{now} = Current day of the year (day)
- t_{shift} = Day of the year corresponding to the minimum surface temperature (day)

The fluctuation of soil temperature profile is shown below. The depth of soil is increased by 1 foot (0.3 meters) each time.

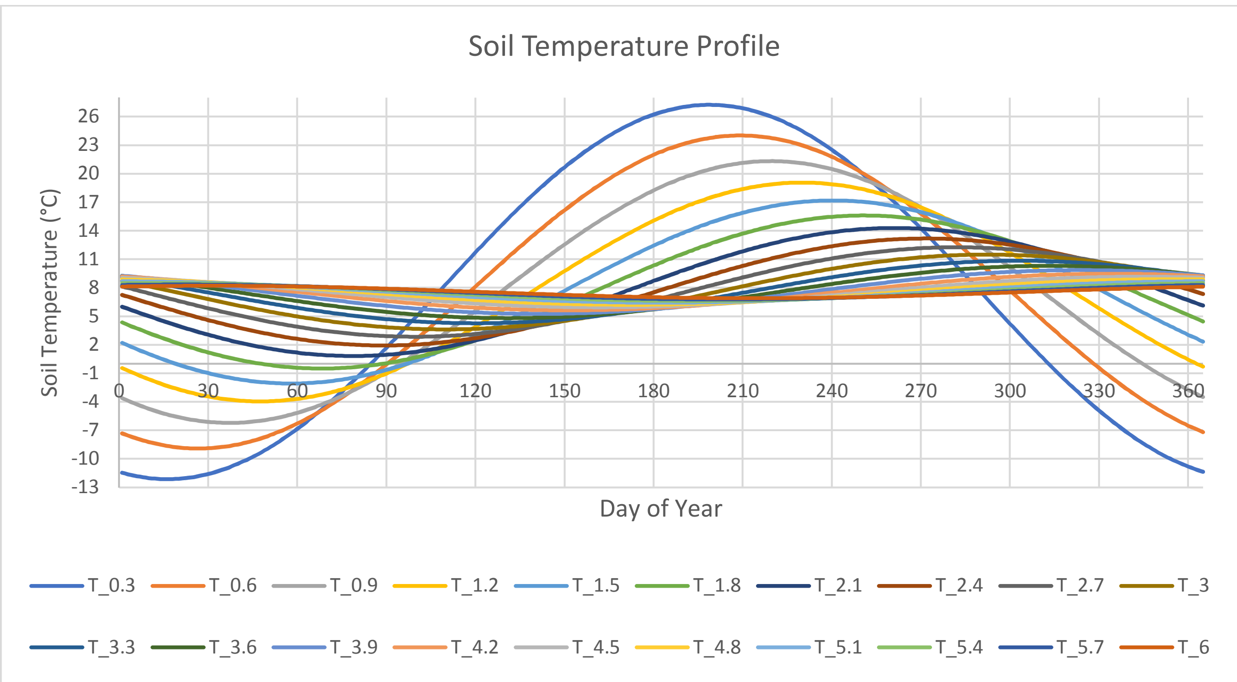


Figure 112. Soil Temperature Profile

As you see, the relationship between the soil depth and temperature is not a linear one. To have a better look, let us consider only 5th of August, and see the temperature change only as a function of soil depth.

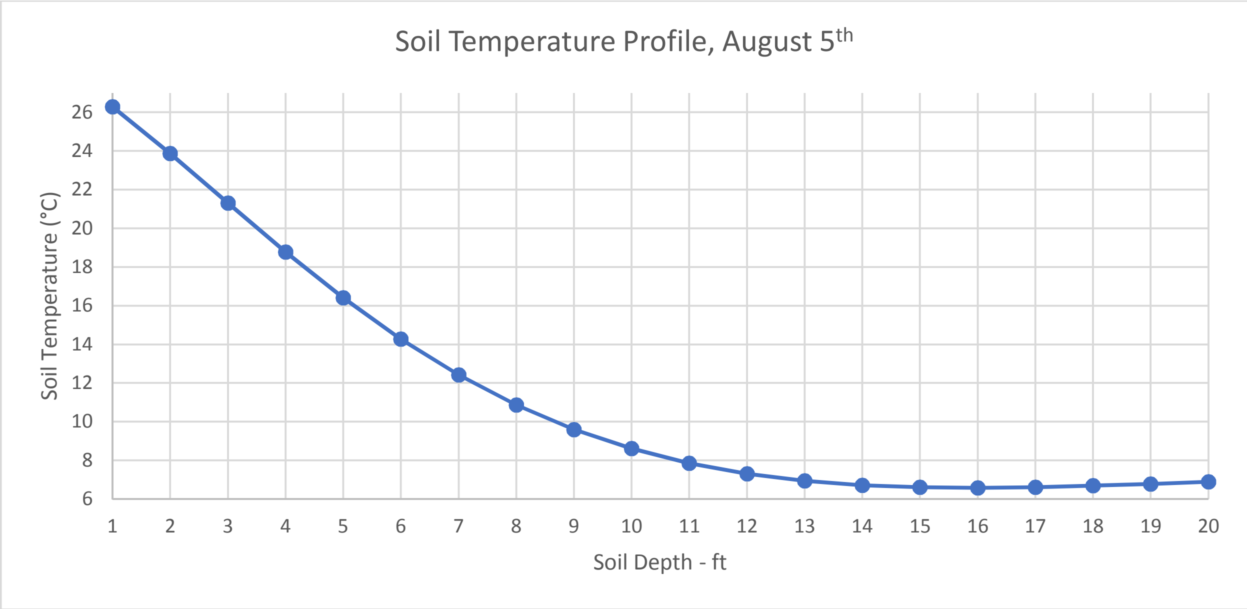


Figure 113. Soil Temperature Profile, August 5th

As you see, in the first 8 to 10 feet, this soil shows more of a linear behavior. As we go further, the soil depth starts to be less significant. Digging further than 15 feet, makes almost no difference. This will vary in soil with different thermal characteristics.

The following figure summarizes the parameters required to calculate soil temperature.

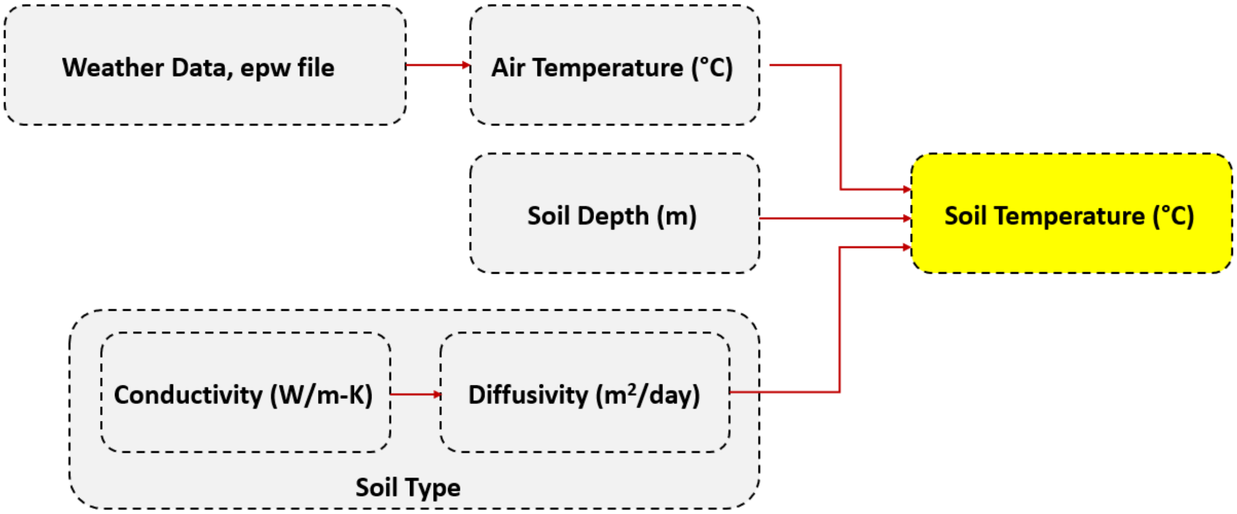


Figure 114. Soil Temperature Parameters

Soil Temperature Validation

In June 2018, Professor Utzinger and I were able to locate a soil sensor 8' below the ground surface. The data kept logging till August 2019. In this part, the Kusuda equation is compared and adjusted to the data. It seems that the soil is about 2 °C warmer than what Kusuda equation shows. This could be due to the vegetation growing over the ground surface since 2007, when the building was first constructed.

While usually the annual average of the soil temperature equals the annual average of air temperature, it is interesting that in this case, the actual soil temperature is about 1.5 °C warmer than the average of air temperature. This corroborates the possibility of the thermal resistance added because of the plants.

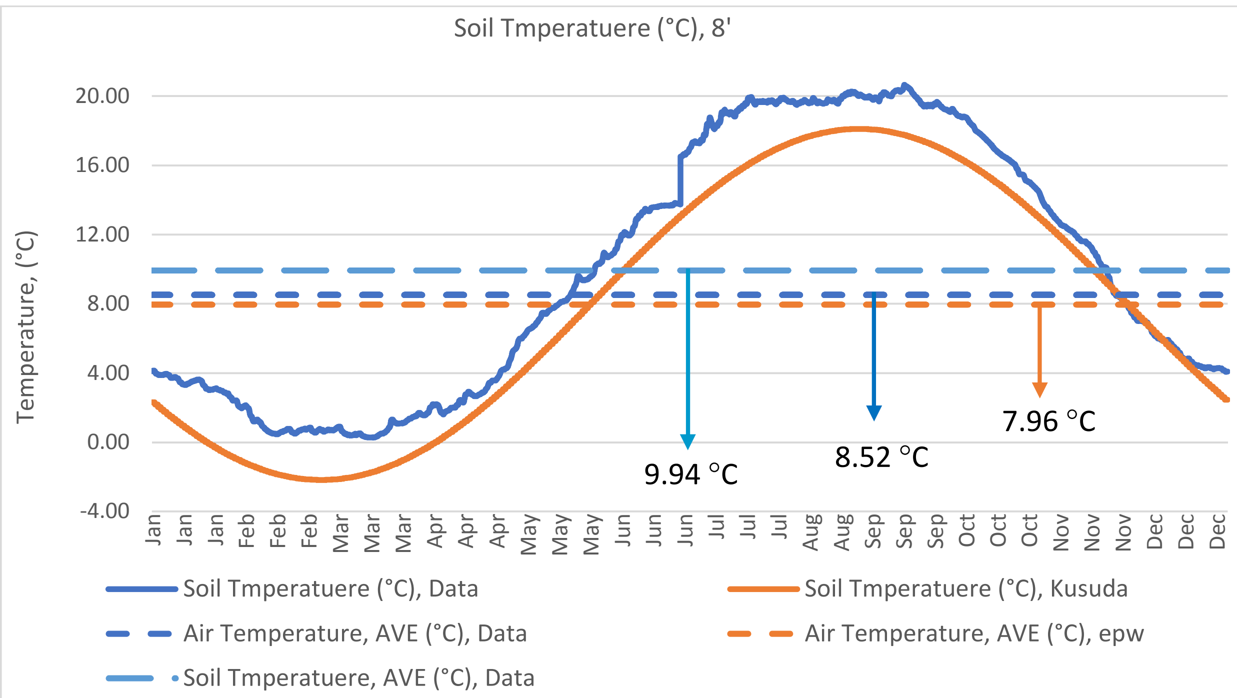


Figure 115. Soil Temperature, 2.4 meters below the ground surface

The following image compares the soil temperature in two consecutive years in June, July and August. Even in two following years, there is a variation of up to 2 °C in soil temperature, 8' deep in the ground.

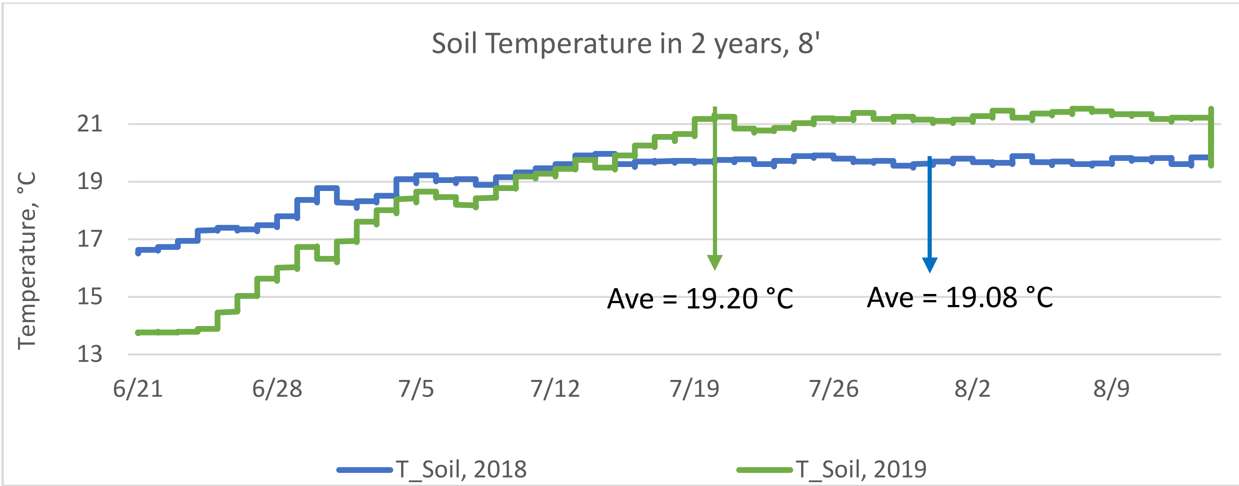


Figure 116. Soil Temperature, two consecutive years

4.3. Earth Tube System, CFD Model

Fan Specifications

Air velocity or volume flow rate is required for convection heat transfer calculations. Volume flow rate is part of fan specifications. Currently, fan is running through a variable frequency drive. The fan is capable of providing 1195 CFM at 60 Hz. Currently, it is set on about 27 Hz. They tend to keep it on this frequency.

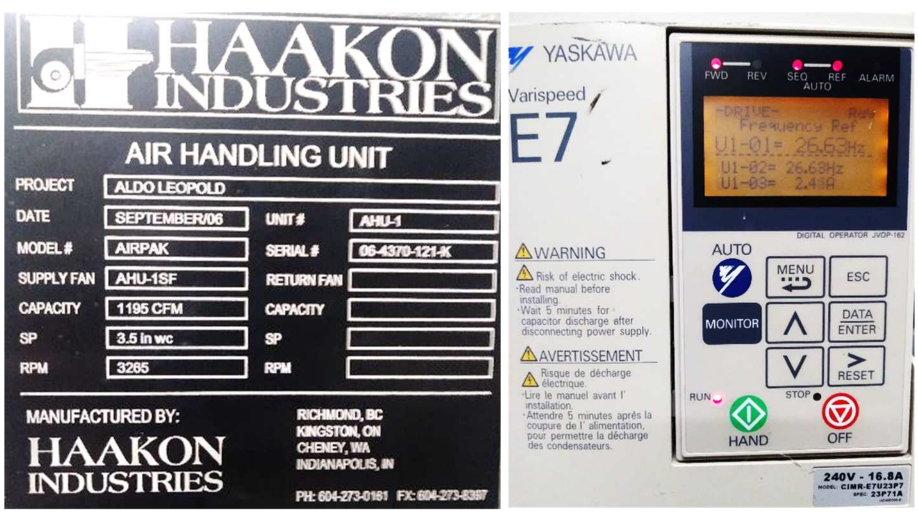


Figure 117. Fan and Variable Frequency Drive Specifications

ASHRAE handbook of air conditioning introduces an equation to relate frequency (f) and speed of motor (n_m) in rpm (Lee and Strand, 2008). According to this equation, motor speed and frequency have a direct relationship. According to Baldor company, the motor has 2 poles. ($n_m \approx 1600$ rpm)

$$n_m = \frac{120f}{N_P} \qquad (32)$$

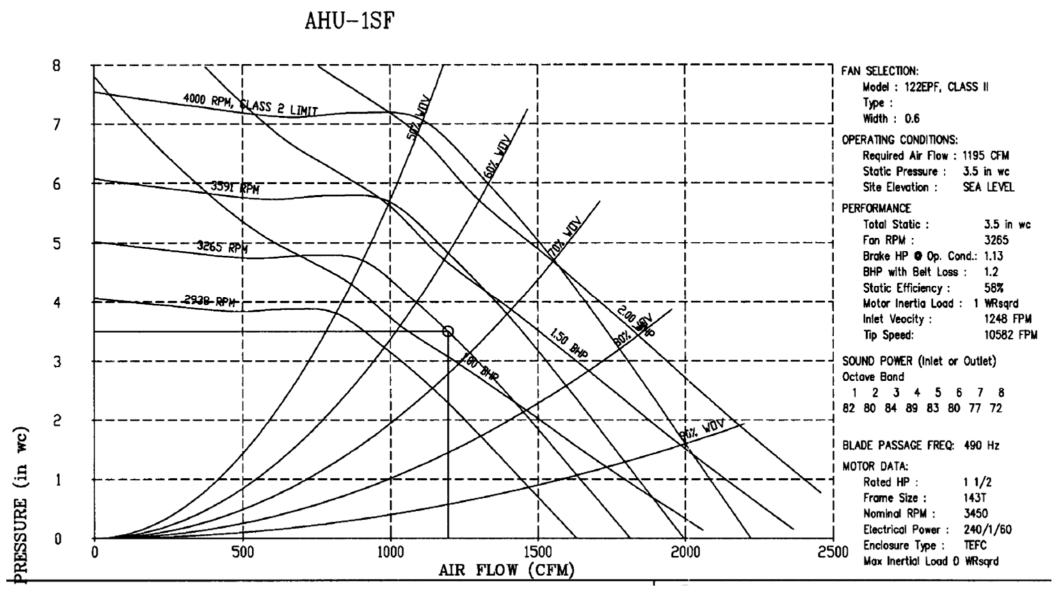


Figure 118. Fan Air Flow

If the fan performs at full capacity, volume flow rate and inlet velocity would be 1195 CFM (560 L/s) and 1248 fpm (6.34 m/s) respectively. In a 2' diameter tube, air velocity would be about 2 m/s. In 1600 rpm, fan volume flow rate is about 600 cfm which results in about 1 m/s air velocity before dividing the pipe into 5 branches.

$$V = \frac{Q}{A} \qquad (33)$$

Existing Geometry

Some Computational Fluid Dynamics (CFD) analysis has been performed to study the air flow pattern inside the tubes.

Basically, the type of there is a forced flow along the tubes since there is a fan in the outlet of the tubes in the Air Handling Unit. As the design team state, the amount of volume flow rate provided by the fan is about 300 L/s (0.3 $\frac{m^3}{s}$) or higher. This is the main input for the CFD analysis. The boundaries conditions and other specifications of the simulation is as follows:

- Boundary conditions
  - ✓ Inlet pressure: 97.5 kPa
  - ✓ Outlet (AHU) pressure: 98.5 kPa
  - ✓ Outlet (AHU) volume flow rate: 300 L/s (635 CFM)
  - ✓ All pipe surfaces material: Concrete
- # of iterations to converge: 337

According to the design team, they expected the 5 tubes to have an evenly distributed flow. Nevertheless, the CFD results seem to show something different. Let us study this in more details.

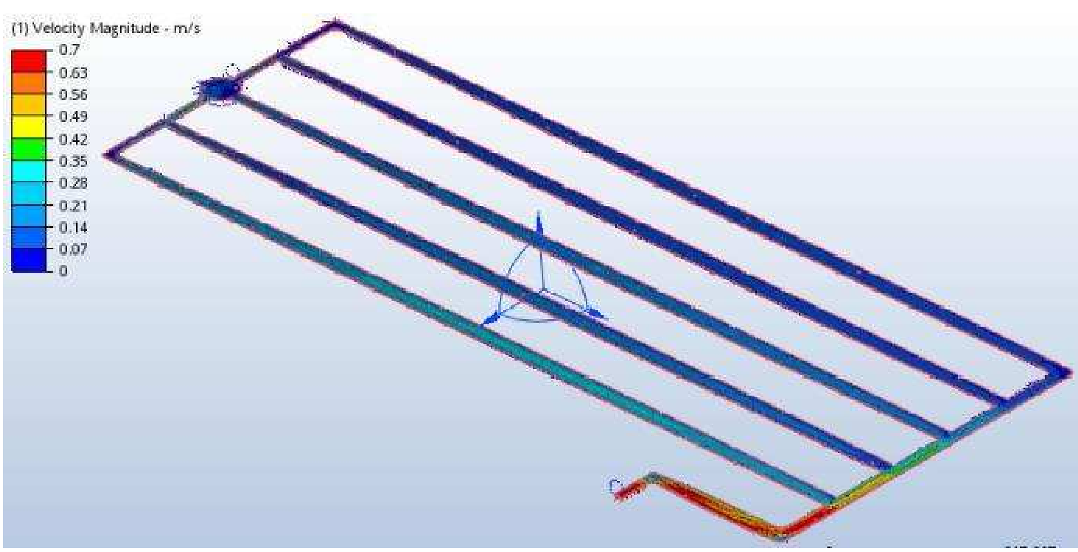


Figure 119. Velocity Profile in the Earth Tubes, CFD Simulation

Based on the Equation 33, the relationship between volume flow rate and velocity is this:

$$Q = VA \qquad (34)$$

The velocity of the air at the outlet surface is:

$V = Q/A = 1.028$

Also, equation number 2 shows how the volume flow rate of tubes connecting to each other combine:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \qquad (35)$$

As the area of all branches is the same, I can develop the equation:

$$V = V_1 + V_2 + V_3 + V_4 + V_5 \qquad (36)$$

Therefore, one should expect the sum of the velocity of the 5 main branches should equal 1.028 $\frac{\mathrm{m}}{\mathrm{s}}$ (velocity at the outlet). However, the simulation verifies a velocity drop due to the 90-degree elbows, the concrete surface, and so on. To study the velocity more carefully, 10 cross sections have been made align the 5 branches.

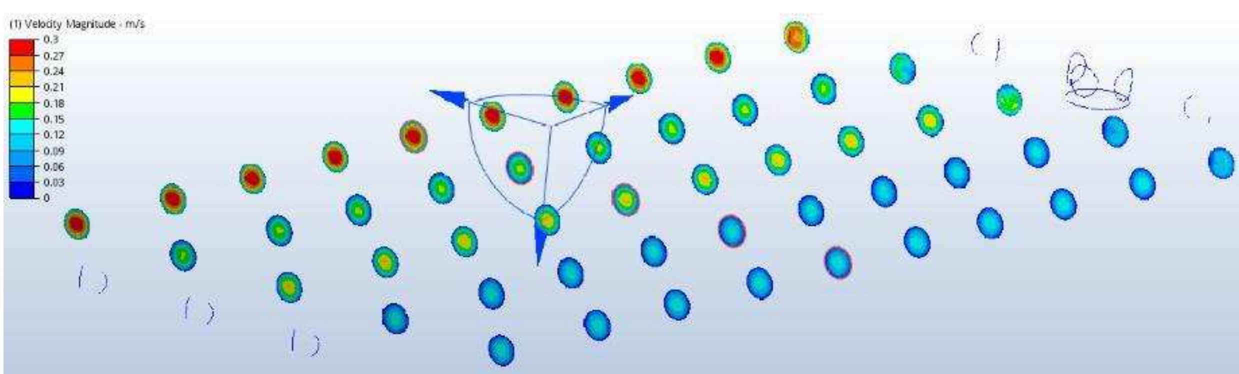


Figure 120. Cross sections of velocity profile Align the Earth Tubes, CFD Simulation

Next figure displays the velocities for main branches. All velocity magnitudes are in $\frac{\mathrm{m}}{\mathrm{s}}$.

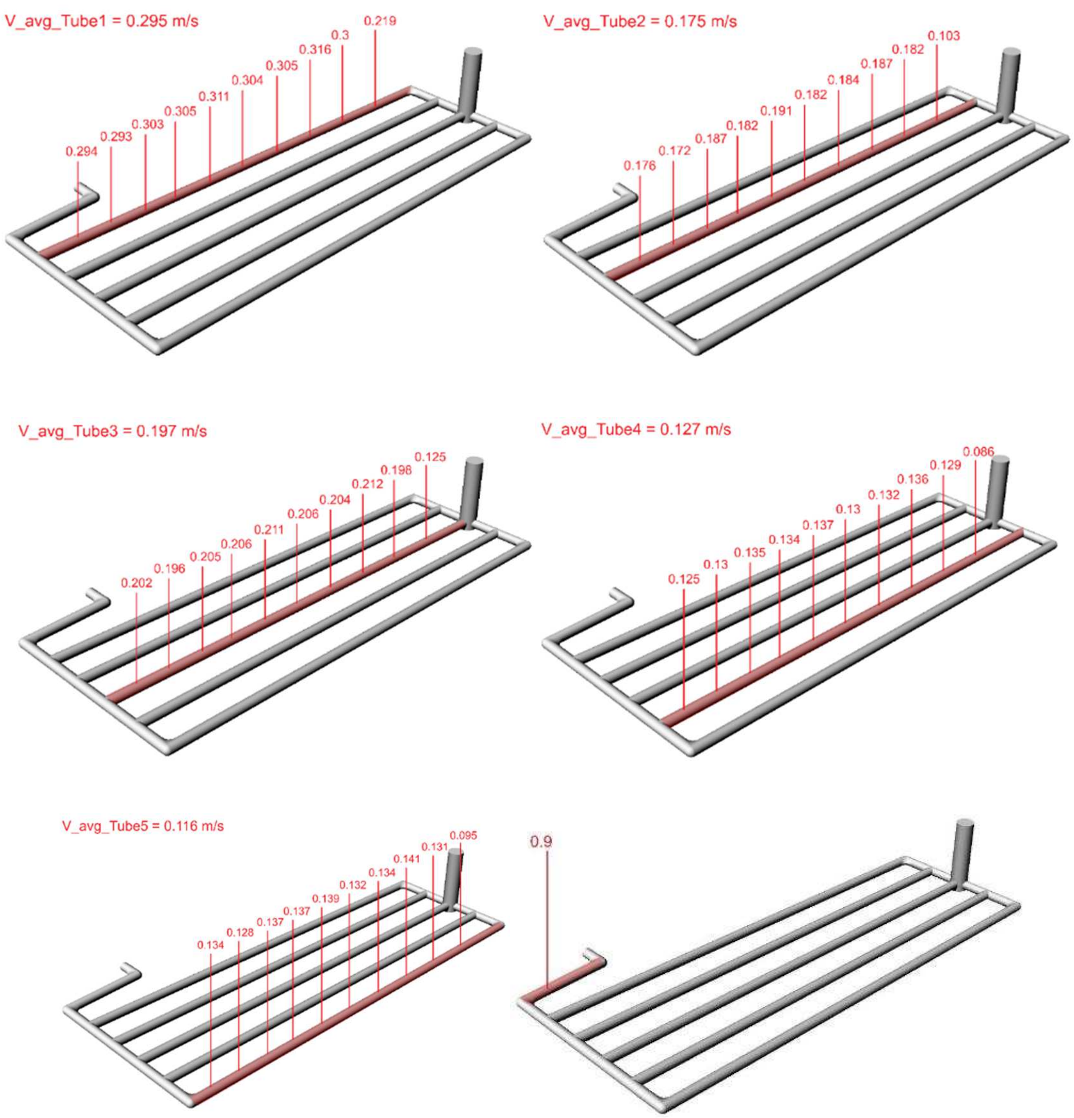


Figure 121. Average air velocities in Main Tube Branches

Recommended Geometry

As the diagrams reveal, there is about 20% velocity drop right after the first 90-degree elbow. Probably, the first elbow is too close to the outlet. Had the designers considered a larger distance between the outlet and the elbow, less velocity drop would have happened. On the other hand, the flow has been unevenly distributed in the 5 tubes. Hence, I suggest another arrangement.

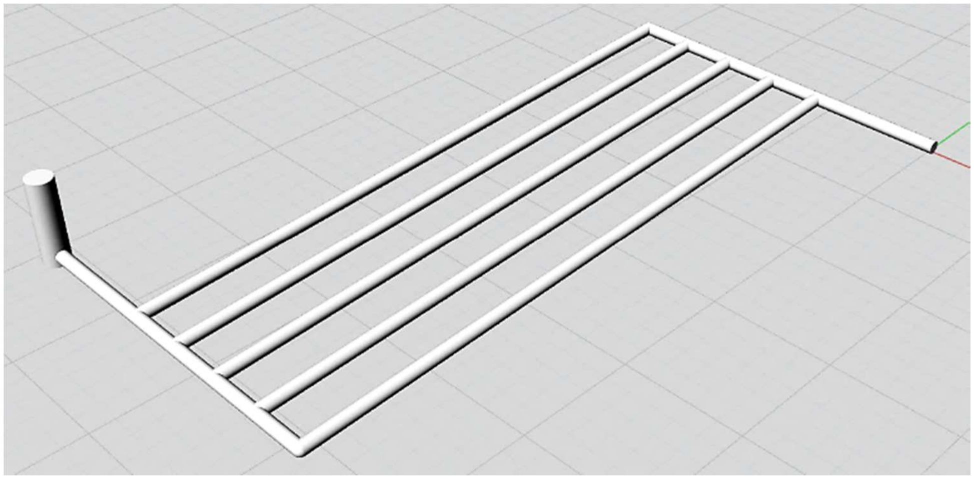


Figure 122. Suggested Tubes Geometry

4.4. Earth Tube System, Bulk Flow Model

Sensible Energy

Convection of Internal Flow

Assumptions

To make it simple, I make some assumptions for the bulk flow model.

i. According to Mach number, air inside the tube is incompressible.
ii. The volume flow rate is constant and is the same amount all over the 5 tubes.
iii. The temperature of the soil sensor 4' below the ground surface is considered as the undisturbed soil temperature.
iv. Solar radiation on the soil surface is neglected in this model.
v. This model accounts for convection between the Soil and air inside tubes, and conduction of the soil.
vi. Based on the geometry of the tubes, this is a case of fully developed flow since: $L_{tube}/D_{tube} \geq 10$

Mach Number (Ma)

Mach number is a unitless parameter which defines the incompressibility of the fluid. As long as Mach number is less than 0.3, the fluid is incompressible. Mach number is presented as the ratio of velocity to the speed of sound.

$$Ma = \frac{V}{a} \qquad (37)$$

In our case, the air velocity is about 1 m/s, and the speed of sound at a regular temperature f 20 °C is equal to 343 m/s.

$Ma = \frac{1}{343} = 0.003$

As this number is far less than 0.3, air is incompressible and incompressible flow equations can be applied.

Reynolds Number (Re)

Based on the 6th assumption, the flow is fully developed. Therefore, I can use the following equation.

$$R_{e_D} = \frac{4m_a}{\pi\mu D} \qquad (38)$$

$$m_a = \rho VA \qquad (39)$$

Calculation of air density (ρ), viscosity (μ), Prandtl Number (Pr), and conductivity (K) is already described in the air specifications section.

Nusselt Number (Nu)

The Nusselt number can be calculated based on the DittusBoelter equation, as I have the three conditions provided (Bergman, 2011).

i. $0.6 \leq P_r \leq 160$
ii. $R_{e_D} \geq 10'000$
iii. $L_{tube}/D_{tube} \geq 10$

DittusBoelter equation:

$$N_{u_D} = 0.023\ (R_{e_D})^{4/5}\ P_r^{\ 0.3} \qquad \text{(Cooling)} \qquad (40)$$

$$N_{u_D} = 0.023\ (R_{e_D})^{4/5}\ P_r^{\ 0.4} \qquad \text{(Heating)} \qquad (41)$$

Convection Heat Transfer Coefficient (h_f)

$$h_f = \frac{N_{u_D} k}{D} \qquad (42)$$

Log Mean Temperature Difference

In Internal flow convection, the fluid may experience a large change in temperature as it moves inside the pipe. Hence, the heat transfer rate could be significantly overpredicted by using $\Delta t = T_s - T_\infty$ which is used in conventional convection equations as the temperature difference in Newton's law of cooling. Instead, log-mean temperature difference is used (Bergman, 2011).

$$\Delta t_{lm} = \frac{(T_{soil} - T_{in})\ - (T_{soil} - T_{out})}{\ln\frac{(T_{soil} - T_{in})}{(T_{soil} - T_{out})}} \qquad (43)$$

If I consider the tube surface temperature is equal to the soil temperature, I can use the following equation for sensible cooling load:

$$Q_t = h_f A_s \Delta t_{lm} \qquad (44)$$

Conduction of Soil

Conduction of the soil can be solved through an existing solution in terms of a shape factors (S) (Bergman, 2011). Using the shape factor, I could use the following equation.

$$q = Sk\Delta t_{1-2} \qquad (45)$$

I could use Case 2, Horizontal isothermal Cylinder of length L buried in a semi-infinite medium (Bergman, 2011).

$$S = \frac{2\pi L}{\ln(4z/D)} \qquad (46)$$

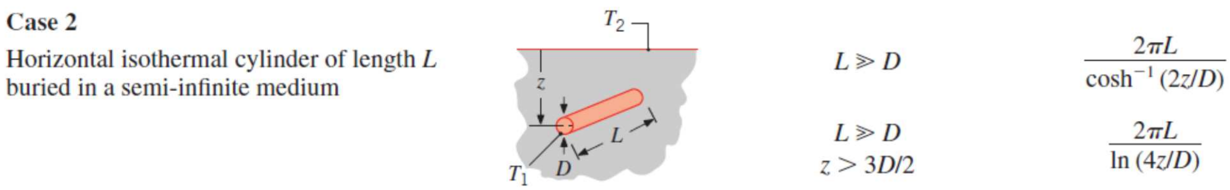


Figure 123. Shape Factor

Existing Model

As mentioned before, existing models tend to use this equation as the basis of their analysis.

$$\dot{q}_{Conv} = \dot{m}_a C_P(T_o - T_i) \qquad (47)$$

I could develop the left side using the convection equation.

$$h_f A_s \Delta t_{lm} = \dot{m}_a C_P(T_o - T_i) \qquad (48)$$

$$h_f \pi DL \frac{(T_s - T_i) - (T_s - T_o)}{\ln\frac{(T_s - T_i)}{(T_s - T_o)}} = \dot{m}_a C_P(T_o - T_i) \qquad (49)$$

$$h_f \pi DL \frac{\cancel{(T_o - T_i)}}{\ln\frac{(T_s - T_i)}{(T_s - T_o)}} = \dot{m}_a C_P\cancel{(T_o - T_i)} \qquad (50)$$

Let us separate T_o as our unknown on one side by itself.

$$T_o = T_s - [(T_s - T_i)(\exp(-h_f \pi DL/\dot{m}_a C_P))] \qquad (51)$$

Recommended Model

If I consider soil conduction as not negligible, I end up with the following equation.

$$\dot{q}_{Conv} + \dot{q}_{Cond} = \dot{m}_a C_P(T_o - T_i) \qquad (52)$$

$$H_f A_s \frac{(T_o - T_i)}{\ln\frac{(T_s - T_i)}{(T_s - T_o)}} + Sk(T_I - T_s) = \dot{m}_a C_P(T_o - T_i) \qquad (53)$$

This equation does not have an explicit way to solve. Therefore, I established some simple numerical calculations to figure out outlet temperature (T_o).

Let us define the two sides of the equation as q_1 and q_2.

$$q_1 = h_f A_s \frac{(T_o - T_i)}{\ln\frac{(T_s - T_i)}{(T_s - T_o)}} + Sk(T_i - T_s) \qquad (54)$$

$$q_2 = \dot{m}_a C_P (T_o - T_i) \qquad (55)$$

In summertime, I know that soil temperature is less that both inlet and outlet temperature. Moreover, outlet temperature should be less than inlet temperature because we are cooling the air.

$$T_s \leq T_o \leq T_I \qquad (56)$$

We can consider the range of numbers between soil temperature and inlet temperature, divide it by like 0.1 °C, and find in which T_o in this range, q_1 and q_2 have the least difference.

In winter time, outdoor air is colder than outlet air, and they are both colder than soil temperature.

$$T_I \leq T_o \leq T_s \qquad (57)$$

We can follow the same procedure starting from inlet temperature, adding 0.1 °C each time and find the minimum difference between q_1 and q_2. The outlet temperature (T_o) in which minimum difference happens is the unknown we are looking for.

Here is the Python code for this numerical analysis.

```
def Cooling(self):
    dic={}
    a=[]
    b=[]
    if self.T>=self.T_Soil:
        T_out=self.T_Soil+0.001
        while T_out<=self.T:
```

```
            a.append(T_out)
            Q1=self.massFlowRate*self.specificHeat*(T_out-self.T)
            Q2=self.h_f_cooling*self.SurfaceArea*(T_out-self.T)/math.log((self.T_Soil-self.T)/(self.T_Soil-T_out))-
self.ShapeFactor*self.SoilConductivity*(self.T-self.T_Soil)
            dif=abs(Q2-Q1)
            b.append(dif)
            dic=zip(b,a)
            dicSet=set(dic)
            dic=dict(dicSet)
            T_out=T_out+0.1
    if self.T<self.T_Soil:
        T_out=self.T+0.001
        while T_out<=self.T_Soil:
            a.append(T_out)
            Q1=self.massFlowRate*self.specificHeat*(T_out-self.T)
            Q2=self.h_f_heating*self.SurfaceArea*(T_out-self.T)/math.log((self.T_Soil-self.T)/(self.T_Soil-T_out))-
self.ShapeFactor*self.SoilConductivity*(self.T-self.T_Soil)
            dif=abs(Q2-Q1)
            b.append(dif)
            dic=zip(b,a)
            dicSet=set(dic)
            dic=dict(dicSet)
            T_out=T_out+0.1
    m=min(b)if b else self.T
    n=dic.get(m)
    return n
```

After finding the outlet temperature (T_o), we can plug it into either q_1 or q_2 to calculate the sensible heating or sensible cooling energy.

Latent Cooling

Latent cooling is calculated by the following equation. L stands for latent heat of water which is 2270 kJ/kg. For ω_{in} and ω_{out}, the equations in the air specification section has been used. That is, the humidity ratio of inlet air is a function of inlet air temperature, pressure and relative humidity. The humidity ratio of outlet air is a function of calculated outlet temperature, and inlet relative humidity and pressure. As there is no way I could calculate the outlet relative humidity, relative humidity of inlet air – which is outdoor air relative humidity – is used for both inlet and outlet calculations, while the temperatures are different. Other papers have used similar approach (Mongkon, et al., 2013) (Hollmuller and Lachal, 2005).

$$LE = m_w L \quad (58)$$

$$m_w = m_a (\omega_{in} - \omega_{out}) \quad (59)$$

Here is the Python code of the latent cooling calculations.

```
def Latent(self):
    LatentLoad=[]
    T_k_in=self.T*1.8+32
    w_s_in=0.00080264+0.000024525*T_k_in+0.000002542*math.pow(T_k_in,2)-
0.000000025855*math.pow(T_k_in,3)+0.0000000004038*math.pow(T_k_in,4)
    P_ws_in=self.P*w_s_in/(w_s_in+0.62198)
    P_w_in=self.RH*P_ws_in/100
    w_in=0.62198*P_w_in/(self.P-P_w_in)
    T_Outlet_c=T_Soil-((self.T_Soil-self.T)*math.exp(-
self.SurfaceArea*self.h_f_cooling/self.massFlowRate/self.specificHeat))
    T_k_out=1.8*T_Outlet_c+32
    w_s_out=0.00080264+0.000024525*T_k_out+0.000002542*math.pow(T_k_out,2)-
0.000000025855*math.pow(T_k_out,3)+0.0000000004038*math.pow(T_k_out,4)
    P_ws_out=self.P*w_s_out/(w_s_out+0.62198)
    P_w_out=self.RH*P_ws_out/100
    w_out=0.62198*P_w_out/(self.P-P_w_out)
    if w_out<w_in:
      LatentLoad.append(2270*self.massFlowRate*(w_out-w_in))

    return sum(LatentLoad)
```

4.5. Earth Tube System, Python Model

The Python model is based on the proposed model considering both convection and conduction for sensible loads. It calculates the latent loads as well considering the same relative humidity at the inlet and outlet of the tubes. Despite outlet temperature, there seems to be no way to predict the relative humidity at the outlet of the tubes.

The Python model interfaces in the form of a few Grasshopper components each of which is responsible for a specific action. The first component creates the tubes geometry based on user inputs. This is the only component which has visual effects in the Rhino environment.

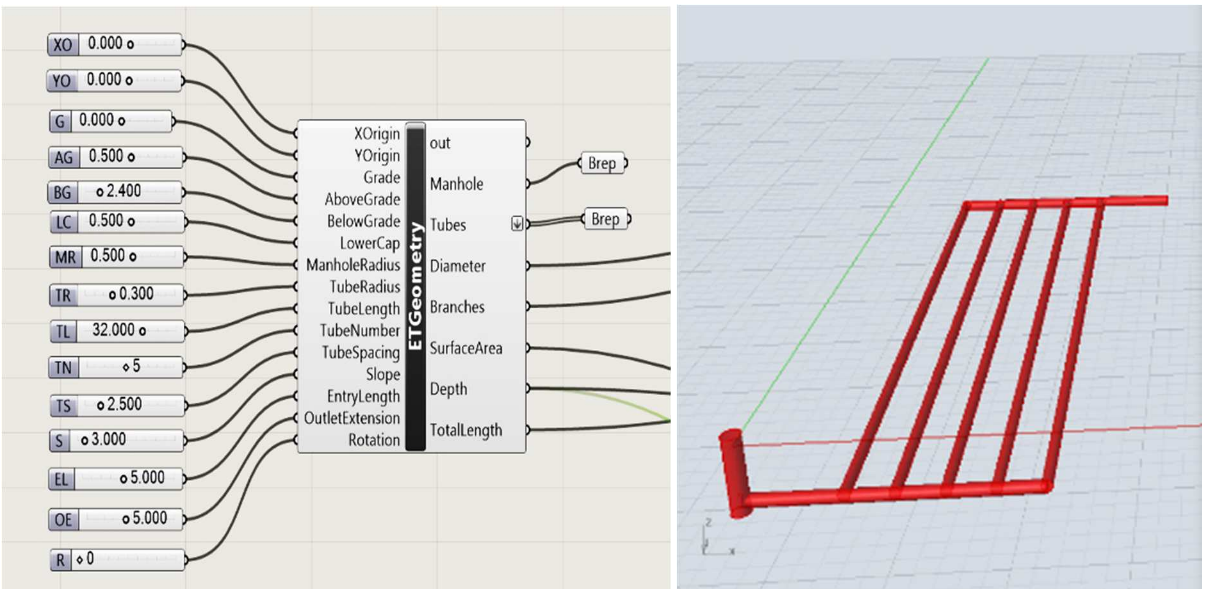


Figure 124. Grasshopper Component, Earth Tube Geometry

The user can define the location of the earth tube system in the Rhino coordinates as well as tubes number, radius, length, slope, distance, and Manhole height and radius. By changing any input, the geometry will update in the Rhino environment instantaneously. Any parameter required as inputs of other components is considered as output of this component including the geometry (Manhole and Tubes), total surface area and length, depth of soil, and number of branches and their diameter. The last two are exactly the numbers that the user has already inserted. I put them as separate outputs to make the connection between the components more smoothly.

Here is the code of the first ETGeometry component.

```
import rhinoscriptsyntax as rs
import math
class Manhole:
  def __init__(self):
    self.Grade=Grade
```

```
        self.AboveGrade=AboveGrade
        self.BelowGrade=BelowGrade
        self.LowerCap=LowerCap
        self.ManholeRadius=ManholeRadius
        self.XOrigin=XOrigin
        self.YOrigin=YOrigin
    def cap(self):
        pointOrigin=rs.AddPoint(self.XOrigin,self.YOrigin,self.Grade)
        pointCap=rs.AddPoint(self.XOrigin,self.YOrigin,self.Grade+self.AboveGrade)
        pointCapLow=rs.AddPoint(self.XOrigin,self.YOrigin,self.Grade-(self.BelowGrade+self.LowerCap))
        ManholePivot=rs.AddLine(pointCap,pointCapLow)
        ManholePipe=rs.AddPipe(ManholePivot,0,self.ManholeRadius,0,1)
        return ManholePipe
class Tubes:
    def __init__(self):
        self.TubeRadius=TubeRadius
        self.TubeLength=TubeLength
        self.TubeSpacing=TubeSpacing
        self.EntryLength=EntryLength
        self.BelowGrade=BelowGrade
        self.TubeNumber=TubeNumber
        self.OutletExtension=OutletExtension
        self.Slope=Slope
        self.XOrigin=XOrigin
        self.YOrigin=YOrigin
        self.Grade=Grade
        self.Rotation=Rotation
    def display(self):
        Pipes=[]
        for i in range(TubeNumber):
            pipeOrigin=rs.AddPoint(self.XOrigin+self.EntryLength+self.TubeSpacing*i,self.YOrigin,self.Grade-
self.BelowGrade)

pipeEnd=rs.AddPoint(self.XOrigin+self.EntryLength+self.TubeSpacing*i,self.YOrigin+self.TubeLength,self.Grade-
self.BelowGrade)
            TubePivot=rs.AddLine(pipeOrigin,pipeEnd)
            pipeCircle=rs.AddCircle(pipeOrigin,self.TubeRadius)
            pipeSection=rs.RotateObject(pipeCircle,pipeOrigin,90,(1,0,0))
            pipe=rs.ExtrudeCurve(pipeSection,TubePivot)
            cap=rs.CapPlanarHoles(pipe)
            Pipes.append(pipe)
        pipeOrigins=rs.AddPoint(self.XOrigin+self.EntryLength+self.TubeSpacing*(self.TubeNumber-
1),self.YOrigin,self.Grade-self.BelowGrade)
        pipeEnds=rs.AddPoint(self.XOrigin,self.YOrigin,self.Grade-self.BelowGrade)
        horizontal=rs.AddLine(pipeOrigins,pipeEnds)
        hCircle=rs.AddCircle(pipeOrigins,self.TubeRadius)
        hCSection=rs.RotateObject(hCircle,pipeOrigins,90,(0,1,0))
        hPipe1=rs.ExtrudeCurve(hCSection,horizontal)
        cap2=rs.CapPlanarHoles(hPipe1)
        Pipes.append(hPipe1)
        hOrigin=rs.AddPoint(self.XOrigin+self.EntryLength,self.YOrigin+self.TubeLength,self.Grade-self.BelowGrade)
        hEnd=rs.AddPoint(self.XOrigin+self.EntryLength+self.TubeSpacing*(self.TubeNumber-
1)+self.OutletExtension,self.YOrigin+self.TubeLength,self.Grade-self.BelowGrade)
```

```
        horizontal2=rs.AddLine(hOrigin,hEnd)
        hCircle2=rs.AddCircle(hOrigin,self.TubeRadius)
        hCSection2=rs.RotateObject(hCircle2,hOrigin,90,(0,1,0))
        hPipe2=rs.ExtrudeCurve(hCSection2,horizontal2)
        Pipes.append(hPipe2)
        rs.BooleanUnion(Pipes)
        rs.RotateObject(Pipes,pipeOrigins,self.Slope,(1,0,0))
        rs.RotateObject(Pipes,pipeEnds,self.Rotation,(0,0,1))
        return Pipes
    def SurfaceArea(self):
        TubesLength=self.TubeLength*self.TubeNumber+self.TubeSpacing*(self.TubeNumber-
1)*2+self.EntryLength+self.OutletExtension
        Area=math.pi*2*self.TubeRadius*TubesLength
        return Area
    def Diameter (self):
        Diameter=self.TubeRadius*2
        return Diameter
    def Depth (self):
        Depth=self.BelowGrade
        return Depth
    def Branches (self):
        Branches=self.TubeNumber
        return Branches
    def Length(self):
        TubesLength=self.TubeLength*self.TubeNumber+self.TubeSpacing*(self.TubeNumber-
1)*2+self.EntryLength+self.OutletExtension
        return TubesLength
M=Manhole()
Manhole=M.cap()
ET=Tubes()
Tubes=ET.display()
SurfaceArea=ET.SurfaceArea()
Diameter=ET.Diameter()
Depth=ET.Depth()
Branches=ET.Branches()
TotalLength=ET.Length()
```

The second component accepts air temperature, relative humidity and pressure and calculates air density, viscosity, Prandtl number, humidity ratio, specific heat, and conductivity. The calculations are already discussed in the air specification section.

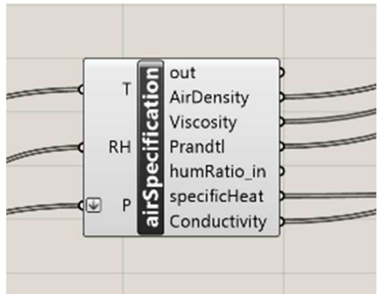


Figure 125. Grasshopper Component, Air Specification

The next component receives the geometric information from the first component, air specification from the second component, and fan volume flow rate as a direct input. Then, it calculates all coefficients including heating and cooling convective heat coefficient, conduction shape factor and mass flow rate.

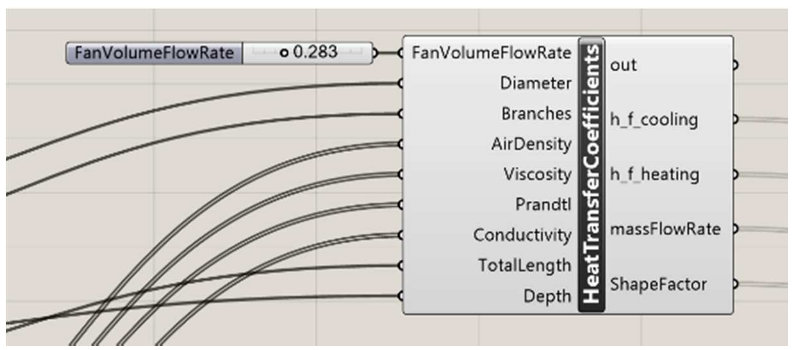


Figure 126. Grasshopper Component, Heat Transfer Coefficients

The next component is only responsible to calculate the soil temperature as a function of depth, time and type of soil based on the Kusuda equation (Kusuda and Achenbach, 1965). For now, I have considered alpha – thermal diffusivity – as input for type of soil which is set on sandy loam soil.

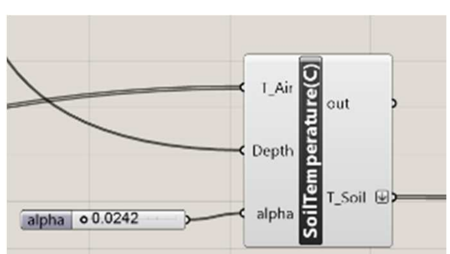


Figure 127. Grasshopper Component, Soil Temperature

The next step calculates outlet temperature, heating, cooling and latent loads (whichever applies), in an hourly manner based on all previous components and soil conductivity.

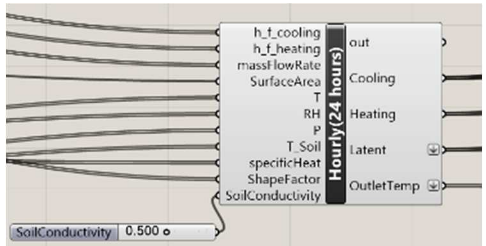


Figure 128. Grasshopper Component, Hourly Data

The next component separates only 8 hours out of 24 in case we are dealing with an office type of building.

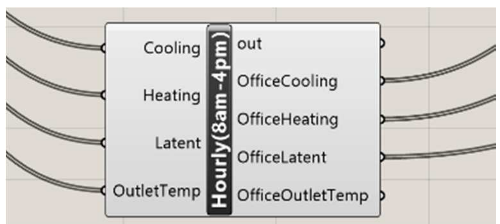


Figure 129. Grasshopper Component, Hourly Data for Office Use

Another component adds up hourly data to provide annual loads. Despite previous items, the output of this component is only a number instead of a list of numbers.

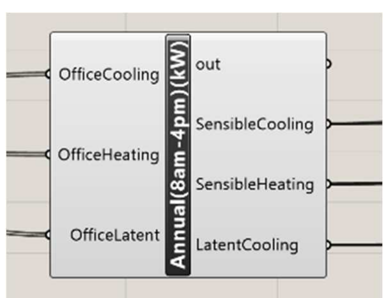


Figure 130. Grasshopper Component, Annual Data for Office Use

The last component adds up all heating, cooling and latent cooling loads to yield only one number as annual amount of saved energy due to using the Earth Tube system.

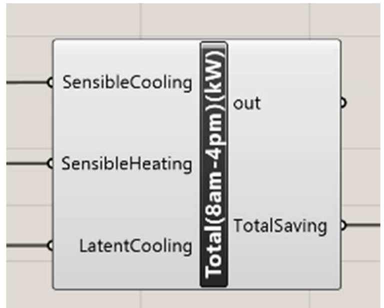


Figure 131. Grasshopper Component, Total Saved Energy in an Office

The following image summarizes the inputs and outputs of the model.

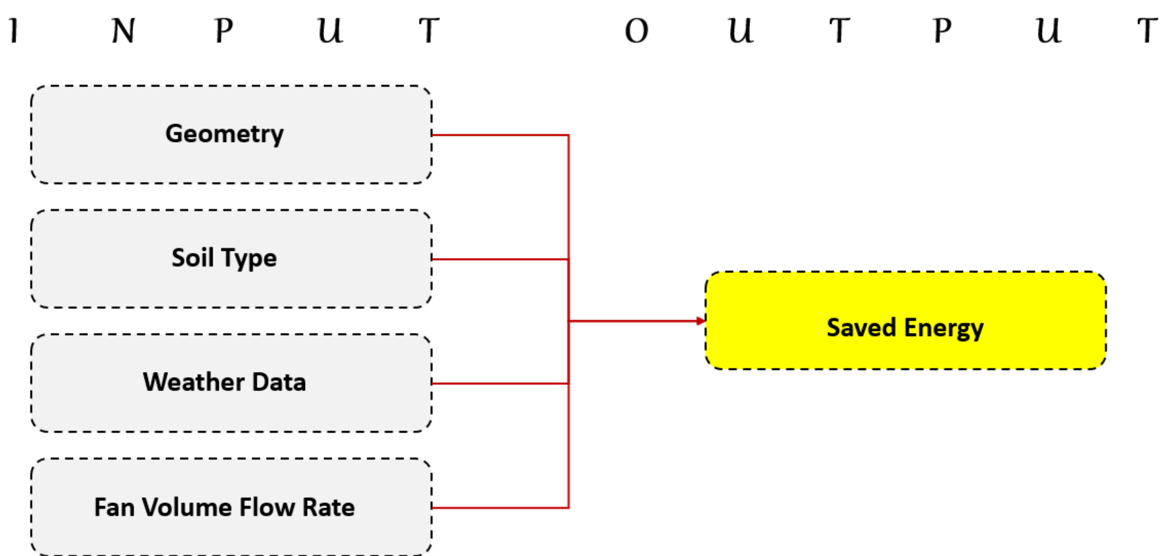


Figure 132. Earth Tube Model, Inputs and Output

4.6. Earth Tube System, Model Validation

Cooling Season Validation

In this section, I am going to validate only the cooling part of the model, both sensible and latent, in July. As the model will use epw (EnergyPlus Weather data) file, I would like to compare the epw file with actual weather data on the experiment site first.

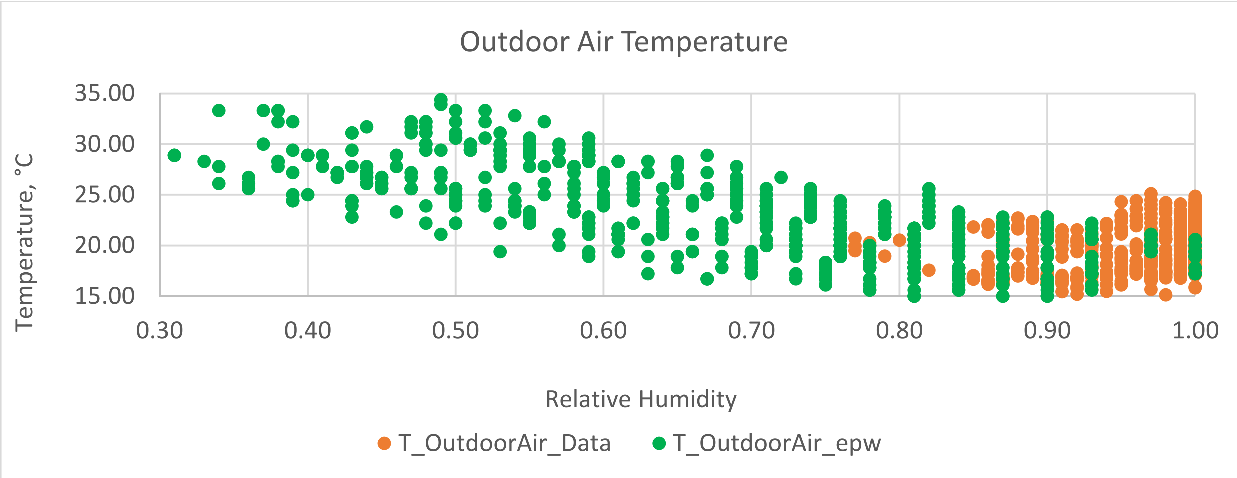


Figure 133. Temperature Comparisons, Outdoor Air Temperature in July

The epw file overestimates the temperature and underestimates the relative humidity. The actual site data indicates cooler yet damper, almost saturated, air. It seems that the plants and trees around the Aldo Leopold Foundation building create a micro-climate, which is cooler but moister. Considering the difference between the weather data file and actual weather data, I validated the model twice. I used actual weather data for the first and epw file for the second validation.

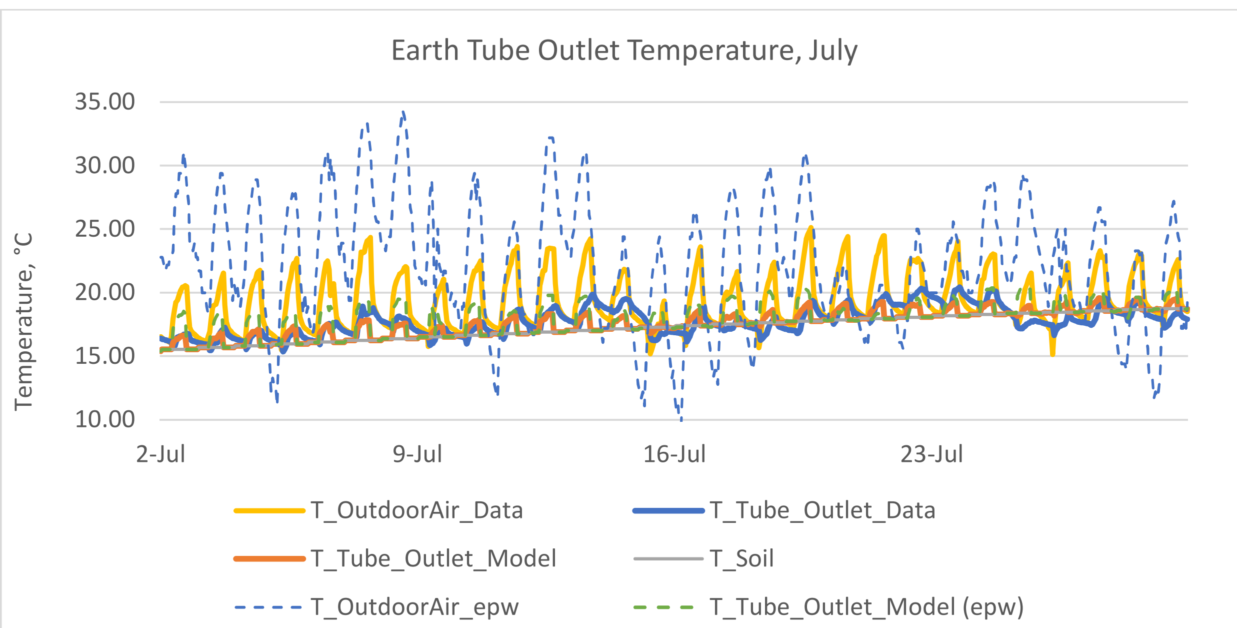


Figure 134. Model Validation, Earth Tube Outlet Temperature, July

As the figure illustrates, the earth tube system is making up for the outdoor air fluctuations by reducing the temperature by about 4 °C. Let us study 1 week of July to get a better sense.

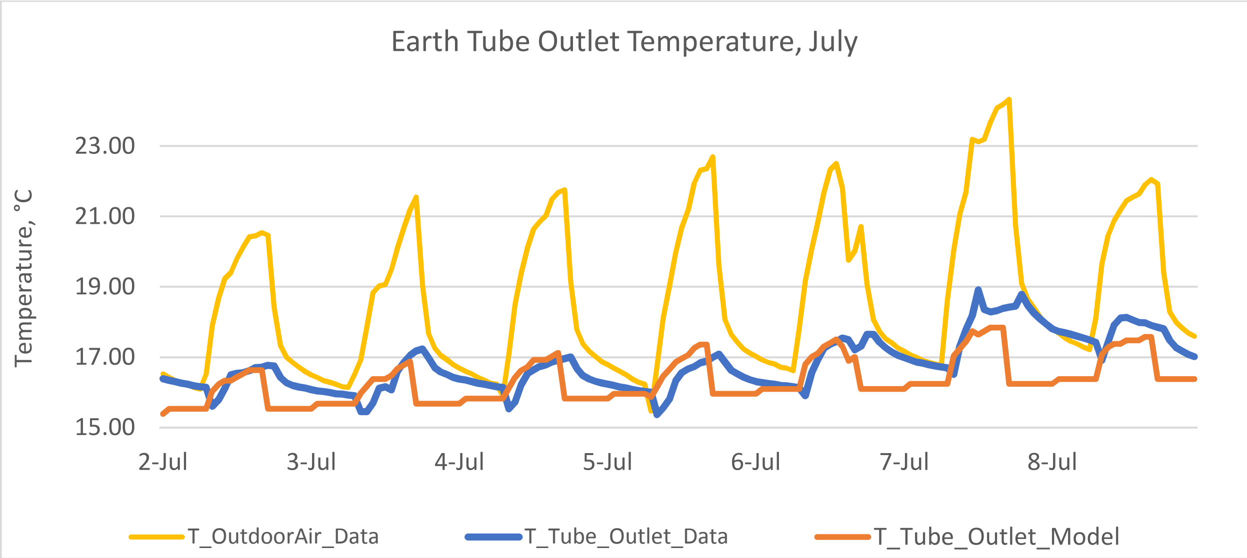


Figure 135. Model Validation, Earth Tube Outlet Temperature, July, One Week

The fan schedule assigned to the model is set on 9 am to 5 pm every day. The MSE (Mean Squared Error) of the model is 0.66.

Now, let us check the saved cooling energy starting with sensible cooling.

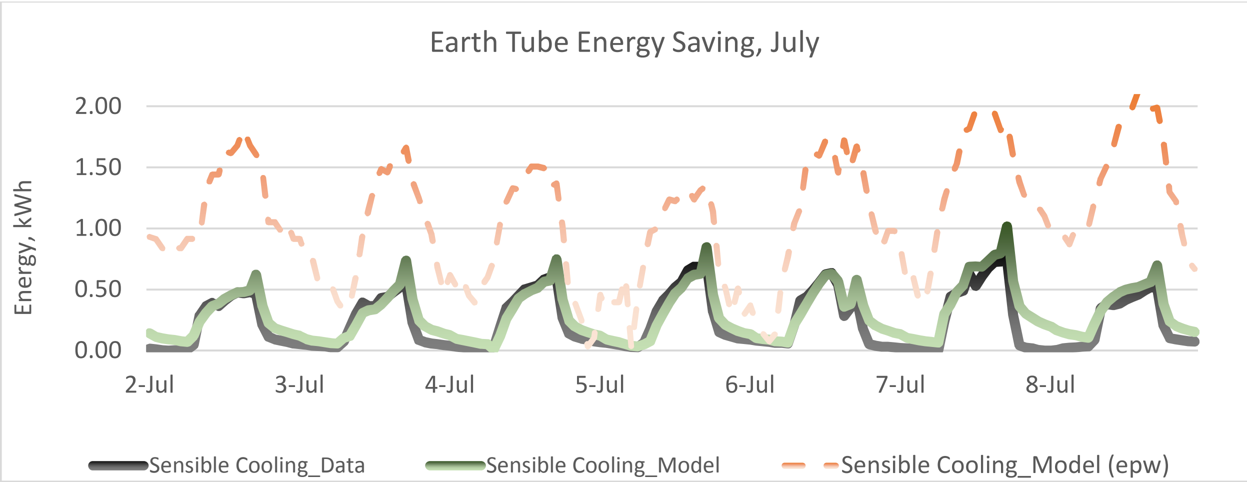


Figure 136. Model Validation, Earth Tube Sensible Cooling Energy Saving, July, One Week

The figure depicts the amount of saved sensible cooling energy resulted from reducing the outdoor temperature. The black line shows the real data, while the green and dashed red line represent the model values based on outdoor weather data and epw file. The MSE (Mean Squared Error) of the two is 0.02 and 0.4 respectively. The next image shows the sensible cooling energy saved in 4 weeks of July.

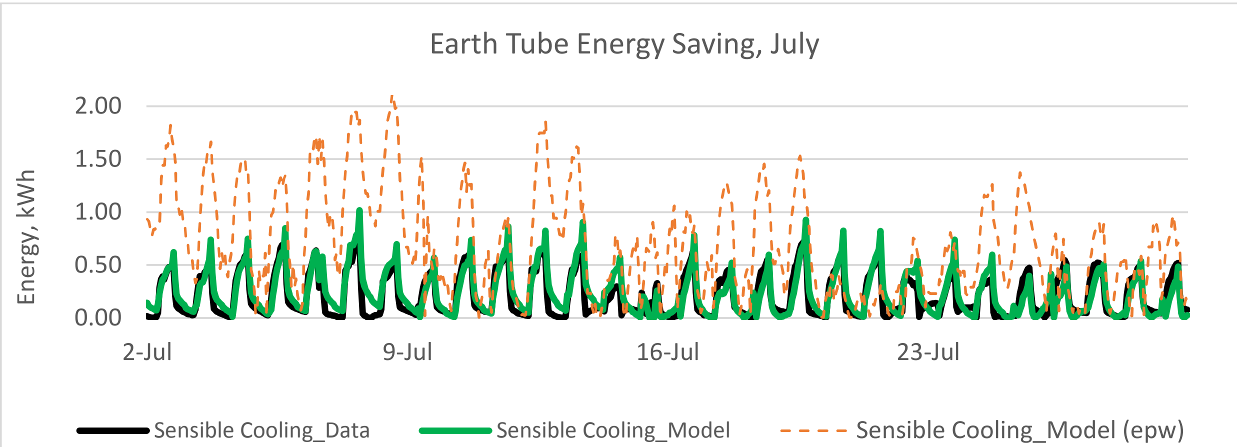


Figure 137. Model Validation, Earth Tube Sensible Cooling Energy Saving, July

The Earth Tube system decreases not only the temperature of the outdoor air in summer, but also its moisture content, saving both sensible and latent cooling energy.

The following figure demonstrates how the Earth Tube system is making the air cooler and drier.

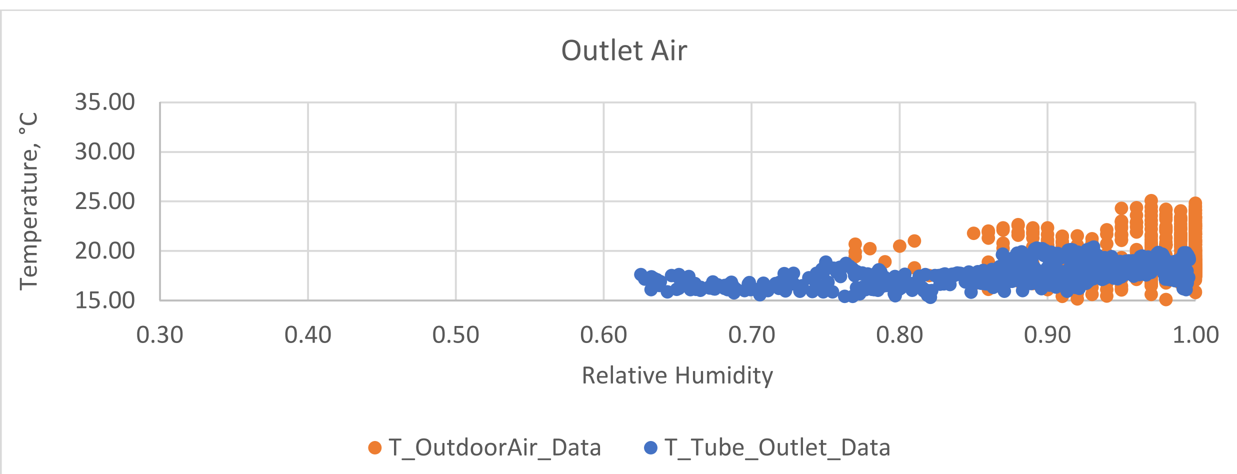


Figure 138. Temperature Comparisons, Earth Tube Outlet Air in July

The next image shows how much the humidity ratio of the outdoor air is lowered in July.

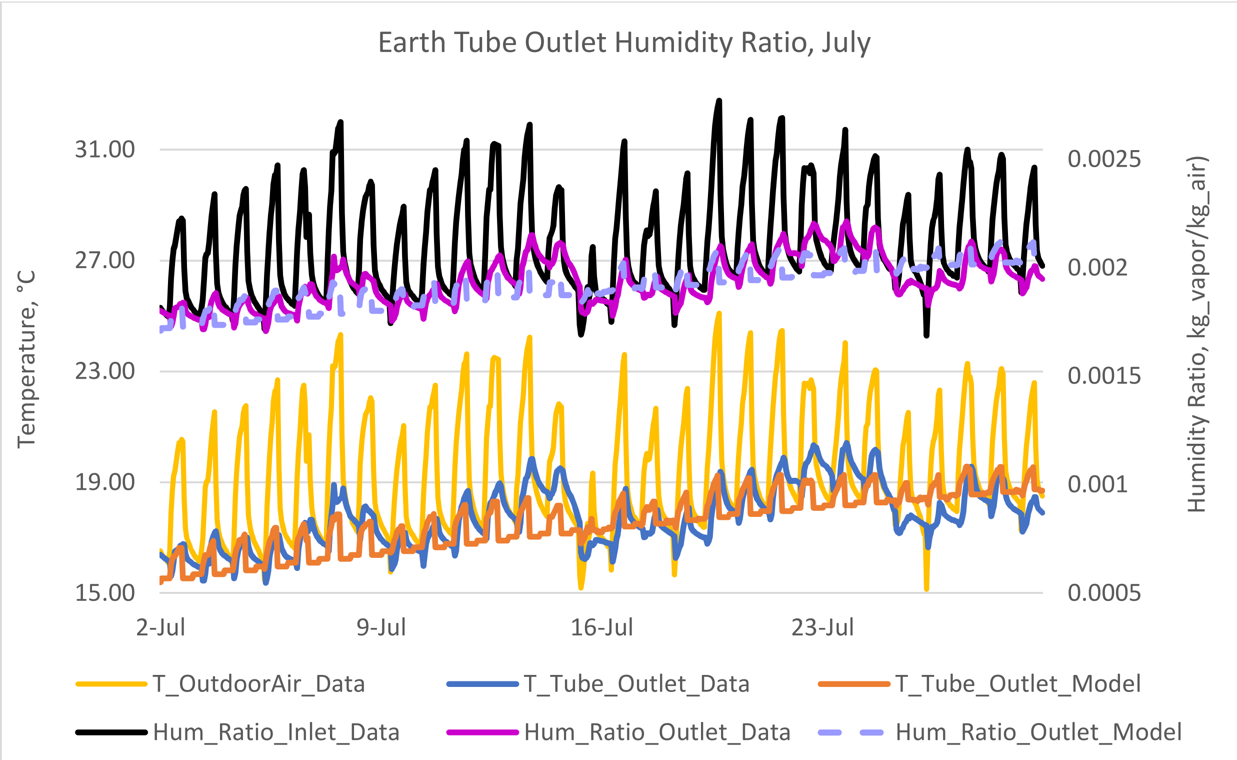


Figure 139. Model Validation, Earth Tube Outlet Humidity Ratio, July

Accordingly, the sensible cooling energy in July looks like this.

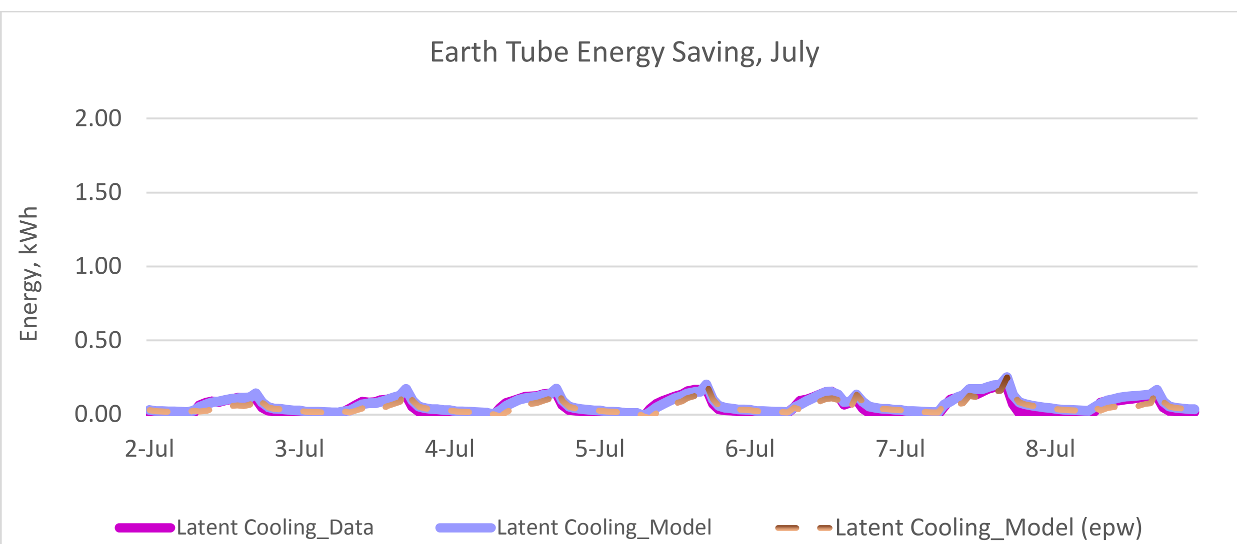


Figure 140. Model Validation, Earth Tube Latent Cooling Energy Saving, July, One Week

The following image shows that the amount of latent cooling energy saved due to the Earth Tube system is almost one tenth of sensible cooling energy.

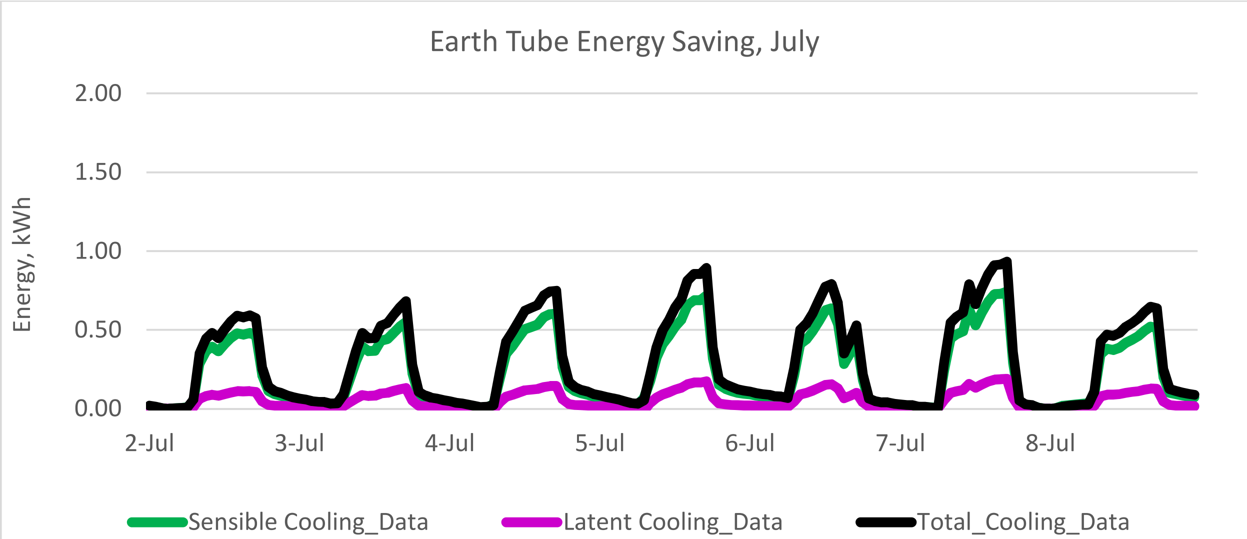


Figure 141. Earth Tube Sensible and Latent Cooling Energy Saving, July, One Week

The next image delineates the total cooling energy, sum of both sensible and latent cooling, of the model compared to the experiment data.

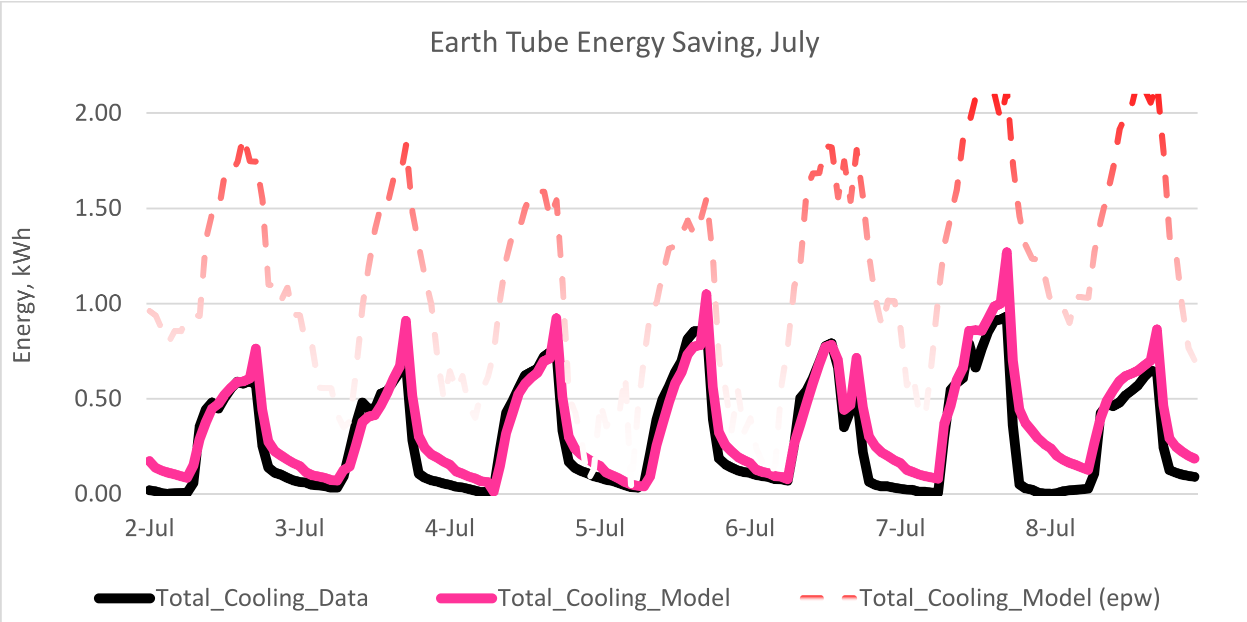


Figure 142. Model Validation, Earth Tube Total Cooling Energy Saving, July, One Week

The pink line presents the model based one the actual weather data and the dashed red line shows the model based on the epw file. The MSE of the two models are 0.015 and 0.39 respectively.

Finally, let us see how the total cooling energy looks like in four weeks of July.

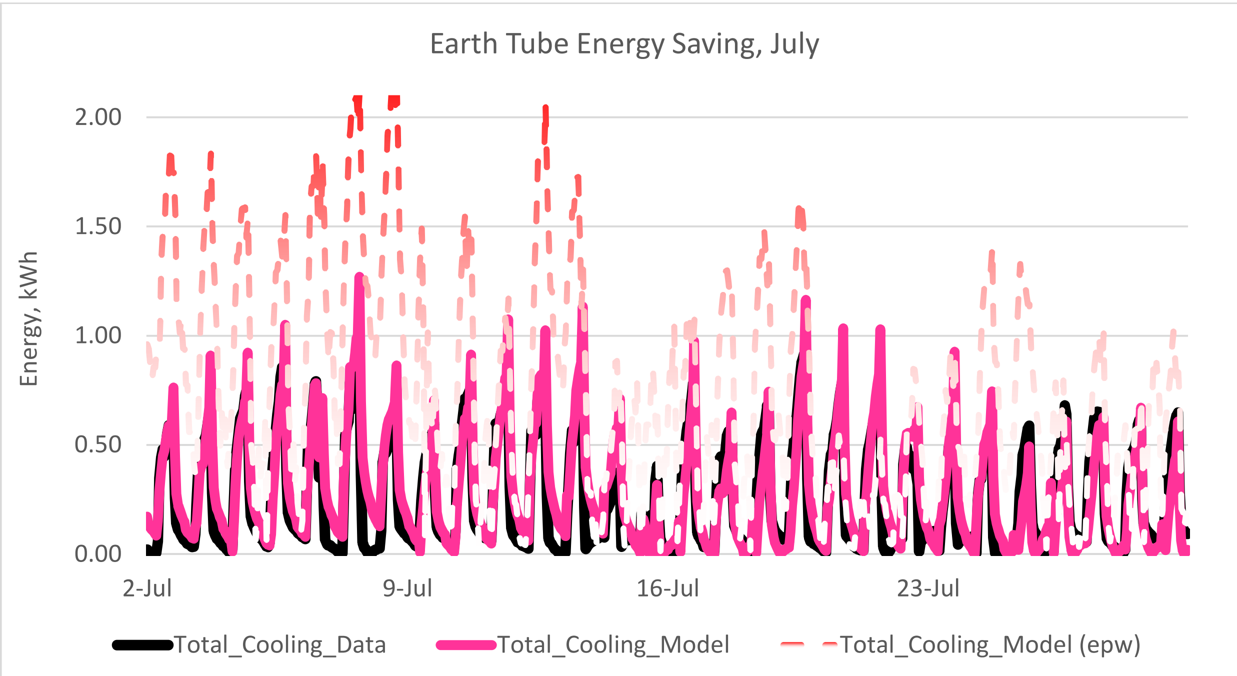


Figure 143. Model Validation, Earth Tube Total Cooling Energy Saving, July

Heating Season Validation

Now, let us study one month in the cold season. The last day we measured the outlet temperature of the tubes was November 10th. Hence, for the heating loads, we consider October 13th to November 9th to have four weeks of heating season. In winter in Baraboo, the main problem is the coldness of the air, not the humidity. Hence, we only study the sensible heating energy.

First, I compare the epw (EnergyPlus Weather data) file with actual weather data on the experiment site.

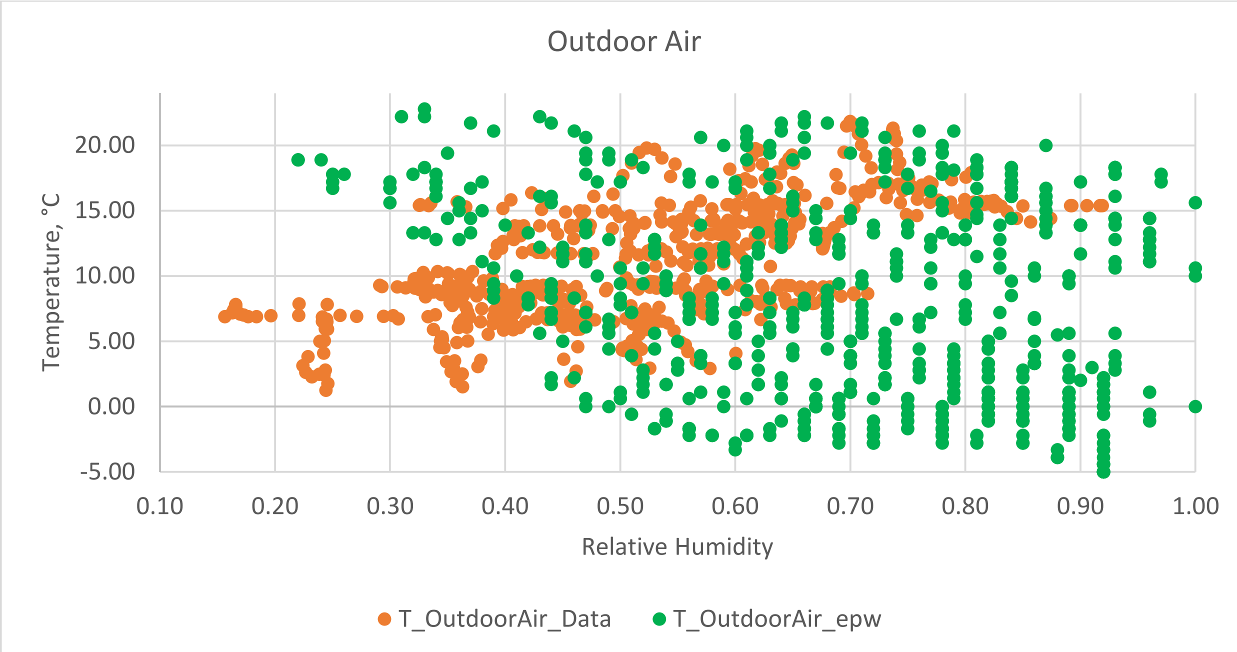


Figure 144. Temperature Comparisons, Outdoor Air Temperature, Heating Season

The epw file shows sporadic data which is more humid and more fluctuating than the actual weather data. Like cooling season, I validated the model twice. I used actual weather data for the first and epw file for the second validation.

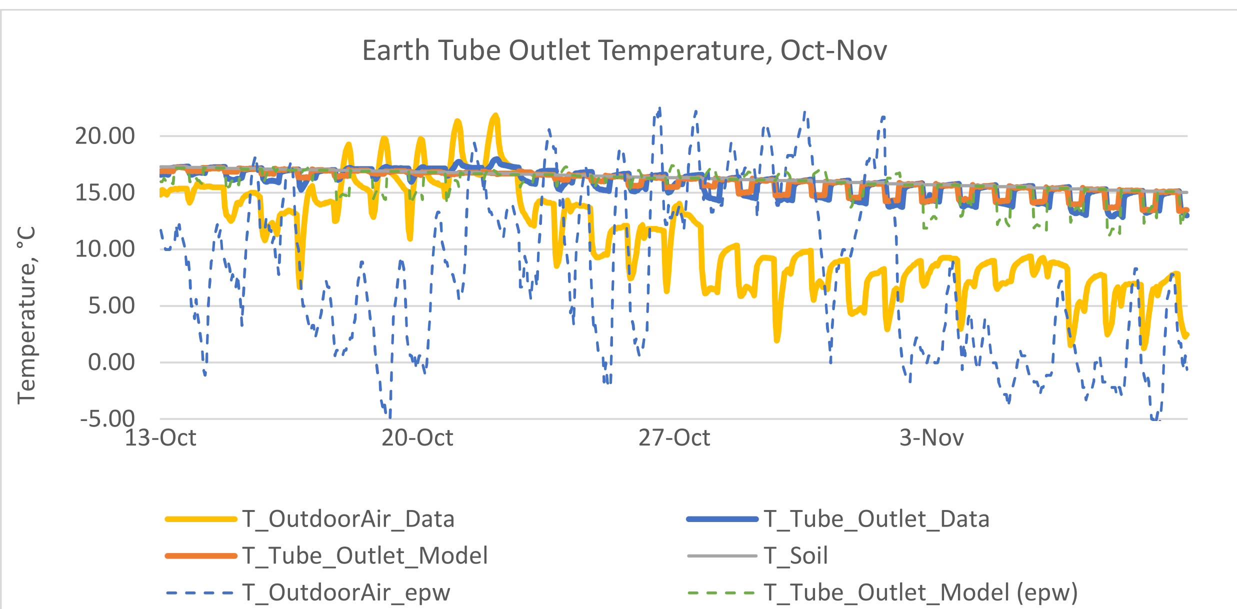


Figure 145. Model Validation, Earth Tube Outlet Temperature, Heating Season

As the figure illustrates, the earth tube system is increasing the air temperature in November and late October. Let us study 1 week in November when we have only heating loads.

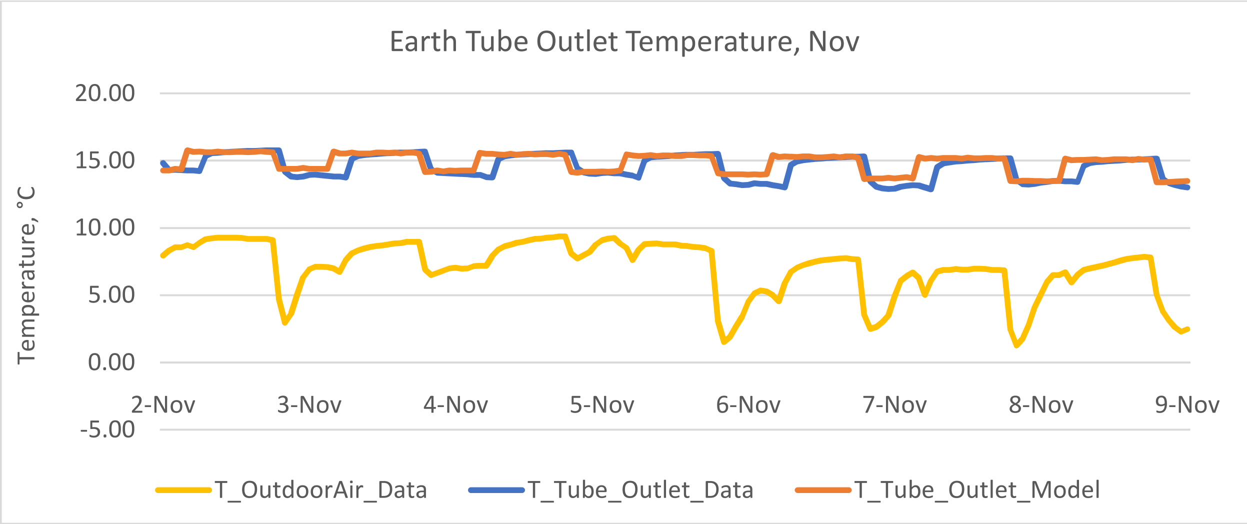


Figure 146. Model Validation, Earth Tube Outlet Temperature, November, One Week

The fan schedule assigned to the model is set on 9 am to 5 pm every day. It is interesting that even when the fan is off, the air inside the tubes is still being warmed up by the soil by more than 5 °C. This clearly shows that even when the fan is off and convection is almost zero, conduction results in warming the air. Accordingly, it is important for an Earth Tube model to include not only convection, but also conduction. The MSE (Mean Squared Error) of the model is 0.4. Now, let us check the saved heating energy.

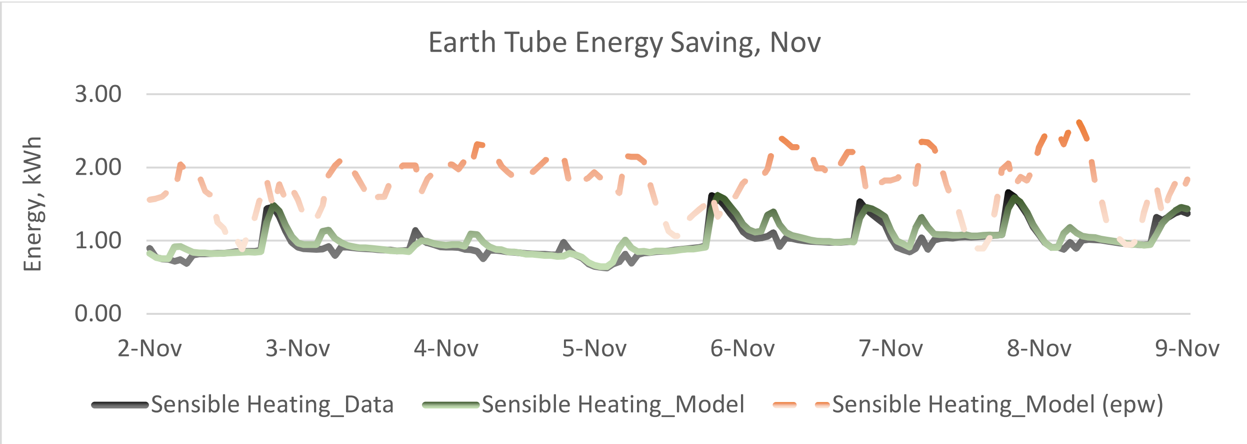


Figure 147. Model Validation, Earth Tube Sensible Heating Energy Saving, November, One Week

The black line shows the real data, while the green and dashed red line represent the model values based on outdoor weather data and epw file. The MSE of the two is 0.01 and 0.87 respectively.

The next image shows the sensible heating energy saved in second half of October and early November. By comparing the energy saving in the two months, we can see that the colder the outdoor air (in November), the more energy will be saved thanks to the Earth Tube system.

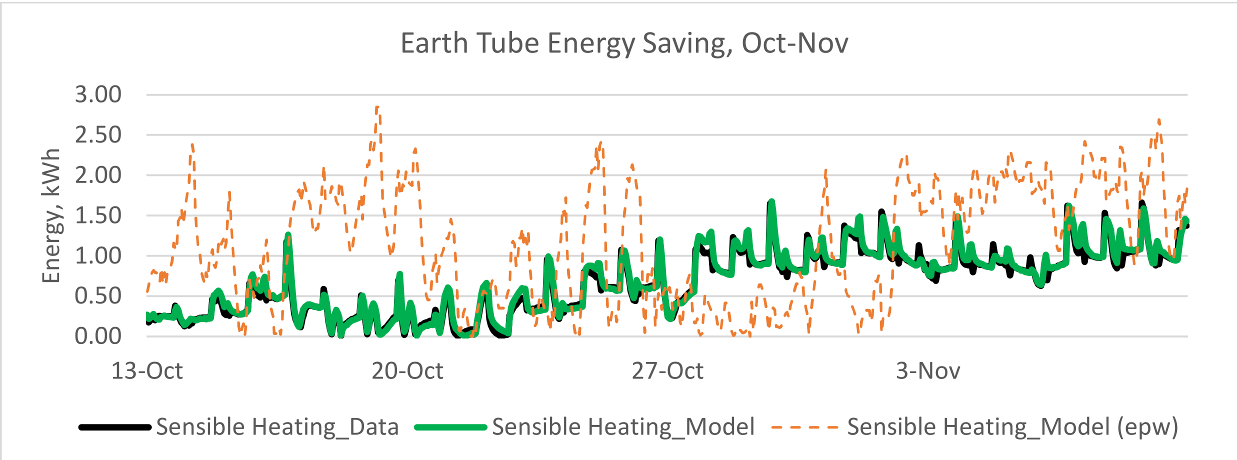


Figure 148. Model Validation, Earth Tube Sensible Heating Energy Saving, Heating Season

The following figure demonstrates how the Earth Tube system is making the air warmer and steadier.

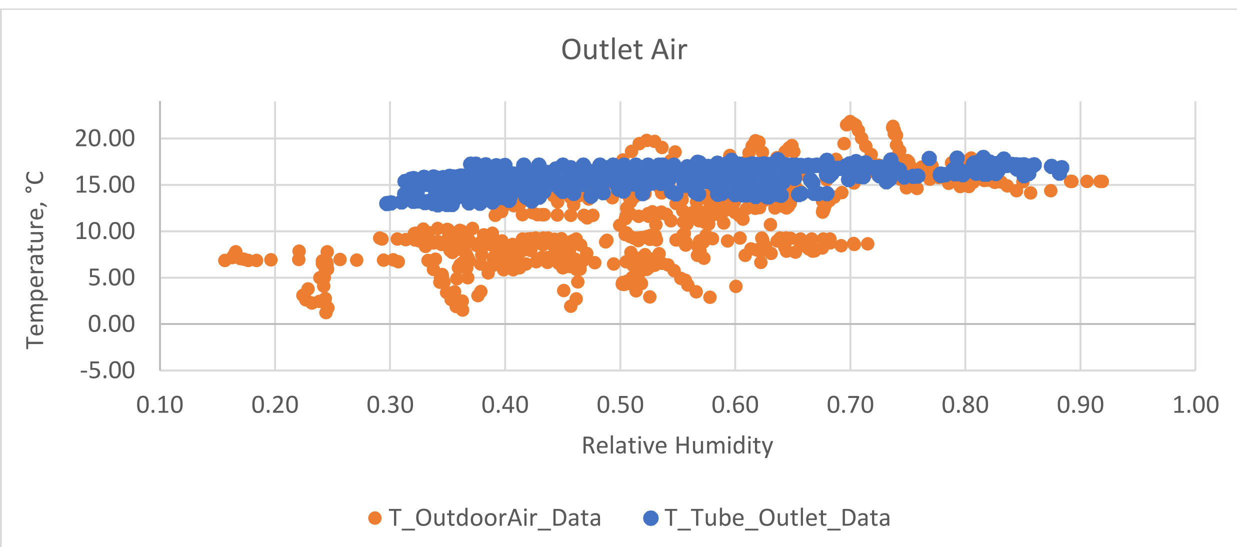


Figure 149. Temperature Comparisons, Earth Tube Outlet Air in Heating Season

5. Conclusions and Future Works

5.1. A Problem of Workflow

Before presenting a design approach, one needs to fully comprehend the existing approaches. Let us look at the building simulation analysis in a larger context through a more practical perspective and studies what approaches are out there in terms of the communication between the architects and the engineers.

The Brundtland Commission and the idea of sustainable development resulted in design strategies aiming to minimize fossil energy consumption, employ renewable sources of energy, reduce CO2 emissions, and create high performance buildings. These ideas have led to technological innovations such as Building Integrated Photovoltaics (BIPV), Double Skin Facades (DSF), Climate Adaptive Building Shells (CABS), Radiant surfaces, passive solar design, efficient natural and electrical lighting design, double and triple glazing windows, natural and hybrid ventilation systems, high-efficient air conditioning, heat recovery systems, etc.

Considering all attempts to achieve *Green Buildings*, it seems that architects have in general come to accept the eco-technical point of view and to consider it desirable as a design goal, but what is still ambiguous is *how* architects are achieving the goal. Has this shift in values been accompanied by a shift in the way architects work?

Do architecture firms still follow the same routine, or is new thinking about sustainability beginning to influence their project methodology? To answer this question, I interviewed North American architects, engineers and sustainability consultants. I studied the workflow patterns in these firms and compared the merits of each workflow. Although the traditional workflow still exists in some firms, a variety of new approaches are being developed, which question the traditional roles of architect and engineer and which facilitate a wide range of buildings with different levels of sustainability.

The AIA has established a sequence of project phases that can be used to analyze the design process in architecture firms. The phases include: Pre-Design Strategy (Programming), Schematic Design (SD), Design Development (DD), Construction Documents (CD), and Post Occupancy Evaluation (POE).

Figure 150. Design Process Phases

Based on the firm size and project type, budget and needs, some steps may be skipped; mainly the last one, the POE phase. Also, there might be some going back and forth between phases (Brian, 2005). The first four phases might overlap to help architects strengthen their design ideas, find and solve obstacles (Soliman, 2017). Our focus here is on the role of each player (architect, engineer, client, contractor, and environmental consultant) in each phase. The timing of each player's contribution seems to affect the outcome and the scope of their responsibilities. The timing reflects how a firm thinks and acts in pursuit of sustainability.

5.2. Workflow Patterns

Merriam-Webster dictionary defines *workflow* as “the sequence of steps involved in moving from the beginning to the end of a working process.” The steps in a workflow are enacted by human players. Together, the players and the workflow make up what I call the *architectural ecosystem*. To visualize this ecosystem, I use diagrams with the players color-coded.

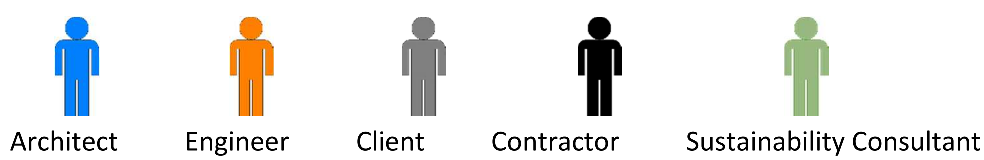


Figure 151. The Architecture Ecosystem, Key Players

The interviews revealed three dominant workflows in North American architecture firms. The first one is the traditional one which is also the simplest one. It is still pretty common. In this workflow, the architect and the client meet during the pre-design phase. The architect listens to the client's concerns and ideas, which usually involve tough compromises between fairly vague sustainability aspirations and the budget. Then, in the SD phase, the architect comes up with a couple of concepts and discusses them with the client – who is still worried about the budget. One of the concepts will be selected and developed further. It is no sooner than the DD phase when the engineer finally appears on board. The engineer designs and fits all the systems into the given design enclosure. The architect coordinates the mechanical, electrical and other plans which he has received from the engineer(s) with the architectural plans. The construction documents are developed and handed to the contractor.

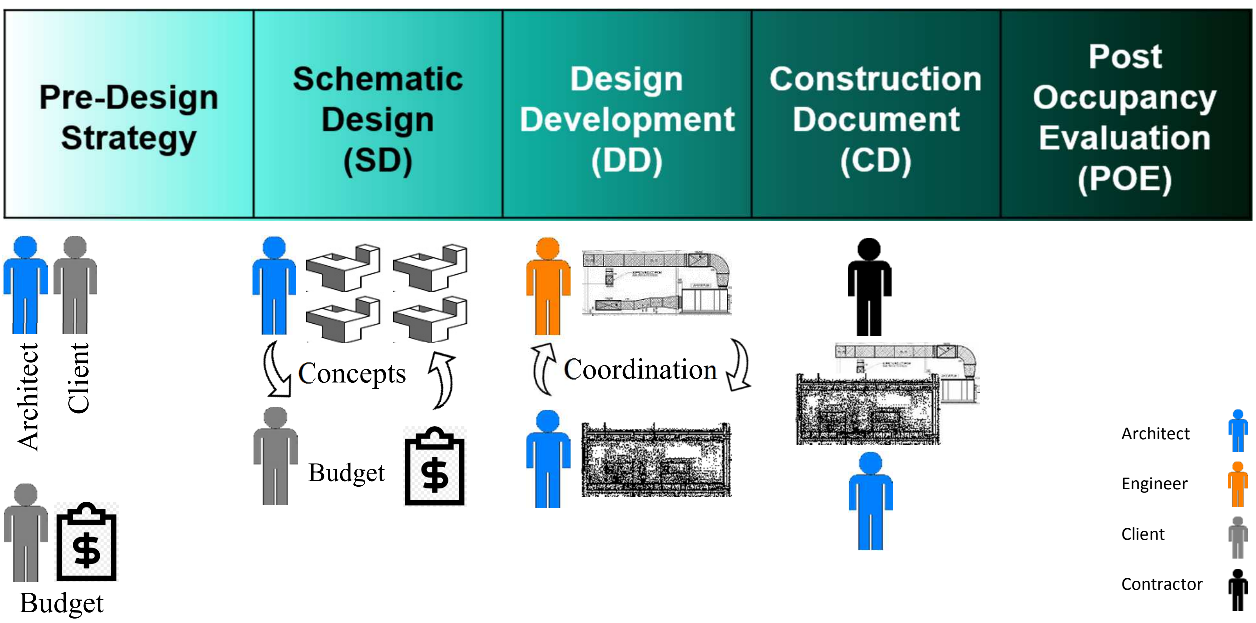


Figure 152. Traditional Workflow

The POE phase in this workflow is often skipped, which is the worst one to skip since it is the only phase whem the design team can evaluate the performance of the building. There is usually no sustainability consultant either. The engineer is invloved merely in the DD phase and his role is limited to only detailed sizing of the components.

As the architects indicate, the type of the mechanical systems could be proposed by both architects and engineers. Architects might have had a vision of the systems in the SD phase, but they rarely have any tangible plan for how to incorporate them into the design.

Considering that the engineer enters the project so late, many coordination problems naturally arise. Lack of early conversation between the architect and the engineer could exacerbate the situation in this workflow. There is usually only a verbal communication if any.

Because client goals are left as vague aspirations, and because architects do not make definitive plans for environmental systems, with or without input from engineers, the traditional workflow tends to default to the “business as usual” solution, which is a forced-air system stuffed into a neutral building volume.

Workflow 2 tends to be more proactive. The overall approach is more holistic in terms of considering the mechanical systems as part of the design of the building volume, not something that follows after.

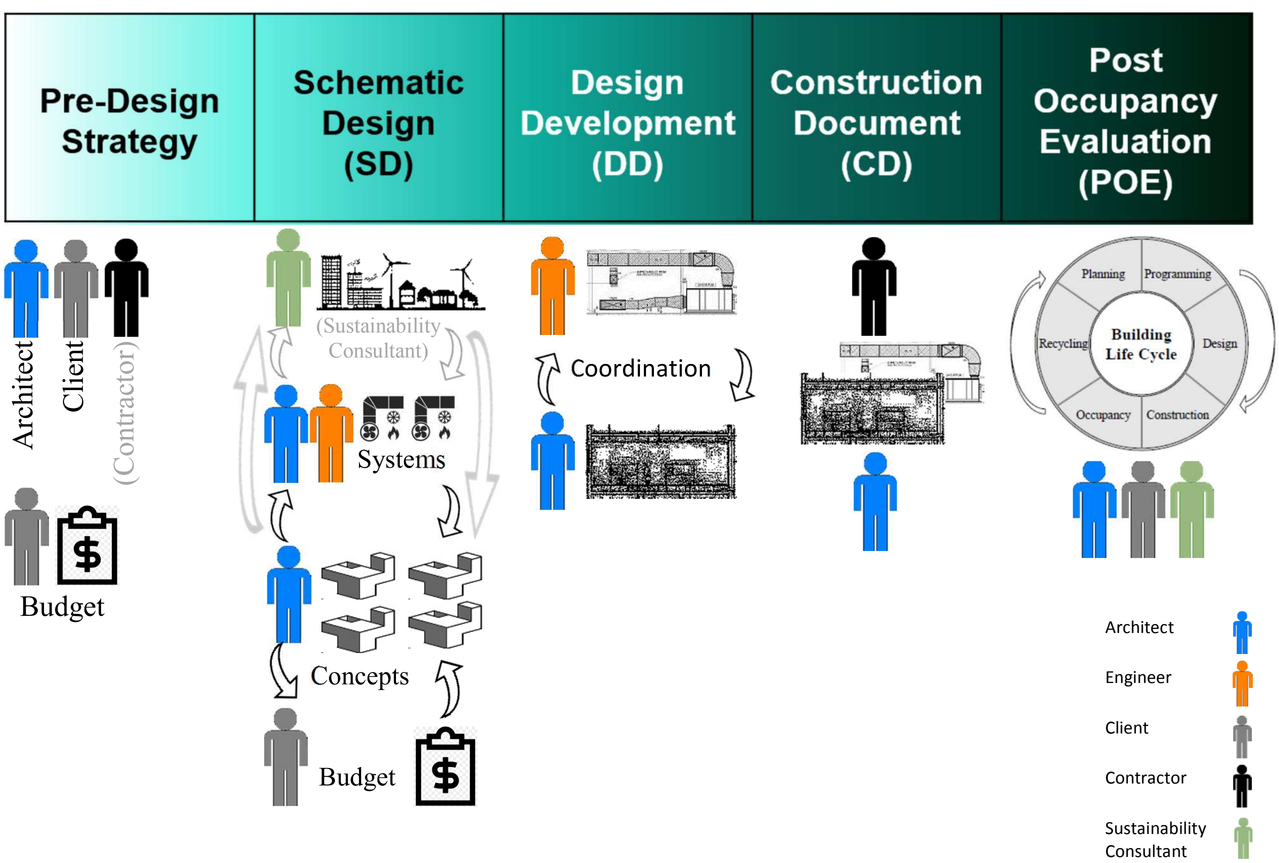


Figure 153. Workflow 2

In workflow 2, the architect, the client (and maybe even the contractor) discuss sustainable design strategies. In this framework, the engineer appears a bit sooner, in the SD phase, rather than DD. In this case, the systems can be discussed a little earlier, and they maybe even develop somewhat in parallel with the building volume. There might be a sustainability consultant who works directly with the architect, or indirectly through the engineer. POE might happen in this workflow, in which case, the architect, the client and the sustainability consultant (or maybe the engineer) would appear in this phase again.

There is a higher possibility of an integrated design outcome in comparison to the traditional workflow. However, the engineers are still considered responsible only for detailing the system components, and they are not involved in the strategic design phase.

Workflow 3 is the most advanced one. Overall, it seems like workflow 2, except that the role of engineer starts even sooner, during the pre-design phase. The engineers brainstorm with the architects regarding building volume strategies, environmental system selection. Integrating passive, hybrid and other alternative systems is much easier in this workflow. The firms using workflow 3 tend to have a higher number of LEED accredited projects. This workflow has the highest possibility of resulting in a successful integrated design.

In these firms, the engineers are willing to go above and beyond their traditional role. That is why the architects tend to keep working with the same engineers across many projects. They gradually strengthen their ability to collaborate effectively over time. It is important to have in mind that not only the spirit of the people, but also the culture and dynamics of the firms involved in each process significantly differ from one another.

The engineers and consultants in workflows 2 and 3 could be in-house or not. While some firms tend to employ in-house engineers, others find it difficult due to the number of experts, especially in large projects.

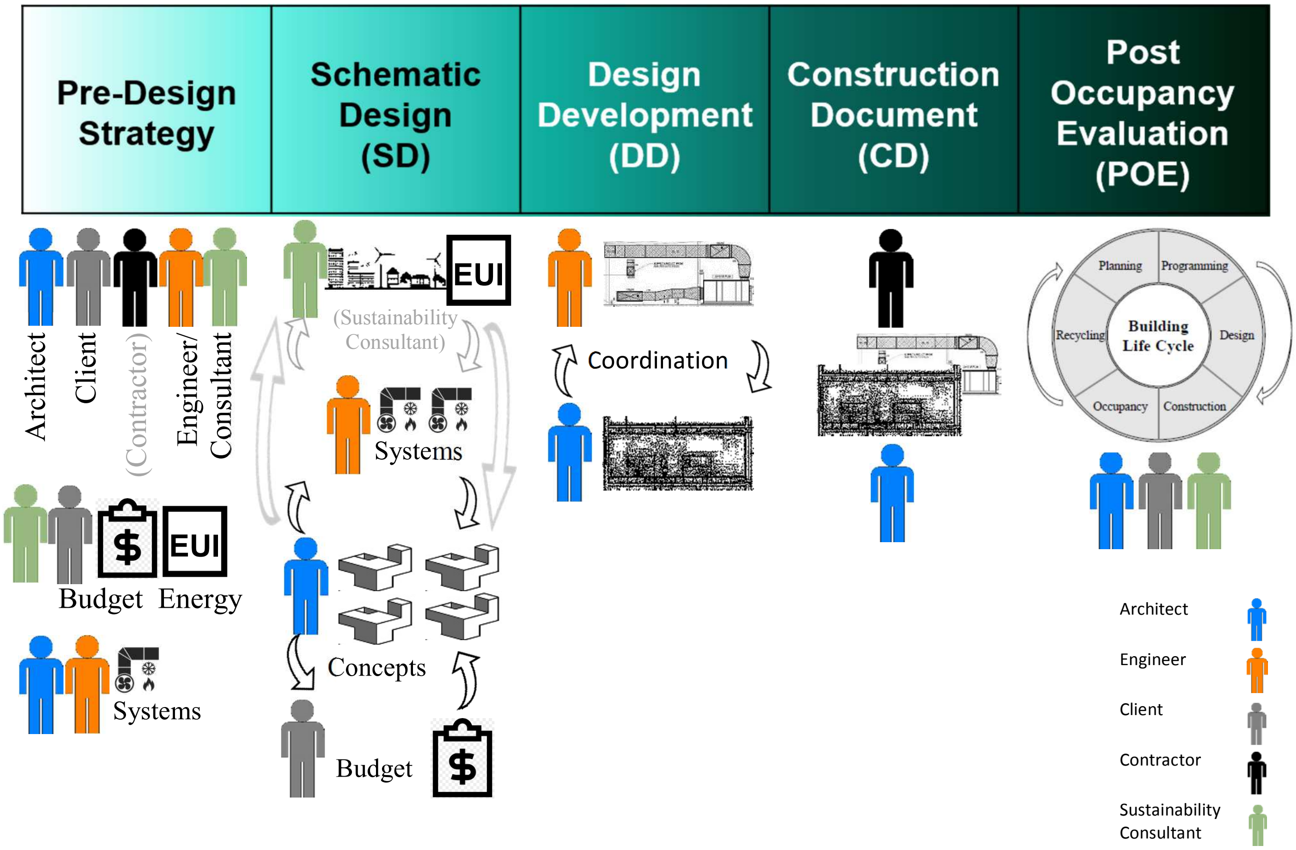


Figure 154. Workflow 3

In the final analysis, it seems that the third workflow is the one smoothly leading to an integrated design. The real power of this workflow relies on the fact that the engineers are involved in the earliest stages of architectural design, where there is the highest chance for changes. As in his article "Architecture Revisited: On Listening to Buildings", Charles Benton states: "I have come to think that the greatest potential for change lies in the earliest stages of architectural design, in the conception, the stroke of the soft pencil." (Scott, 1998)

5.3. Information Exchange

Three information exchange workflows emerged from the interviews. Each architectural ecosystem I studied uses one of these methods to share digital information. There is not a one-to-to correlation of collaboration workflows to information exchange workflows. Any type of collaboration workflow (traditional, workflow 1, workflow 2) might adopt any of the following three information exchange workflows, but It seems that one of the data exchange workflows is superior in fostering the kind of effective collaboration noted above in the description of Workflow 3.

In the traditional workflow information is exchanged among players in the architectural ecosystem through a method I call *Import-Export Interaction*. In this approach, the architect develops the design of the building for a substantial period of time in whatever computer-aided design software is comfortable to her. The software is usually geared toward the effective visualization of the architectural space-making systems only. At one pre-defined point in the design process (often at the transition between the SD phase and the DD phase), the architect's information is exported to a generic file exchange format and sent to the engineer. The engineer imports this information into her preferred software, which is specific to the issues of engineers. The engineer then uses her software to analyze the architect's model, and to size the components of the ventilation and other systems, completing the detailed design work.

The Import-Export exchange usually happens only once because it is very time-consuming and fraught with technical difficulties to move the architect's data into the engineer's software. The transfer becomes a "no turning back" moment in the project, which gives architects and engineers little opportunity to learn from each other through series of constructive feedback loops. By obstructing workflows that attempt to adapt and evolve a design, this data exchange approach works against an effective architect-engineer collaboration.

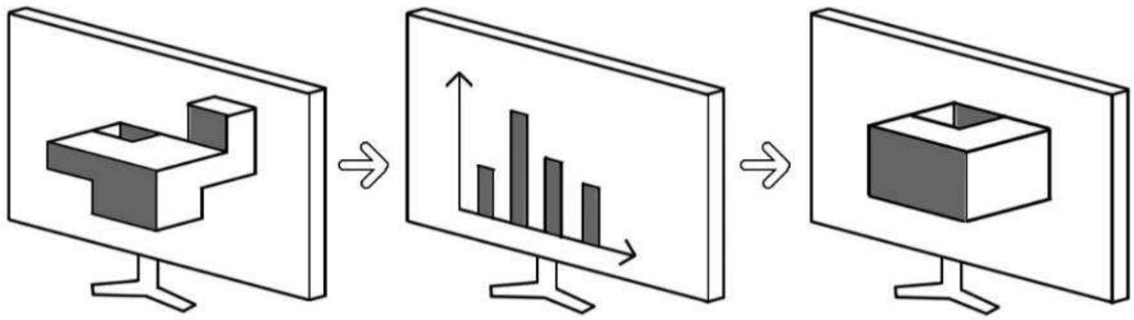


Figure 155. Approach 1, Import-Export Interaction

The second approach regarding data exchange relies on the *Architect's Interoperability*. In this case, the architect would master both the kind of software used by architects to organize space and the kind of software traditionally used by engineers to calculate and size specific system components. The architect would almost certainly need the engineer to design the systems in detail, but the architect manages the geometric information for all systems.

By keeping the architectural and engineering systems together in one unified digital representation, systems integration is fostered. By removing the burden of data conversion from the engineer, the engineer is usually more open to some back-and-forth interaction in the development of the design. Despite this advantage, the Architect's Interoperability approach is rarely used. The reason is that engineering software is geared toward the detailed analysis and sizing of *system components* (e.g., ducts, pipes, circuits) and it offers few, if any, tools to support the assessment of general approaches to system design in the early phases. So even though architects have access to both architectural and engineering information in the Architect's Interoperability approach, they cannot get the strategic-level analysis from the engineering data that they need to make good decisions in the early phases of design. Consequently, there is little incentive for architects to take on the additional burdens involved in mastering two kinds of software, and this approach is rarely used.

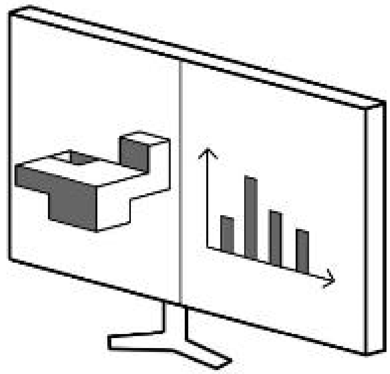


Figure 156. Approach 2, Architect's Interoperability

The interoperability approach is also useful when a new unconventional system is used in design and the current software do not have predefined modules to evaluate it. In that case, there might be need for some codes to be written within the software which requires a higher level of software knowledge.

Let us call the third approach *Performance Sketching*. It is quite new but quickly growing and more promising. In this approach, tools for strategic analysis of environmental systems are embedded in the software architects use to study early issues of placement, orientation, size and shape of building volumes. The architect can easily switch between design and quick, ballpark evaluation of building performance. This tactic allows the architect to enter performance evaluation into the earliest phase of design with a level of detail that is appropriate to that phase of development. At this point in the process there is no time or need to undertake a time-consuming elaboration of precisely sized ducts and equipment, which can produce a highly precise analysis of performance. Instead, in this approach, rough estimates of performance are made based on grossing factors as applied to a sketch model of building volumes. The quickness and roughness of the engineer's performance analysis harmonizes with the rapidly-changing sketchiness of the architect's early design.

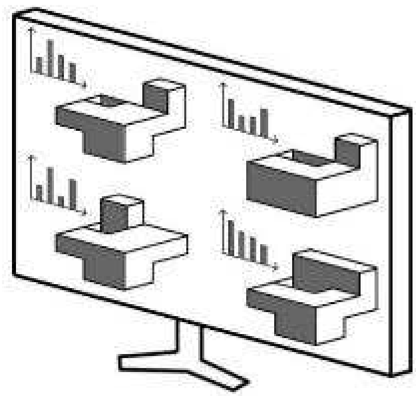


Figure 157. Approach 3, Performance Sketching

The Performance Sketching approach has the greatest potential to augment the 3rd workflow because it has the greatest potential to facilitate architects' and engineers' collaboration at the strategic level of system design in a visual medium rather than merely through words. In fact, one of the main obstacles to the 3rd workflow is lack of early visual communication between architects and engineers which can be solved by the Embedded Engineering approach. As Guy Battle says: "I think architects do not use enough communication in a graphical form, actually imagining what a space is going to be like in terms of light, heat, sound, and movement; and then painting it, or drawing it, or communicating it." (Scott, 1998)

The Performance Sketch should be correct but does not need to be precise. More precise simulation can be done by the engineer or the sustainability consultant later, maybe in the DD phase, when particular system components are being sized.

> "Accurate is different than precise. Simulations in the pre-design level should be accurate, but not precise. They get more accurate and more precise later in the design." (Sean, architect)

5.4. Performance Sketching Evolution

Performance Sketching has evolved through the time. Early sketches were and are mainly done by hand. Renzo Piano's sketches show the most exemplary integration of performance and design.

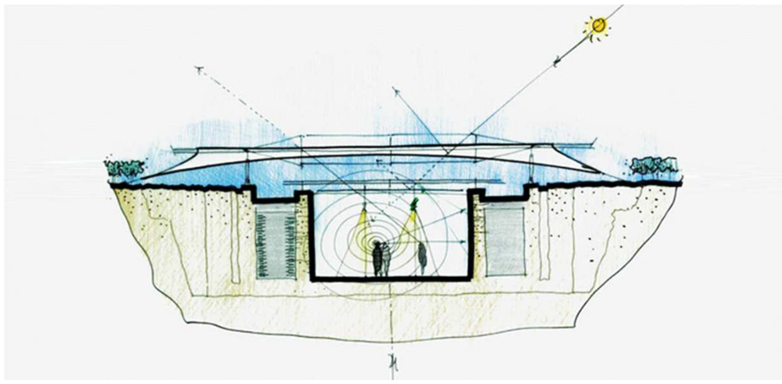


Figure 158. Renzo Piano Performance Sketching by hand

Gradually, this approach transformed into computer-based diagrams the same way the other design sketches did. Most diagrams of this kind use arrows on the building 3D model to show light, air, sound.

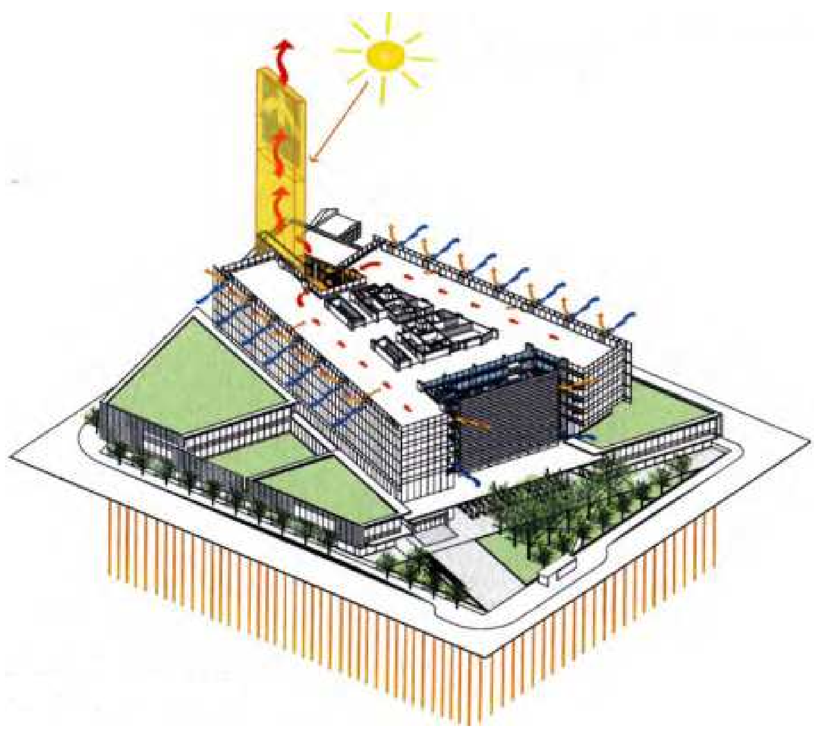


Figure 159. Digital Performance Sketching, Manitoba Hydro, Transsolar

Nowadays, performance sketching has developed even further. Illustration of thermal performance of various design concepts can be obtained in a fracture of a second. The design team do not necessarily have to be selective about having which configuration ready for simulation as plurality of digital performance sketching is no more an issue thanks to the advent of parametric simulation tools.

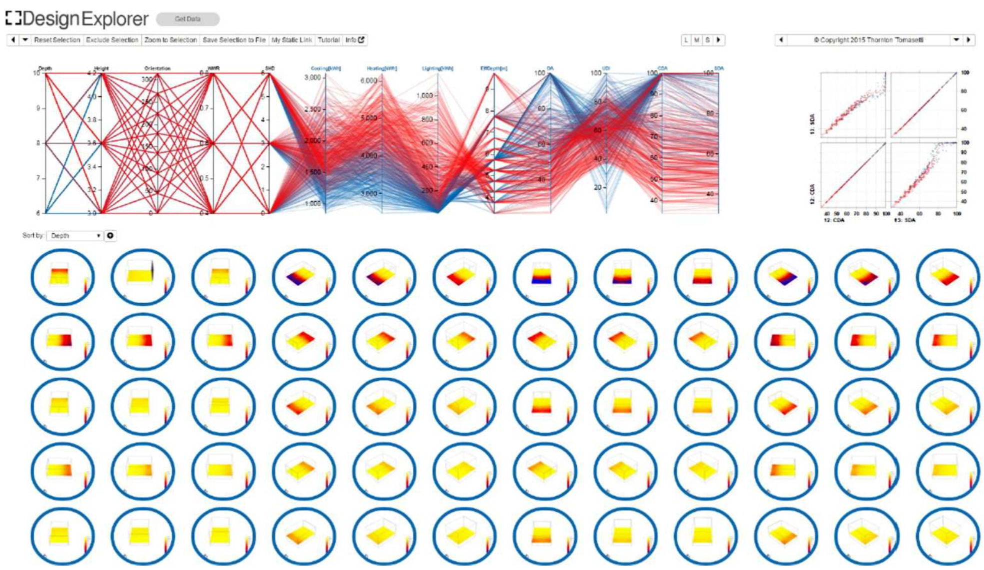


Figure 160. Digital Performance Sketching, Design Explorer, Ladybug team

Today, architects mainly use Sketchup, Rhinoceros and Revit for 3D modeling. Each software has developed plugins to facilitate environmental design, form and geometry, structural design, landscape, etc. Some of these plugins enable the architect to consider performance in the modeling software.

While more and more plugins are being added to distinct architecture software, there seems to be some gaps in this trend. First, although there are numerous plugins for some building performance aspects such as daylighting or energy modeling, there are not appropriate software for other fields such as ventilation. Second, many of these plugins are based on mathematical models; however, many of them have not been validated in real-world conditions. Third, some of these plugins result in numeric data and do not have a proper visualization which goes with the building model.

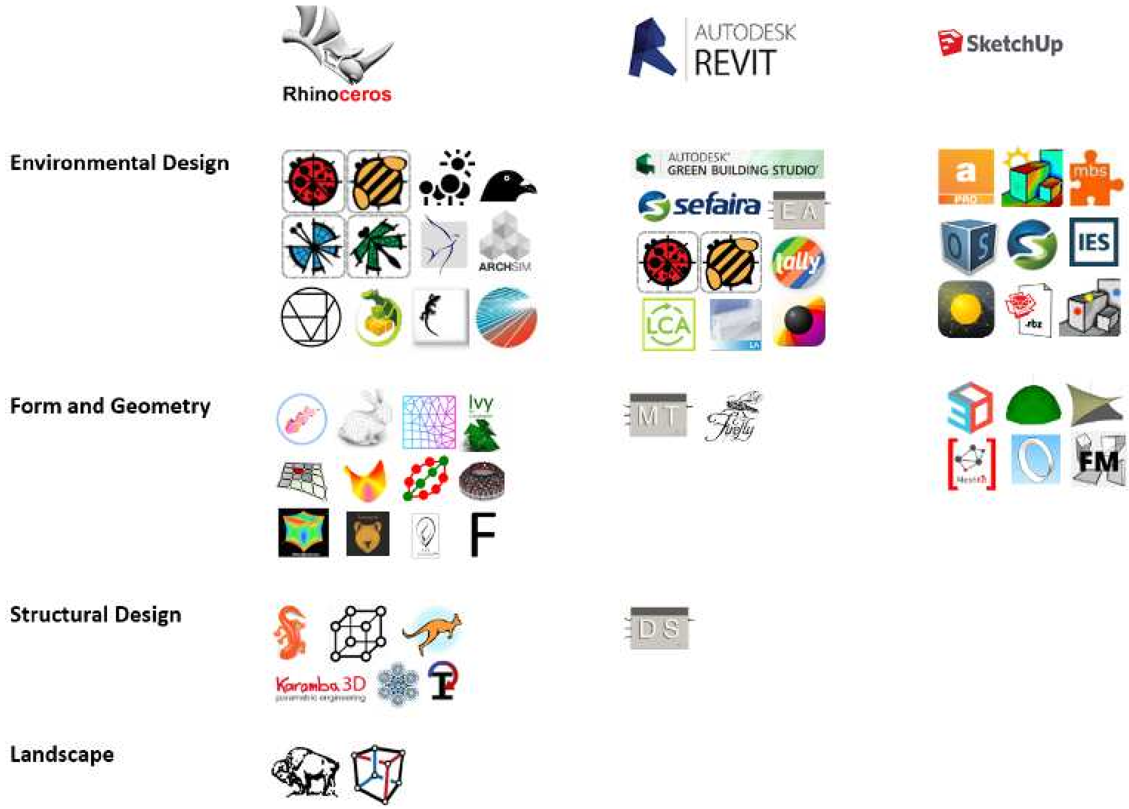


Figure 161. Rhinoceros, Revit and Sketchup Plugins

In order for engineers to join in the process of strategic system design, I found that an architectural ecosystem needs a compatible information exchange approach, and the most compatible one is Performance Sketching. Many architects still think of an integrated design as a rather complicated concept which will drastically change the way they work. This research reveals that it is not necessarily true. Rather than revolutionizing the whole workflow, architects only need to make changes in the order and scope of the tasks, embracing their long-beloved method of sketching to environmental system performance data. There are still some problems in this approach such as lack of inclusivity of all building physics facets, lack of validation, and lack of proper visualization in some cases. However, the Performance Sketching approach promises more innovative and efficient buildings aligned with the 2030 Challenge's goals.

5.5. Conclusion

The 2030 goals regarding sustainability missions are relatively clear today; however, the framework as a path to achieve them is not exactly defined. While there are criteria to measure the progress, there are not enough guidelines on *how* to get there. This dissertation focuses on *how* to include performance earlier in the design.

In this approach, the principles of Performative Based Design are applied in a parametric manner. This has several benefits. First, modeling the geometry and the performance simultaneously results in both time saving as well as the possibility to see the effect of the changes in design on the performance instantly. Second, the merits and demerits of the early design concepts can be realized much sooner in the design process in terms of both performance and aesthetics. Third, the design process would be more holistic which prevents neglecting any of the design factors.

Performance Sketching involves the engineers in the strategic design phase to elevate the chances of creating a more innovative systems with a higher performance. This encourages the Integrated Design approach to bring together the specialisms.

As a case in point, the creation of the Earth Tube model has been an attempt to make the study of this system easier in the design process. This approach can be further generalized to include different building needs such as thermal, lighting, acoustics, etc.

The ventilation system studied in this research is a hybrid ventilation. Hybrid ventilation takes advantage of both natural and mechanical ventilation benefits. It will lower the energy costs since the mechanical ventilation is not applied for the whole year. It will reduce the Sick Building Syndrome and will increase the occupant satisfaction by allowing the natural ventilation to happen whenever possible. It does not raise any reliability issues, which exists in natural ventilation, since it is always possible to switch to the mechanical mode if the natural mode is not capable of providing the required fresh air.

Unfortunately, while there are some parametric components to simulate natural and mechanical ventilation systems, there are not enough studies on how to combine the two sets of components to simulate a hybrid ventilation system. Chapter 4 demonstrates how to define a control strategy to switch between the natural and mechanical modes to model a hybrid ventilation system. I further explain how to keep all the simulation pieces in one single platform so that one would not need to switch between different software. All the design, visualization, evaluation, and even optimization happens in one platform. To corroborate the results, simulation is validated using the measured data from the Schlitz Audubon Nature Center (SANC) in Bayside, Wisconsin.

Another gap in the ventilation analysis is the lack of inclusivity of all systems. One of the systems which has been understudies is the Earth Tube ventilation. In this system, ground works as a heat sink in summer and heat source in winter. Passing through buried pipes, air is cooled in summer and heated in winter.

Aldo Leopold Foundation building located in Baraboo, Wisconsin, has been employing the Earth Tube system for more than 10 years. We have been monitoring the Aldo Leopold Foundation since May 2017. Pressure, temperature and relative humidity sensors, soil temperature and water content sensors as well as a weather data station, and a micro-station were set up. A Python-based model has been developed to simulate the Earth Tube system. Many studies on Earth Tube neglect the conduction of the soil and consider only the convective heat transfer between the air and the soil. The model presented in this dissertation considers both the convection and the conduction of the soil. I validated the model using the data from the Aldo Leopold Foundation.

The methodology used in this study in terms of creation of Python-based simulation components in the design software, validation and finally optimization of the system is a process which can be extended to other aspects of Performative Based Design. Considering the shift towards Autodesk products, future researches can use the same methodology in the Autodesk platform.

Future Works

Future works include but are not limited to:

- Script in Python>Dynamo>Revit
- Compare the Earth Tube Model to the EnergyPlus ZoneEarthtube[130]
- Study the Model connected to a central atrium/stack, such as in the Datapec center in Germany and Dolat Abad garden building in Iran
- Study the Model in a different climate
- Develop the Ventilation & Design Matrix further

[130] https://bigladdersoftware.com/epx/docs/8-4/input-output-reference/group-airflow.html#zoneearthtube-earth-tube

6. Nomenclature

A	Cross sectional area (m^2)	$\dot{q}_{Cond}$	Conductive heat transfer rate (kW)
A_s	Tube surface area (m^2)	$\dot{q}_{Conv}$	Convective heat transfer rate (kW)
A_z	Zone floor area (m^2)	Q	Volume flow rate (m^3/s)
CO_2	Carbon Dioxide	Q_t	Sensible Cooling Energy (kW)
C_d	Specific heat of dry air (kJ/kg-K)	R_a	Outdoor airflow rate per unit area (L/s-m^2)
C_p	Specific heat of air (kJ/kg-K)	R_{e_D}	Reynolds number
C_s	Specific heat of water vapor (kJ/kg-K)	R_p	Outdoor airflow rate per person (L/s-person)
C_v	Specific heat of air in constant volume (kJ/kg-K)	RH	Relative Humidity
d	Soil depth (m)	S	Soil Conduction Shape Factor
D	Tube Diameter (m)	T	Temperature (°C)
f	Frequency of fan motor	T_{amp}	Amplitude of surface temperature (°C)
HETS	Horizontal Earth Tube System	T_i	Air inlet temperature (°C or K)
h_f	Convective heat transfer coefficient of air inside tubes (W/m^2-K)	T_{mean}	Average air temperature (°C)
k	Thermal conductivity (W/m-K)	t_{now}	Current day of the year (day)
k_B	1.381×10^{-23}, Boltzmann's constant (J/K)	T_o	Air outlet temperature (°C or K)
l	Length of tubes (m)	t_{shift}	Day of the year corresponding to the minimum surface temperature (day)
L	Latent heat of vaporization (kJ/kg)	T_s	Soil Temperature (°C or K)
LE	Latent Cooling Energy (kW)	U	Wind speed (m/s)
Ma	Mach Number	Δt_{lm}	Log mean temperature difference (°C or K)
m_a	Mass flow rate of air inside tubes (kg/s)	V	Air velocity (m/s)
m_w	Water condensation rate inside tubes (kg/s)	V_{bz}	Outdoor airflow of the breathing zone (L/s)
$\mathcal{M}$	0.02897, Molecular weight	v_dot	Volume flow rate (m^3/s)
n_m	Speed of motor (rpm)	ω_{in}	Inlet air humidity ratio (kg_vapor/kg_air)
N_P	Number of fan motor poles	ω_{out}	Outlet air humidity ratio (kg_vapor/kg_air)
N_{u_D}	Nusselt number	α	Soil thermal diffusivity (m^2/day)
ℵ	6.022×10^{23}, Avogadro's number	μ	Air viscosity (kg/m-s)
P_r	Prandtl number	ρ	Air density (kg/m^3)
P_z	Zone population	ɣ	Poisson constant of air
P	Pressure (kPa)	ϕ	Relative Humidity

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Barzegar Ganji, H., Talbott, K. (2019) Sustainable design advocacy in the workflow patterns of architectural firms, Environmental Design Research Association (EDRA), Edra50, Brooklyn, NY, USA

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Utzinger, D. M., & Bradley, D. E. (2009). INTEGRATING ENERGY SIMULATION INTO THE DESIGN PROCESS OF HIGH PERFORMANCE BUILDINGS: A CASE STUDY OF THE ALDO LEOPOLD LEGACY CENTER. Paper presented at the 11th international IBPSA Conference, Glasgow, Scotland.

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Zelenay, K., Perepelitza, M., & Lehrer, D. (2011). High-Performance Facades, Design Strategies and Applications in North America and Northern Europe. In C. Center for the Built Environment (Ed.), Public Interest Energy Research (PIER) Program (Vol. CEC-500-99-013): California Energy Commission.

Curriculum Vitae

Hoda Barzegar Ganji

Education

Doctor of Philosophy (Ph.D.) 2015 – 2020
University of Wisconsin Milwaukee, Milwaukee, WI, USA
Major: Sustainable Architecture, Minor: Mechanical Engineering
Advisor: D. Michael Utzinger
Dissertation Title: "A Parametric Approach to Performative-based Design, Case Study: Earth Tube Ventilation"

Master of Science (M.S.) 2010 – 2013
University of Tehran, Tehran, Iran
Major: Energy & Architecture
Thesis Title: "An Introduction on Different Green Wall Species and Their Effect on Lowering Energy Usage in Iran"

Bachelor of Architecture 2005 – 2010
University of Tehran, Tehran, Iran
Thesis Title: "Design a Residential-Recreational Complex in Zanjan"

Teaching Experience

George Brown College, Toronto, ON, Canada Aug 2019 – Present
Professor
ARCH 3026: Sustainable Rating Systems
ARCH 1164: Fundamentals of Building Science
CADE 3003: BIM - Digital Design Technologies for Architecture 2
CADE 3002: BIM - Digital Design Technologies for Architecture 1
CADE 3001: BIM - Revit for Architectural Technology 2

University of Wisconsin Milwaukee, Milwaukee, WI, USA Aug 2015 – May 2018
Graduate Teaching Assistant
Arch-303: Architecture and Environmental Response
Arch-420: Architectural Design II (Volunteer Assistant)
Arch-510: Survey of Structural Design and Analysis
Arch-520: Environmental Systems: Illumination and Thermal Comfort

Grant

National Science Foundation Innovation Corps (NSF I-Corps) Aug 2018
Milwaukee I-Corps Program, Team Name: MechArch Platform
Role: Entrepreneurial Lead

Professional Experience

Architecture Unfolded, Toronto, ON, Canada May 2019 – Aug 2019
Architectural Technologist

- Prepare constructional drawings, details, schedules and manuals for residential and commercial projects,
- Mediate between AutoCAD, Revit and Excel teams
- Develop full set of drawings for renovation projects using a timeline to indicate existing, demolish and new construction phases

ESCA-Tech, Inc., Milwaukee, WI, USA May 2016 – May 2018
Project Assistant, Senior Architectural Drafter

- Design and draft for battery manufacturing plants renovation, with high pressure exhaust and low-pressure supply air duct system
- Prepare drawings of ventilated workstations
- Generate and prepare building evacuation plan
- Compile documents for air permit applications
- Provide graphic design services for marketing
- Study ventilation, Heat Stress Index (HSI) and thermal comfort in industrial work environment
- Prepare proposal drawings for ventilation modifications to reduce HSI in hot climates

LanilCo., Tehran, Iran Oct 2012 – Apr 2015

- Architect and Co-designer of a Commercial Recreational Complex in Chaboksar, Gilan, Iran
- Design Assistant, 3D modeler, and constructional plans designer of a Residential Complex in Tehran, Iran

Iranian National Building Regulation, Tehran, Iran Apr 2015 – Sep 2015
Co-author

Energy Efficiency Document (No. 19)
Chapter of Passive Systems, Section of Green Roofs and Green Walls

Design Competitions

2017 Student Design Project Competition, USA May 2017

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
University of Wisconsin Milwaukee, Architecture Team
University of Wisconsin Madison, Engineering Team

Apr 2015

Cool School design competition, Mongolia

Building Trust International, Honorable mention, Link to Project

Publications and International Conferences

Create and Validate Hybrid Ventilation Components in Simulation using Grasshopper and Python in Rhinoceros — Sep 2nd to 4th, 2019

16th IBPSA International Conference and Exhibition, Rome, Italy
Hoda Barzegar Ganji, Michael Utzinger, David Bradley
Link to Paper

Sustainable Design Advocacy through the Workflow Patterns in the Architectural Firms — May 22nd to 26th, 2019

Environmental Design Research Association (EDRA)
Edra50, Brooklyn, NY, USA
Hoda Barzegar Ganji, Kyle Talbott
Link to Abstract

Flavor-Town: Architectural Recipes for Thermodynamic Fantasy — Oct 11th to 13th, 2018

Association of Collegiate Schools of Architecture (ACSA)
2018 Fall Conference, *PLAY* with the Rules, Milwaukee, WI, USA
Filip Tejchman, Hoda Barzegar Ganji, Nasim Shareghi

An analysis on the Thermal Performance of a Horizontal Earth Tube System — Sep 26th to 28th, 2018

2018 Building Performance Analysis Conference and SimBuild
Co-organized by ASHRAE and IBPSA, Chicago, IL, USA
Hoda Barzegar Ganji, Michael Utzinger, Kevin Renken
Link to Paper

From pre-design to post-occupancy evaluation, simulation and data analysis interaction — Jun 6th to 9th, 2018

EDRA49, Oklahoma City, OK, USA
Hoda Barzegar Ganji, Michael Utzinger
Link to Abstract

An analysis on the perception of the building's threshold based upon three theories of perception: Gestalt, Transactional, and Ecological theory of perception — May 18th to 21st, 2016

EdDRA47, Raleigh, NC, USA
Hoda Barzegar Ganji

Thermal Performance of Vegetation Integrated with Building façade — Nov 14th to 15th, 2013

E.nova International Congress 2013, Pinkafeld, Austria
Hoda Barzegar Ganji, Behrouz Kari, Hirbod Norouzianpour
Link to Paper

Paper Under Review

Optimization of an Earth Tube System by Means of Factorial Analysis June 15th to 16th, 2020
eSIM2020, IBPSA-Canada, Vancouver, BC, Canada
Hoda Barzegar Ganji, Michael Utzinger

Workshops

Innovative AVR Educator ThinkShop, ON, Canada Oct 2019
EON Reality, eCampus Ontario

Student Startup Challenge, Milwaukee, WI, USA Jan 2017
Lubar School of Business, Virtual Reality, The Empathy Lab

University Innovation Fellows, UIF 2016 Aug 2016
Student change agent for innovation on campus, Link to UIF

3rd Design-Fabricate Workshop (Fablab), Tehran, Iran Sep 2014
Center of Excellence in Architectural Technology (CEAT)

AA Visiting School, "The 3rd Place – Urban Machines" Sep 2013
Unit 1: Computing the Anatomy of Tehran, Link to Project

Professional Memberships

Architectural Research Centers Consortium, Inc. (ARCC)
International Building Performance Simulation Association (IBPSA)
Association of Collegiate Schools of Architecture (ACSA)
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
Environmental Design Research Association (EDRA)
Iran Construction Engineering Organization (IRCEO)

- Grade 3 in Architectural Engineering, Architectural Supervision & Architectural Construction

Computer Software and Skills