Addressing the Problem with Natural Ventilation:
Producing a Guide for Designers to Integrate Natural Ventilation into the Early Stages of Building Design

by

Kristian Fennessy

Submitted to the
Department of Architecture
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ABSTRACT

Currently, the United States alone is responsible for approximately twenty percent of the world's total energy consumption. This consumption is equivalent to roughly 100 quadrillion Btu of energy, or in plainer terms, over $1 trillion in energy expenditures annually. This sector alone comprises nearly half of all the energy consumed in the United States. Additionally, about seventy-five percent of all electricity produced in the U.S. is consumed by building operations. This precedent has convinced me that finding an alternative is worth the investment.

The purpose of my thesis project is to explore substitutes to mechanical heating, ventilation, and air conditioning (HVAC) building systems. My project revisits the concept of natural ventilation and explores and evaluates its feasibility as an energy-saving and comfortable alternative to mechanical ventilation systems. Additionally, my project focuses on how buildings can be designed to naturally condition the indoor environments of our buildings.

More specifically, I would like to help architects discover how they can utilize natural ventilation effectively. Using the TRNSYS simulation environment, I methodically show how a designer would use TRNSYS to make informed decisions about natural ventilation in their designs. My research is meant to be a valuable tool for other designers who are unsure or uncomfortable with utilizing this natural process to condition their buildings.

The final deliverable of my thesis project is a comprehensive strategy for designers to incorporate natural ventilation in the early stages of their building design.

Thesis Supervisor: Leslie Keith Norford

Title: Professor of Building Technology

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1. INTRODUCTION

In 2008, the world reached a momentous yet largely unnoticed milestone: For the first time in history, more than half the human population was living in urban areas. At the time, this was equivalent to nearly three and a half billion urbanites. This figure is expected to swell to five billion people by 2030 according to the United Nations Population Fund.[1] Additionally, the United Nations Secretariat prospects that by 2050, a startling seventy percent of the world's projected nine billion people, or 6.3 billion people, will be urbanized.[2]

This rapid growth in the urban population of the world has several consequences. One noticeable consequence associated with overpopulation is the subsequent increase in the cost of housing due to city densification.[3] A higher population density can also cause viruses to spread faster.[4] However, perhaps the most pertinent issue that the world must address is the fact that each of these future urbanites will require some amount of resources to sustain themselves. These resources include food, water, shelter, and energy. This thesis will focus on the implications related to energy.

As discussed above, an increase in population will likely result in increases in energy consumption. At first glance, this may not seem like a pressing issue, but it may soon become one if one understands exactly how much consumption the U.S. is accountable for. Currently, the United States alone is responsible for approximately twenty percent of the world's total energy consumption. This consumption is equivalent to roughly 100 quadrillion Btu of energy, or in plainer terms, over $1 trillion in energy expenditures annually.[5] With regards to energy, consumption in the building sector refers to any energy expended in the construction and operation of buildings. This sector alone comprises nearly half (47.6 percent) of all the energy consumed in the United States[6] (See Figure 1[7]).

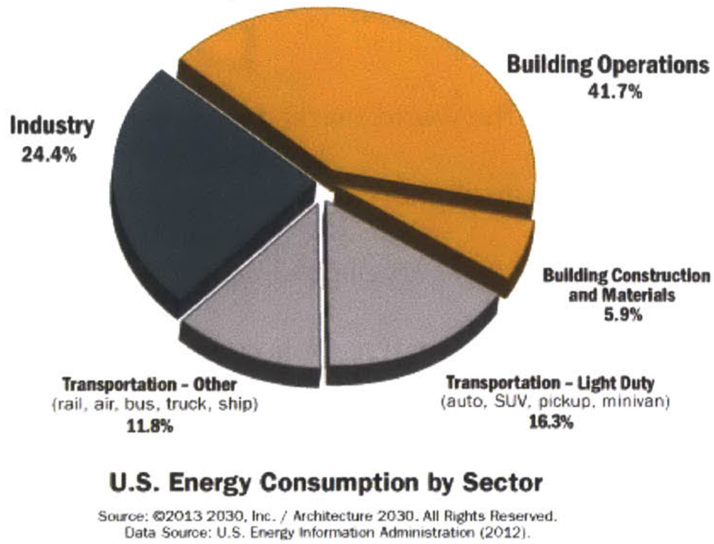


Figure 1: U.S. Energy Consumption by Sector

Additionally, about seventy-five percent of all electricity produced in the U.S. is consumed by building operations[8] (See Figure 2[7]).

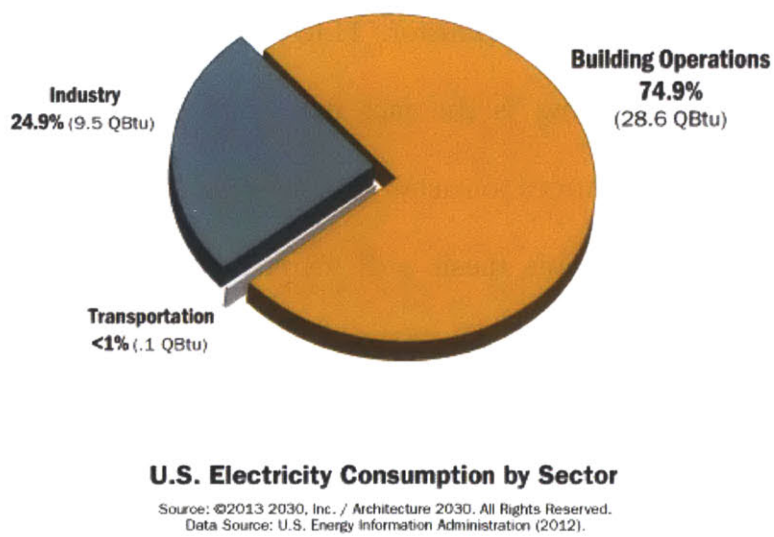


Figure 2: U.S. Electricity Consumption by Sector

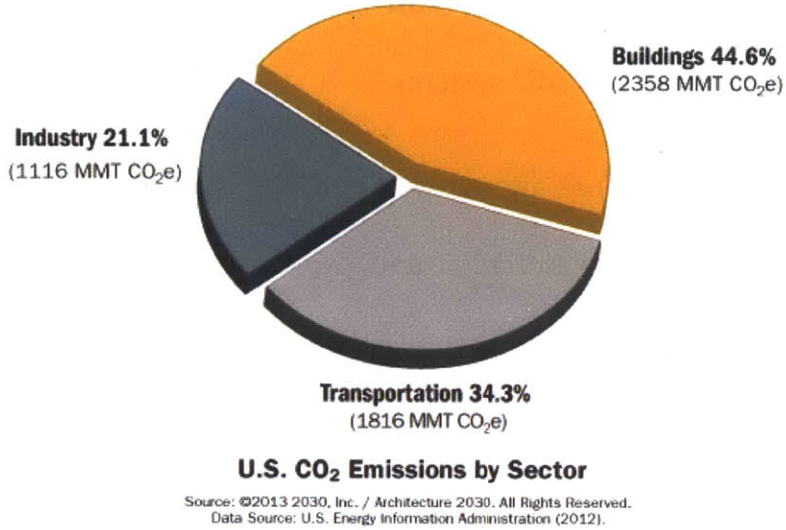


Figure 3: U.S. CO_2 Emissions by Sector

Interestingly enough, although most people generally associate transportation with the high amount of pollution in the United States, buildings actually contribute more to this than transportation. The building sector in the U.S. contributes 44.6 percent of the country's total carbon emissions, as opposed to 34.3 percent by transportation and 21.1 percent by industry[9] (See Figure 3[7]).

Furthermore, The U.S. Energy Information Administration predicts that there will be a 0.7 percent annual increase in energy demand for the foreseeable future due to the aforementioned population growth and the accompanying growth in housing needs, transportation, goods, and services.[10]

It may not be surprising that buildings are the primary contributor to energy usage in the urban environment, but it may not be immediately apparent what component of a building consumes the most energy. According to Perez-Lombard, Ortiz, et al., building energy consumption trends indicate that the recent trend of high energy consumption is being influenced primarily by increased building sector business, wider availability of building services, and more specifically, the large use of heating, ventilation, and air conditioning (HVAC) systems.[11]

The purpose of this thesis is to explore alternatives to HVAC building systems. This thesis revisits the concept of natural ventilation and explores and evaluates its feasibility as an alternative to mechanical ventilation systems. The thesis focuses on how buildings can be designed to naturally condition the indoor environments of our buildings. More specifically, I would like to help architects discover how they can utilize natural ventilation in their building designs. My end goal for my thesis project is to be able to provide designers with a comprehensive guide to natural ventilation in buildings. Chapter 2, HVAC Systems, will provide a background on HVAC systems, as well as outlining the major consequences resulting from using this technology in building design. Chapter 3, Natural Ventilation, will discuss what natural ventilation is and why it may be a viable solution for the energy problems in urban areas. Chapter 3, Literature Review – Naturally Ventilated Building Design, will review three separate building designs that successfully utilize natural ventilation for space conditioning purposes. Chapter 4, Methodology, details the outline of how I intend to accomplish my goal. The remainder of the thesis discusses each of these steps in my research in great detail, encapsulating my comprehensive guide.

2. HVAC SYSTEMS

The main purposes of an HVAC system are to regulate the ventilation and thermal comfort within buildings.[12] These systems mechanically alter the air conditions within a space by one of two methods: mixing or displacement.[13] Mixing systems supply a high-velocity stream of air to a space which mixes with the ambient air within the space. By altering the conditions of the supplied air, the occupant's desired interior temperature and humidity can be achieved.[14] A typical mixing HVAC system is featured at left[15]. On the contrary, displacement ventilation systems supply a low-velocity air steam to a space with the intention of avoiding interior air mixing.[16] This system relies on convection from heat sources within a space, such as humans and appliances, to create vertical air motion to ventilate and decontaminate the space.

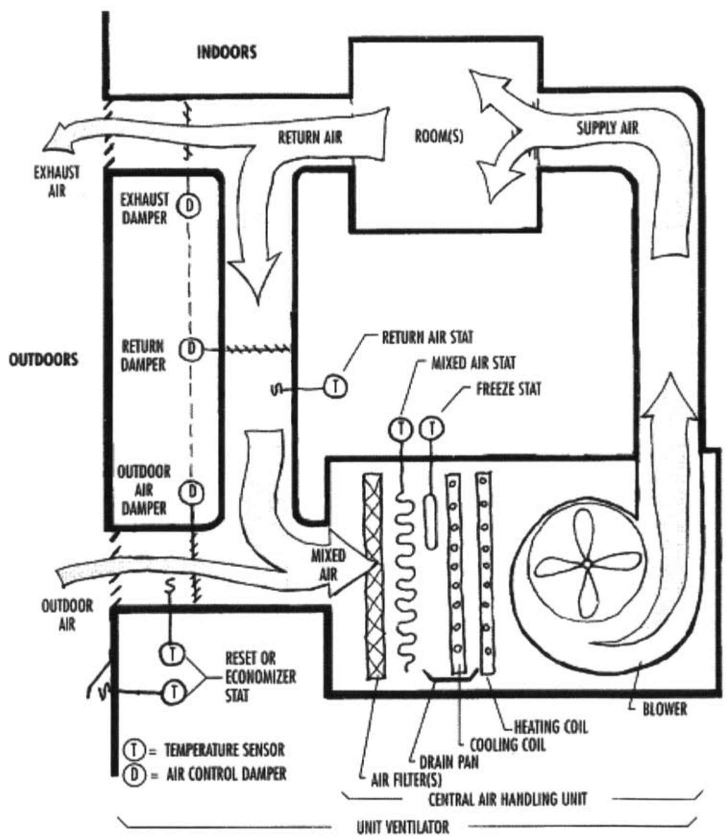


Figure 4[15]: Mixing HVAC system

LEED Fellow Jerry Yudelson conducted a study of high-performing buildings in order to inform low-energy building design. Upon reviewing estimates of building electrical energy use, he predicted that air movement and conditioning accounts for forty percent of building electrical energy use.[17] The Council on Tall Buildings and Urban Habitat (CTBUH) Sustainability Working Group estimated that, based on its research in non-domestic buildings, HVAC systems are the main end use with a rate of about fifty percent.[18] According to the U.S. government's Office of Energy Efficiency & Renewable Energy, space heating and cooling are the largest contributor to energy consumption in homes, accounting for a total of 52.7 percent.[19]

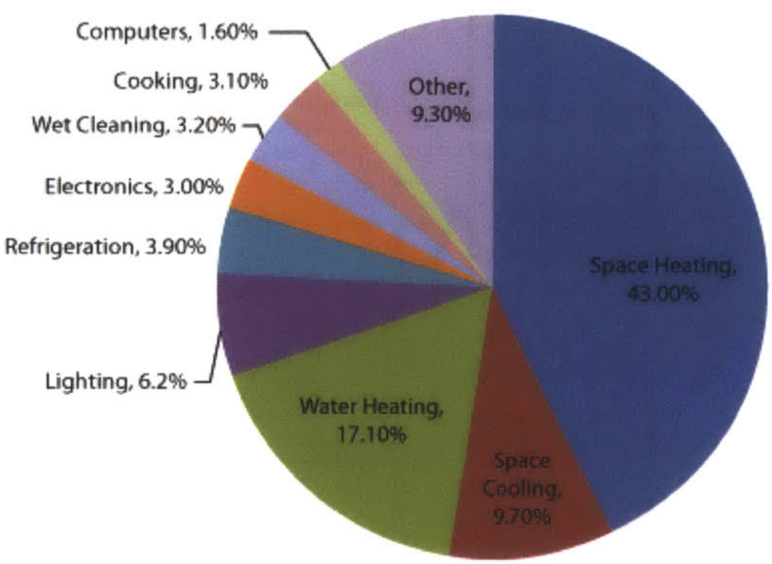


Figure 5[3]: Energy consumption in buildings by end use

As depicted[20], it would seem that HVAC systems are the largest source of energy consumption in buildings.[3] Under this postulation, it is arguable that the elimination or modification of these mechanical HVAC systems could be the most important step in making buildings more energy efficient.[11] That, however, is no small feat.

The following thesis focuses on how to reduce or eliminate the use of HVAC systems by reintroducing the concept of natural ventilation. The emphasis here is on reintroduction because natural ventilation is not a new concept to humans; it just seems to have been displaced for so long that it may seem new. For many centuries, buildings and homes relied exclusively on natural ventilation strategies to provide the desired thermal comfort and air control.[21] Because modern-day HVAC systems had not been invented until 1902[22], building occupants had to rely on natural means for their air conditioning needs. Opening windows to utilize cross-ventilation within a space and using chimneys to exploit buoyancy flow were much more common occurrences prior to 1902 than they are today.[22]

Mechanical ventilation emerged as the prominent ventilation strategy during the post-World War II period. Advances in energy generation during this time period resulted in energy becoming much cheaper for the end user, allowing architecture to deviate from the use of natural ventilation strategies. It became more convenient for people to utilize mechanical ventilation systems to condition their buildings because they did not have to deal with the considerations required to integrate natural ventilation. As a result, the advent of the sealed, air-conditioned, Modernist box proliferated around the world.[9] From that point forward, the use of mechanical driving forces to power our ventilation systems, as opposed to utilizing natural ventilation, became the dominant strategy.[23]

Since then, mechanical ventilation has come quite a long way. Present-day ventilation equipment is advanced enough such that humans can create virtually any thermal environment desired.[24] However, the cost of installing and operating such equipment is incredibly high and thus its use is prohibited in a number of building situations. The environments that can afford the equipment, however, are simply contributing to greater inefficiency and energy costs.

There are several reasons why exploring natural ventilation is justified. It is no surprise that many people desire a cooler environment than nature can offer them in most of the United States during the summer months.[19] However, mechanical ventilation systems can only offer this at a high price tag. That is one drawback that can often be too costly to overcome for certain regions. Despite this, there has not been a sufficient compulsion to adequately cool a large number of buildings naturally. This can result in unhappiness, ill-health, and inefficiency for these buildings' occupants.[19] Furthermore, mechanical ventilation systems are extremely complex and have a large number of components, a great need for space, and a high energy usage.[11] As mentioned previously, they constitute the greatest share of the building's construction and operation costs.[25]

A study on natural ventilation is even more necessary because proven design approaches that incorporate natural ventilation into commercial building systems designs are currently not available in the United States. Natural ventilation strategies are not likely to reach the U.S. market until design strategies are investigated and demonstrated for our specific climates and construction types.[26] As one of the world leaders in energy usage, this research is critical to becoming a more efficient and less detrimental nation.

3. NATURAL VENTILATION

Natural ventilation is the process of supplying and subsequently removing air through an indoor space without the use of any mechanical systems.[27] In the world of architecture, natural ventilation is a passive means by which one can alter the thermal comfort of occupants and indoor environment of a structure. This is accomplished in the form of wind-driven ventilation or buoyancy-driven ventilation. Natural ventilation relies on the wind as the main mechanism for wind-driven ventilation, and directional buoyancy is the driving force for buoyancy-driven ventilation.[28]

Wind is the result of a difference in air pressure. Wind-driven ventilation within a space is accomplished when there is a pressure differential between the indoors and the outdoors. More specifically, if there is positive pressure on the windward side of a building, and negative pressure on the leeward side, there will be wind through the building. This wind results in horizontal cross ventilation within the building.[29]

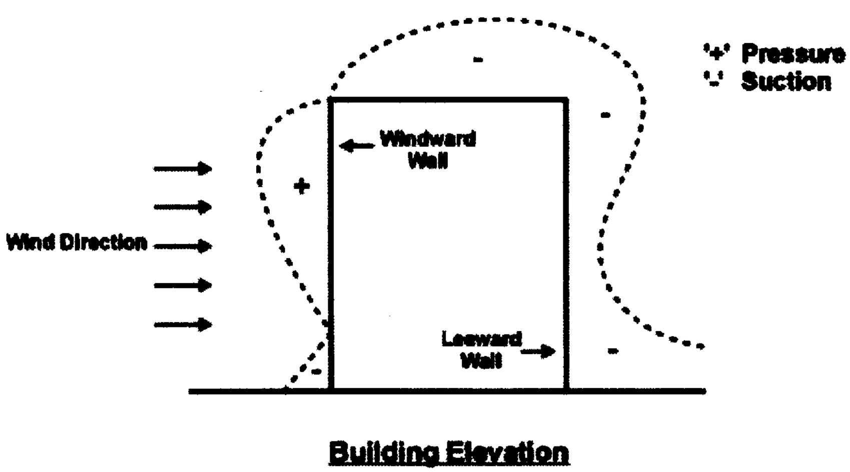


Figure 6[29]: Wind-driven flow

To take advantage of this natural wind effect, there are several design choices to consider. First and foremost, the windward and leeward sides of the building must have direct paths between them for the wind to flow.[12] The location of the building is very important as well, because open-plan, naturally ventilated buildings can be susceptible to being penetrated by environmental pollutants such as noise and air contaminants. Naturally ventilated buildings are also heavily reliant on the temperature and humidity of the surrounding environment, due to how locations with ample wind conditions are also desirable. It is often, though not always, easier to reduce the amount of wind allowed into a building through design choices such as louvers than it is to improve stagnant wind

conditions.[29] Contrarily, extreme, prevailing wind conditions are also quite difficult to design for, due to their ability to negatively affect the thermal comfort of a building's interior. [30]

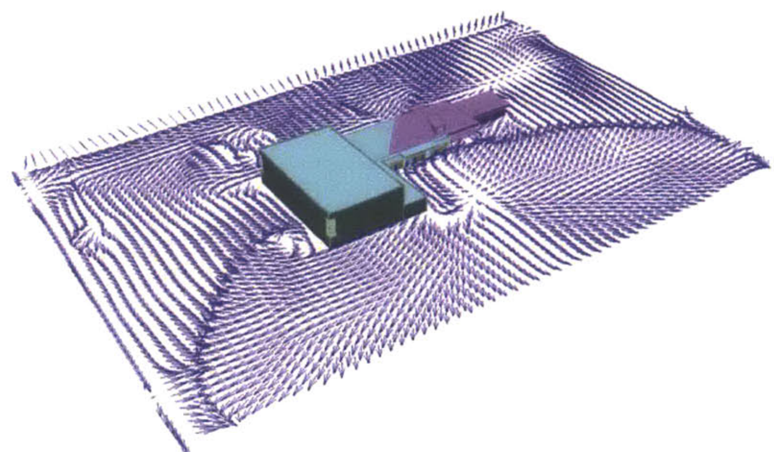


Figure 7[29]: Example wind conditions

The depth of the space and the ceiling height must also be taken into consideration, for if the space is too deep or tall, adequate air flow may not be achieved.[31] Other design choices that can greatly affect the feasibility of natural ventilation include window and opening details, external building elements, and the surrounding environment.[29]

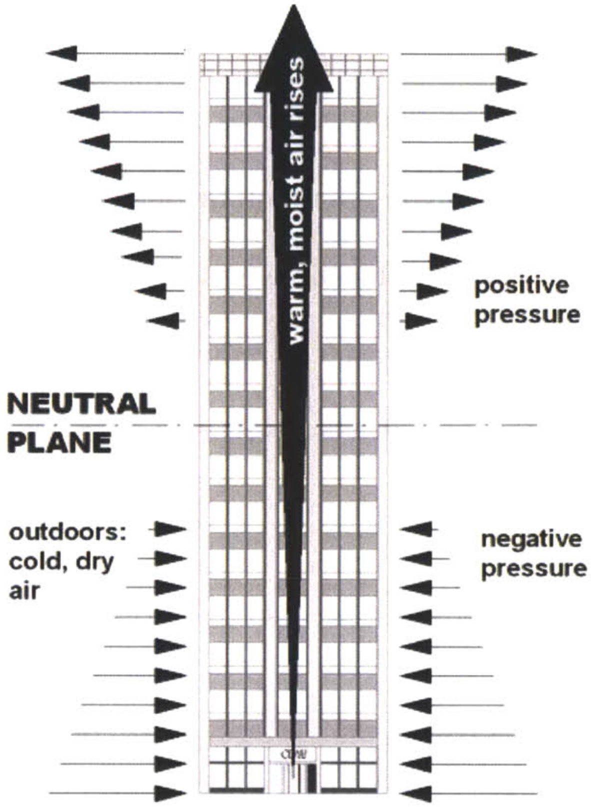


Figure 8: Buoyancy-driven flow

In the vertical direction, the buoyancy effect, also known as the stack effect, takes advantage of the vertical distance between incoming outdoor air and exhausted indoor air. Hot air that enters the lower levels of a building will be naturally expelled towards the top of the building if there is an exhaust opening (See Figure 8[32]).

This subsequently causes cool air to drawn into the lower levels of the building. In order to make buoyancy-driven ventilation possible within a building, one would need to allow air openings by which to enter as well as exit the building. Additionally, the air would also need an egress through the building that

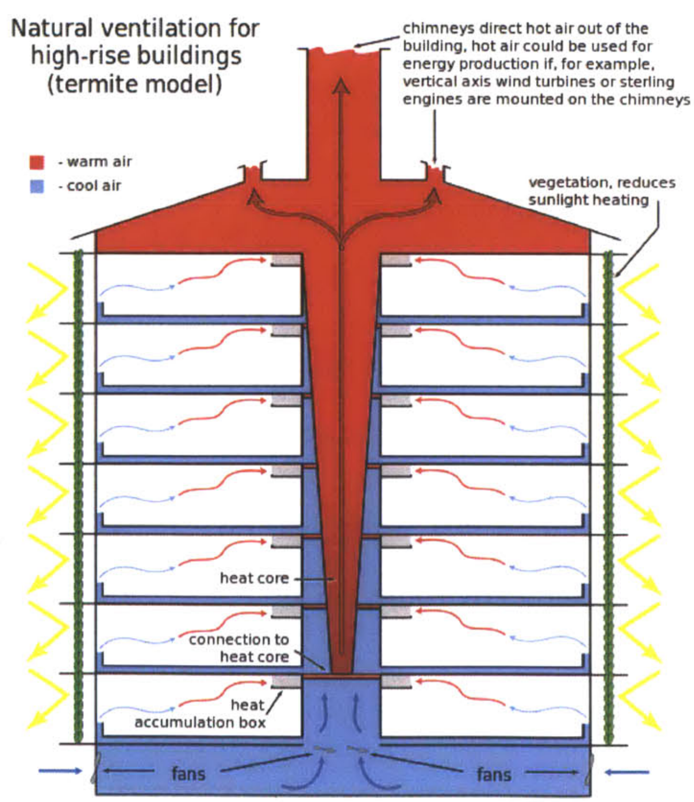


Figure 9: Natural ventilation for high-rise buildings (termite model)

allows it to rise vertically (See Figure 9[33]).

While there are numerous factors to take into account when designing for natural ventilation, there are also numerous benefits to the owner and the operator of the building. The capital initially invested to construct the building can be lower if heating and cooling systems can be smaller. In other words, if a building can maintain heating and cooling using natural systems, large HVAC systems will not be need because the building can perform efficiently with smaller systems. Most importantly, as discussed above, if natural ventilation is incorporated into the building, the amount of energy consumed to move and condition the air in the building, and therefore the operating costs of the building can be drastically lowered for the end user.

The health and comfort of the indoor environment can see a great deal of improvement with the introduction of natural ventilation. Several studies have shown that occupants report fewer symptoms of illness in buildings with natural ventilation as compared to buildings with mechanical ventilation.[34] Along with these improved indoor environmental conditions, occupant productivity can be significantly increased through reduced absenteeism, reduced health care costs, and improved worker productivity.[35] Furthermore, natural ventilation is an easy mechanism to maintain. These benefits all fit quite nicely into the realm of sustainable energy.

In recent years, there has been some renewed interest in environmentally friendly, passive building strategies in the U.S. Strategies such as natural ventilation are becoming more widely known as viable solutions to the problems of energy crisis and environmental pollution.[3] There is also an increased awareness of the problems associated with mechanical ventilation. For example, the Lawrence Berkely National Laboratory published an article this year outlining the health and economic disadvantages caused by mechanical ventilation systems.[36] This awareness is reinforcing the notion that we should invest in researching alternative forms of ventilation.[37] Additionally, as mentioned previously, the potential benefits of natural ventilation provide some incentivizes to the building owner and the building operator to utilize it.

4. LITERATURE REVIEW – NATURALLY VENTILATED BUILDING DESIGN

One case study I researched is entitled "Is day natural ventilation still possible in office buildings with a double-skin façade?" by Gratia and De Herde is a study in which natural ventilation was simulated to greatly reduce energy use and energy costs in a Belgian office building. The study's main focus was to test the effects of the double-skin façade on natural ventilation. However, they also did standalone simulations of the office without the double-skin. I focused on these simulations in order to avoid potentially misleading data. The building studied was a middle-size office building with 150 office modules aligned on two facades distributed over five floors separated by a central corridor (see Figure 10[38]).

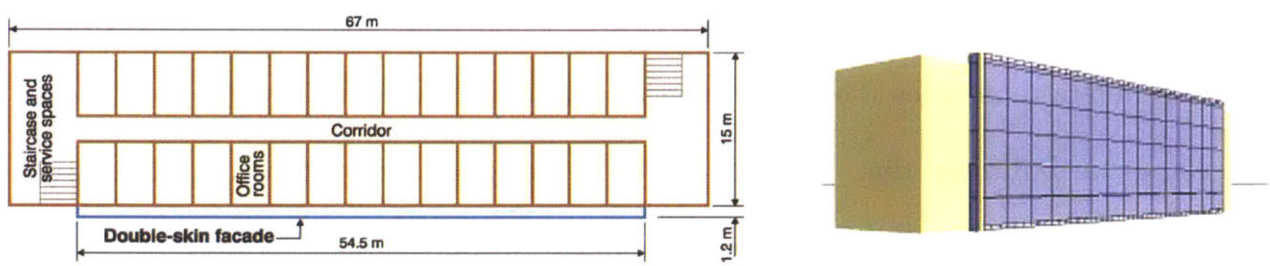
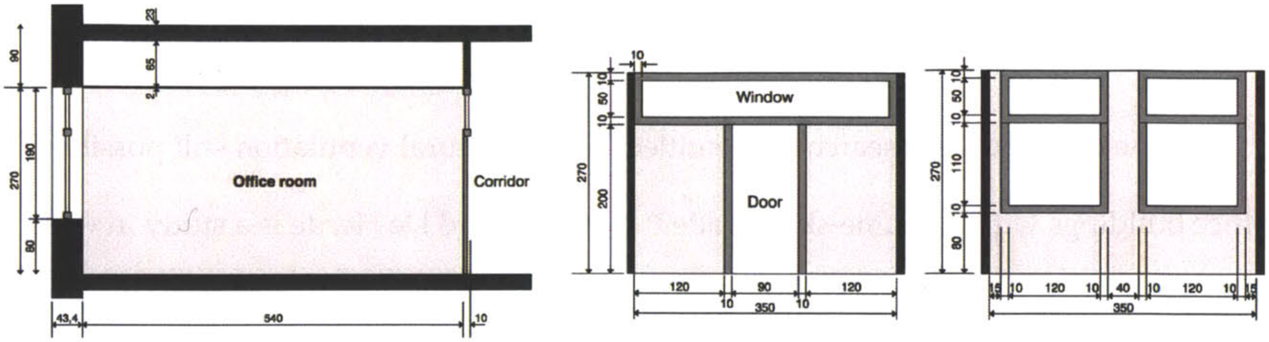


Figure 10: Gratia and de Herde office building

The internal walls between the office modules and the corridor have operable windows above the door to allow the flow of air between the northern and southern spaces. Each individual office module has four windows, two upper and two lower, in order to allow natural ventilation (see Figure 11[38]).



Vertical cross section of office module.

Internal wall between office module and corridor.

External wall of the office.

Figure 11: Vertical cross section of office module

The study utilized the Thermal Analysis Simulation (TAS) software package to generate the simulations that were analyzed in the study. TAS is a software package designed specifically for the thermal analysis of buildings. The TAS package contains a three-dimensional (3D) modeler, a thermal energy analysis module, a systems simulator, a two-dimensional computational fluid dynamics (2D CFD) package, and report generation facilities. The TAS program was designed to fully assess the thermal aspects of a building that can be used by designers to optimize a building's environmental, energy, and comfort performance.[39] These simulations were performed using the climatic data of Uccle, Belgium and on July 24, a sunny summer day.[38]

The study's results were very supportive of the use of natural ventilation. The cooling load of the building without external shading devices and without natural ventilation was 1033 kilowatt hours (kWh) per day. When shading devices were added, the load reduced to 685 kWh per day. When both shading devices and natural ventilation during the day and night were utilized, the cooling load dramatically reduced. Introducing cross natural ventilation lowered the cooling load to 358 kWh per day, while adding single-sided natural ventilation resulted in a cooling load of 252 kWh per day.[39]

As the results above, natural ventilation is quite effective at reducing the cooling load on a building. In this study, the office building was able to see a simulated cooling load reduction of sixty-three percent simply by the addition of single-sided natural ventilation.[39] Gratia and De Herde also suggested methods as to increase the efficacy of natural ventilation further, if, for example, their site saw reduced wind speeds. Two simple methods would be to increase the size of the window openings and to place additional windows at various levels to encourage the stack effect.[39]

The next case study I have reviewed is one in which natural ventilation has the potential to vastly improve occupant health in health care facilities. This study is entitled "Natural Ventilation for the Prevention of Airborne Contagion." The transmission of drug-susceptible and drug-resistant tuberculosis (TB) is a major health issue in health care settings. A group of researchers from PLOS Medicine evaluated how natural ventilation affects air exchange rates and the estimated transmission risk of TB in hospitals in Lima, Peru.[40]

In order to assess this, the group utilized a carbon dioxide decay technique to measure ventilation in air changes per hour (ACH). They also evaluated the room types to determine the factors that affect the ACH. They then used the Wells-Riley equation to estimate the transmission risk of TB.[40] They evaluated seventy naturally ventilated rooms and twelve mechanically-ventilated rooms in eight hospitals during the study.

Five of these hospitals were built prior to 1950, whereas three of these hospitals were more modern, having been built between 1970 and 1990. [40]

The older rooms were mechanically ventilated with a constant ACH of twelve and an estimated TB transmission risk of 39% following a twenty-four exposure period to an infectious TB carrier. The modern, natural ventilated rooms were similar to the mechanically ventilated rooms in their basic design, but differed because they had open windows and doors. These rooms had an average ACH of seventeen, and an estimated TB transmission risk of 33%. The older, natural ventilated rooms were distinct in their design, having large windows and tall ceilings. Unsurprisingly, these rooms had the highest ACH among the selected group (forty), and an estimated TB transmission risk of 11%.[40]

Though we are not as concerned with TB in the United States as in other regions, it still remains a public health problem in many areas in the world. This study highlights the potential for prevention of infectious airborne diseases through the use of natural ventilation in health care settings. That is something that cannot be said for mechanical ventilation systems.

The next case study, "Assessing Building Performance in Use 4: The Probe Occupant Surveys and Their Implications," comes from Leaman and Bordass, faculty for the Usable Buildings Trust (UBT) in the United Kingdom. They conducted a series of surveys with the intent of linking occupants' indoor environments with their health, comfort, and productivity at work.[41] While the article is not specifically focused on natural ventilation, their research provides insight into how natural ventilation relates to occupant productivity and comfort, an often overlooked aspect of building design.

According to the study, the general rule is that the deeper a building gets, the lower the overall satisfaction and productivity of the occupants are. The optimal depth that they found is about 12m across the building.[42] This is close to the limit of simple natural ventilation which is 15m across. If a building becomes deeper than this, mechanical systems must be added to adequately ventilate the building.[42] Therefore, these researchers suggest that ventilation type and occupant comfort and productivity are closely linked. Though this detail represents a design limitation for natural ventilation, it also indicates that humans have a preference for buildings with natural ventilation as opposed to mechanical ventilation.

The study also states that occupants simply prefer natural ventilation over mechanical ventilation in the fall, winter, and spring seasons, but they prefer mechanical air conditioning, unsurprisingly, in the summer.[42] This would make sense, considering how hot certain regions can get during the summer. However, I would like to cite my original case study when I say that perhaps we can change how people feel about natural ventilation in the summer. Though a stigma may exist that air conditioning is necessary in the summer, the study conducted by Gratia and De Herde would indicate that natural ventilation dramatically reduces the cooling load of a standard office building in the summer without sacrificing thermal comfort.[39]

In addition, better occupant health is also statistically associated with natural ventilation. As shown in the previous study by BMC, the transmission of airborne decisions is reduced by incorporating natural ventilation.[40] Furthermore, Leaman and Bordass state that buildings which rely on mechanical ventilation systems have historically had more reports of ill-health, more specifically with chronic, building-related symptoms such as dry eyes and a stuffy nose than those with natural ventilation systems.[42] This close linkage suggests that HVAC systems are almost certainly the cause of these building-related symptoms.

The research I have reviewed suggests that it is beneficial to consider natural ventilation as an alternative to mechanical ventilation. However, I feel it is a necessary component of research into energy efficiency. The urban environment is very rapidly approaching a state at which humans will no longer be able to sustain it. Soon enough, the price of the resources required for our cities to maintain themselves will become too great. However, natural ventilation provides a very promising solution to the majority of our cooling concerns. If we can utilize it as an alternative to mechanical ventilation, we can move towards become a more efficient, sustainable society.

The problem that most designers face with regards to natural ventilation is that they often cannot implement it. Architects are typically not trained in the building sciences, and therefore do not have knowledge of how natural ventilation systems work. This makes it very difficult for architects to incorporate natural ventilation into the early stages of their building design. At the point when a skilled engineer is able to intervene in the architect's original design, it is too late for natural ventilation to be integrated into the design. This is due natural ventilation having so many design considerations that must be accommodated for. Additionally, mechanical ventilation and natural ventilation do not complement each other in design, exacerbating the issue. My approach to tackling this research problem is outlined in chapter 5, Methodology.

5. METHODOLOGY

This chapter discusses my approach to the research problem outlined in Chapter 4, Literature Review – Naturally Ventilated Building Design. I conducted my research in an iterative process, ensuring that my work can be followed and replicated by anybody who wishes to. As my research is intended to be used as a guide, this specification is critical to its success in that regard. Additionally, I approached this project from a designer's point of view, as if I were an architect with the intent of designing a sustainable building.

I began my thesis research with choosing a modeling program to work with. Though this task may sound trivial, choosing the correct program was an essential part of ensuring proper simulations. The programs that I considered were CONTAM, CoolVent, EnergyPlus, and TRNSYS. Though all the programs can be used for simulating natural ventilation, they differ dramatically in their usage and capacity.

CONTAM, though a competent tool for running natural ventilation simulations, does not have a very user-friendly interface. Due to how much time I would need to dedicate to simulations, I decided that my time would be better spent in simulations than in working with the CONTAM interface. CoolVent also did not make the cut, due to the limited geometry that it allows users. As I intended to work with custom geometry, CoolVent was simply not an option. And while EnergyPlus is a useful tool for whole building energy simulations, its natural ventilation component is a bit lacking as compared to other programs. TRNSYS combines the useful aspects of the other programs with the additional benefit of allowing the user to have instant quantitative feedback on their simulations. This made TRNSYS the best choice for my thesis research. My detailed selection process is outlined in Chapter 6, Choosing a Modeling Program.

I then turned my research towards defining building typologies. I eventually decided on two building typologies to each serve different purposes. These are 1) an office building based on the Department of Energy (DOE) Medium Office reference building[43] and 2) a residential building based on my fraternity (Sigma Alpha Epsilon or SAE) house.

I chose my first typology for several reasons. The first was to dispel the notion that office buildings cannot be properly naturally ventilated. The details of this hypothetical building are also carefully documented by the DOE, making modeling this building in TRNSYS relatively straightforward. This allowed me to produce very accurate simulations.

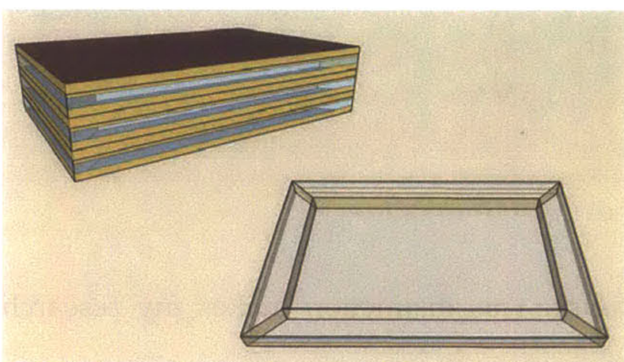


Figure 12[43]: DOE Medium Office reference building

I chose to model my fraternity's brownstone because I had access to all of the construction details I needed as a result of being a fraternity brother. Furthermore, I lived at the fraternity house during several summers of my undergraduate career, allowing me to compare simulation results to my own personal experience.

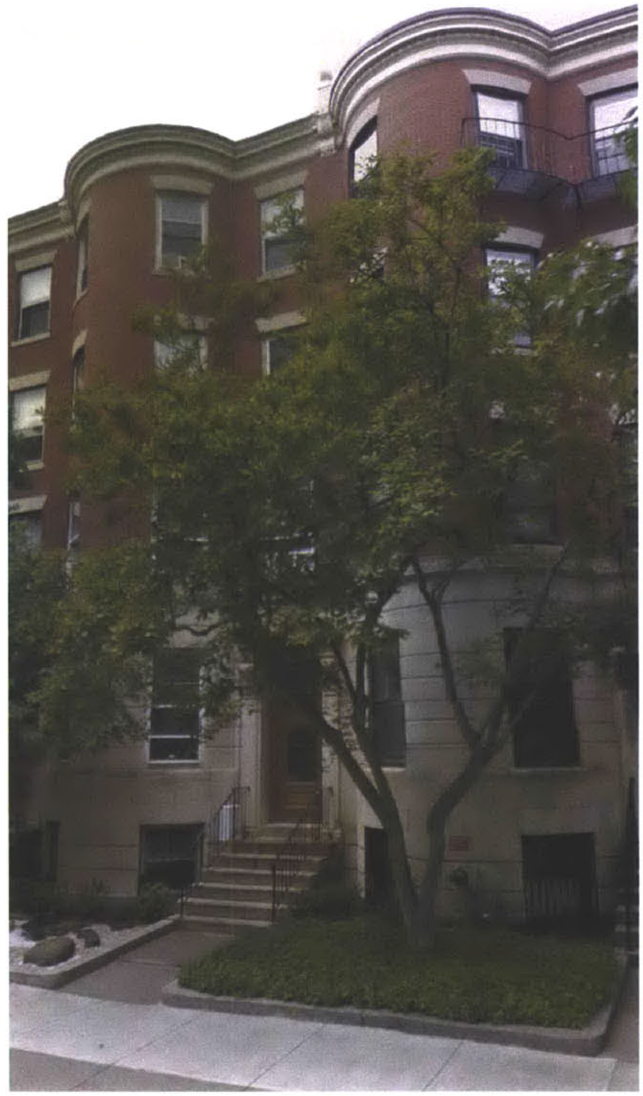


Figure 13: 165 Bay State Road

Additionally, as the SAE house is an existing building, I could then make distinctions between the research process for SAE and for the DOE reference building. As the DOE reference building is not an existing building, different considerations needed to be taken into account. This distinction makes my research more comprehensive and applicable to my readers.

More details about my building type modeling process can be found in Chapter 10, Modeling Building Typologies.

The next step I took in my research was to learn how to utilize the TRNSYS programming environment. The detailed guide to using TRNSYS for building simulations can be found in Chapter 7, Building Modeling in TRNSYS.

The next step was to create these models of my proposed building typologies in TRNBuild. TRNBuild is an interface within the TRNSYS environment used for creating and editing all of the non-geometry information required by TRNSYS for simulation.[44] The detailed process for modeling building systems in TRNBuild can be found in Chapter 8, Building Editing in TRNBuild.

I initially modeled both building types as standard, mechanically ventilated buildings in Boston. The next step was to introduce my new design interventions to the original models. This process was made possible through the use of TRNFlow, a component of the TRNBuild interface used for natural ventilation calculations. Because TRNFlow is fully integrated into the TRNBuild environment, it acts simply as an extension of an existing building project. This makes natural ventilation calculations relatively straightforward. TRNFlow will be discussed further in Secton 9, TRNFlow.

The next step in my project was to analyze the data I received in order to make informed decisions about my designs. Though TRNSYS is a great simulation tool, for the purposes of my thesis, it will only be used to supplement my design process, as opposed to being the primary form-giver. This will be discussed further in Chapter 11, Results.

6. CHOOSING A MODELING PROGRAM

One modeling program I considered was CONTAM. CONTAM is a multizone indoor air quality and ventilation analysis program.[45] The primary benefits of CONTAM in the context of my research are the ability to calculate infiltration, room-to-room airflows driven by mechanical ventilation, wind pressures, and buoyancy effects. Though it is a competent tool for calculating airflows, it does not have a very user-friendly interface. TRNFlow is also a better program for calculating effects from natural ventilation.

CoolVent is another program that I could have potentially used in my thesis research. CoolVent is an airflow network tool that uses energy and airflow calculations to model buoyancy-driven flow.[46] CoolVent is used specifically for predicting the effects of natural ventilation on occupant comfort and energy savings. It is also aimed to be a simple program that can be used by architects, designers, and engineers in the early design stages.[47] This is pretty much exactly what I want to do. However, CoolVent is too limited of a program for my research because you are restricted in the geometry that you can use. My project intends to allow the users of my methods to be very specific in their geometry.

EnergyPlus, unlike CoolVent or CONTAM, is a whole building energy simulation program. It allows users to model energy performance and water use in buildings.[48] It is mainly used for the optimization of building performance. Multizone air flow, thermal comfort, and natural ventilation are just some aspects of this program. However, the natural ventilation model is simply not as advanced as that of TRNFlow.

I eventually decided on using TRNSYS as my program. TRNSYS is a transient systems simulation program.[49] To name just a few use cases, TRNSYS is utilized to simulate renewable energy, high performance buildings, and electric power generation. For the purposes of my thesis, I used TRNSYS as a tool for running various building energy simulations on my building models. The real advantage, however, was TRNFlow.

TRNFlow is a tool that allows a user to make ventilation-related calculations within TRNBuild.[50] By converting the mechanically ventilated models to naturally ventilated models, I was then able to quantitatively compare results from my original simulations to my new simulations. This ability of TRNSYS to test and immediately receive feedback on the efficacy of model changes is a very useful aspect for designers.

7. BUILDING MODELING IN TRNSYS

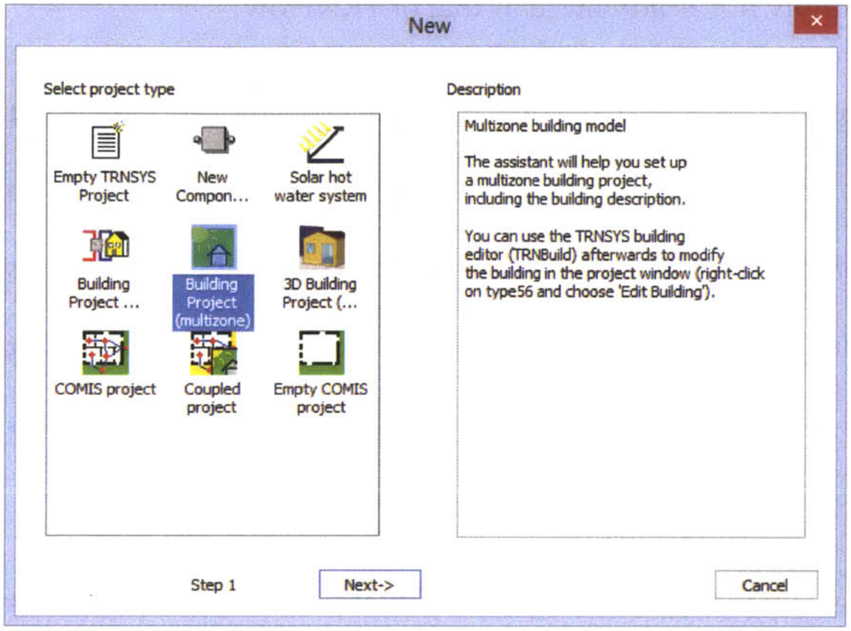


Figure 14: New Building Project

Modeling a building in TRNSYS starts with acquiring the TRNSYS software package from the Pricing & Ordering Chapter of the TRNSYS website.[51] The next step is to open the Simulation Studio and start a new project. You will then want to create a new Building Project (multizone) as shown below. Take note that most parameters defined in the Simulation Studio can later be changed in TRNBuild. You are also able to move forward and backward through the model assistant to edit variables as you please.

You are then asked to create a building floor plan

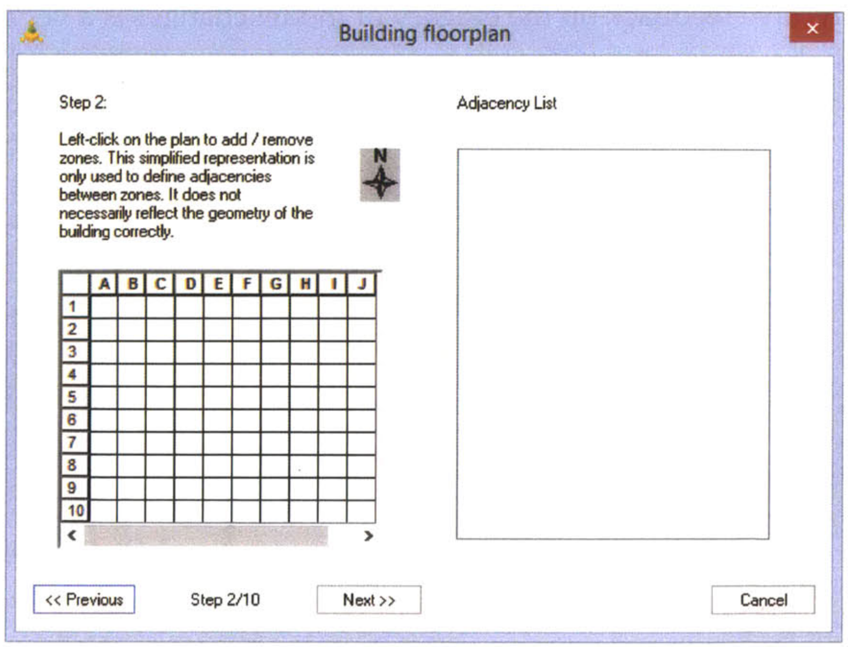


Figure 15: Building floorplan

to define zones and their adjacencies (see Figure 15). It is important to note that actual geometry will not be taken into account in this building model; you will have to keep a separate model if you desire one. This is highly preferred, so that you can relate the technical model to a more visual one in order to preserve the connection between your simulations and your architecture. Additionally, parameters defined in setting up your building project will apply to all zones, but each zone can be customized in TRNBuild after the fact.

You will then have to define your zone dimensions (not pictured). The helper will ask you to name each zone, as well as define its height, width, and depth in meters. This is when keeping keep a separate computer-aided design (CAD) model saved to use as a reference for your TRNSYS model can be very beneficial. It is also possible to add or edit zones and zone dimensions in TRNBuild, so there is no need to restart this whole process if you change your mind about your initial design.

The next step will ask you to define a few more parameters related to the building project (below). The first is the window to wall ratio (WWR) for each façade of your building. The second is the building's rotation relative to the north axis. Then you will have to input a TRNSYS weather file to define the location of your building. Upon clicking the 'Browse' button, TRNSYS will direct you to your weather file directory in your TRNSYS folder. From there, you will be able to select a weather file from those that were downloaded during the TRNSYS installation. Additionally, you can also navigate to any weather file that you have downloaded on your computer, provided it is a weather file readable by TRNSYS. TRNSYS can read weather files in the TMY, TMY2, TMY3, IWEC, CWEC, EPW, TM2, and TRY formats. This weather file can be altered in the Simulation Studio after your model is complete.

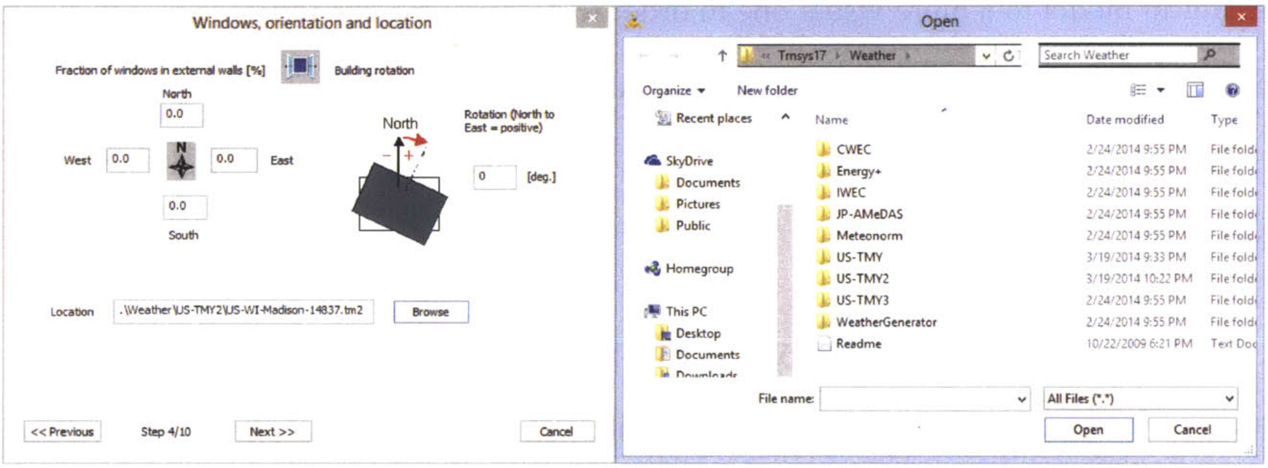


Figure 16: Windows, orientation and location

The next two steps refer to ventilation and air exchange within your building. The image below details the various parameters you are asked to provide for TRNSYS. You can specify the infiltration rate, mechanical and natural ventilation controls, and heating and cooling constraints. These values can be changed in TRNBuild after model completion. In addition, these parameters can be left blank and adjusted for individual

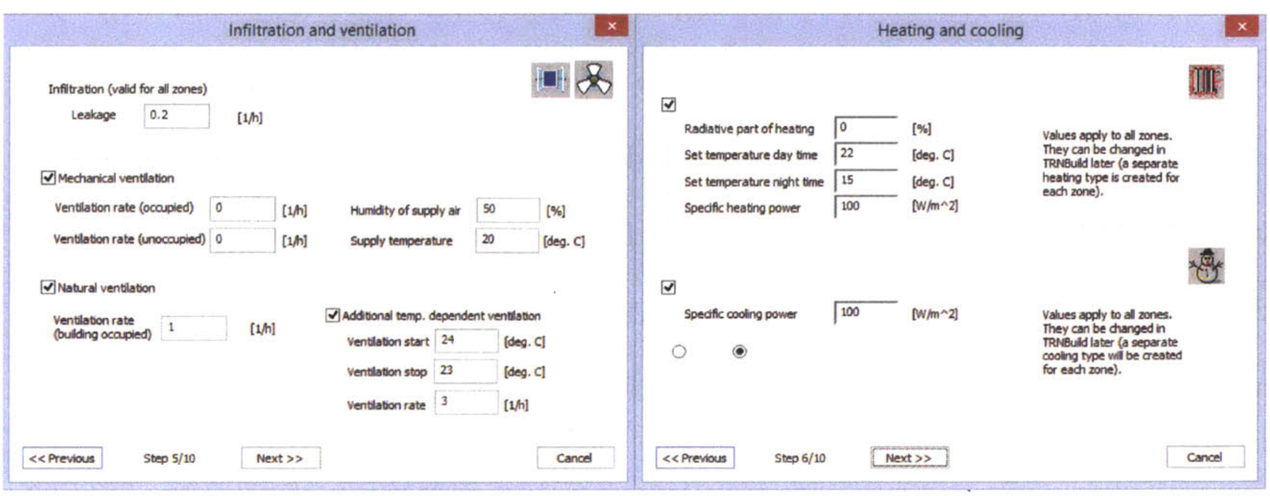


Figure 17: Infiltration and ventilation; heating and cooling

zones in TRNBuild.

You will then be prompted to define the internal gains in your space. This step includes gains from lighting as well.

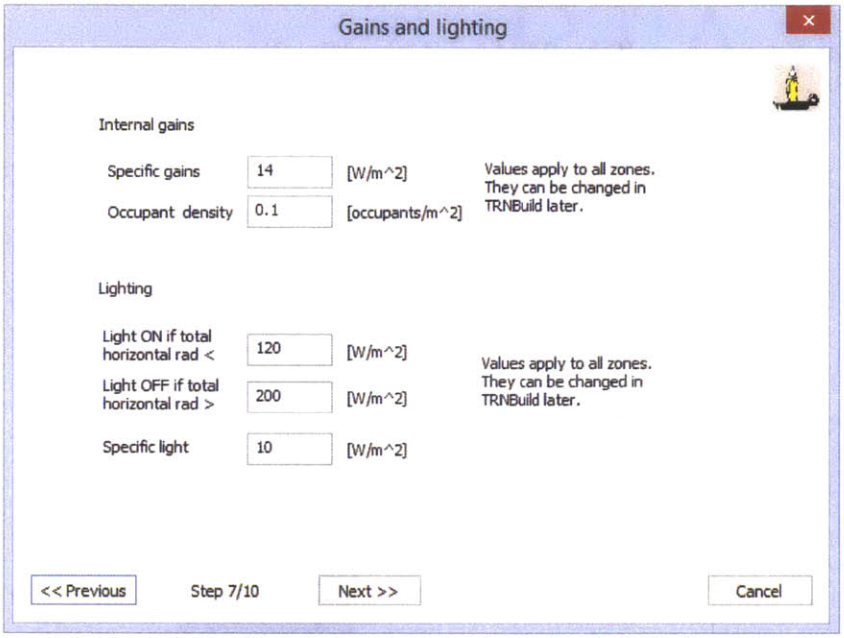


Figure 18: Gains and lighting

TRNSYS also allows you to define the shading parameters for your building. You can specify both fixed shading and movable, or active, shading. As you can see, TRNSYS offers a lot of design specificity. This level of detail is incredibly useful for designers.

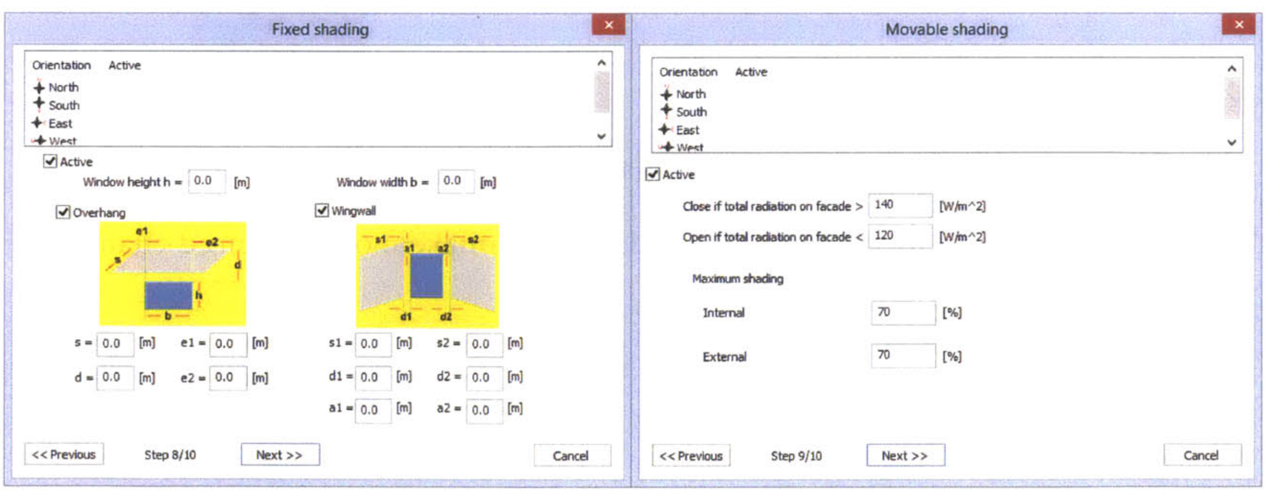


Figure 19: Fixed and movable shading

The final dialog box in the assistant is simply for completing the process. At this point, you can return to any of the previous dialog boxes to edit your model, you can cancel the project entirely, or you can complete the project description. If you choose to complete the project, you will find yourself in the Simulation Studio environment as seen in Figure 20.

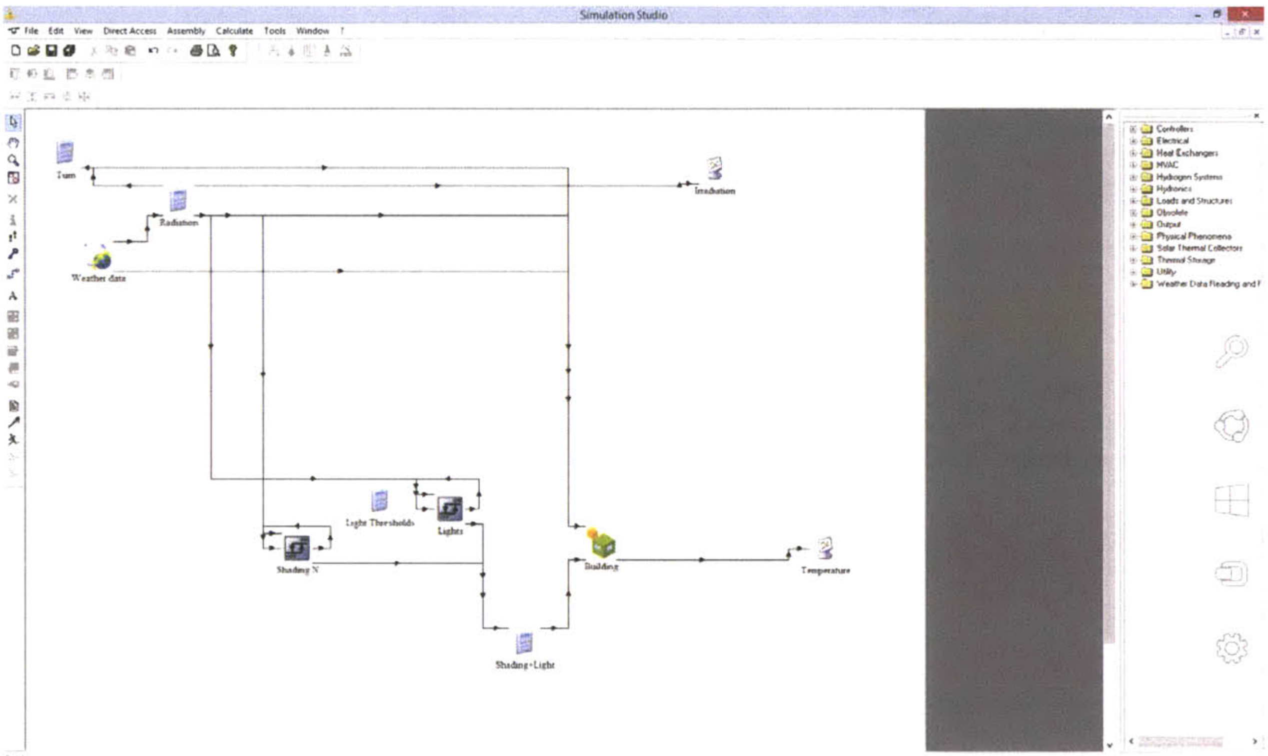


Figure 20: Simulation Studio

At this point, you have successfully created your first building project. The next chapter will detail how to use the TRNBuild editor to make more advanced changes to your building.

8. BUILDING EDITING IN TRNBUILD

In order to begin editing in TRNBuild, you must navigate to your building project in the TRNBuild editor. This can be accomplished in several ways. The first is to open your building project directly from the Simulation Studio. To do this, you have to right-click on your Building, and click the Edit Building option (see Figure 21).

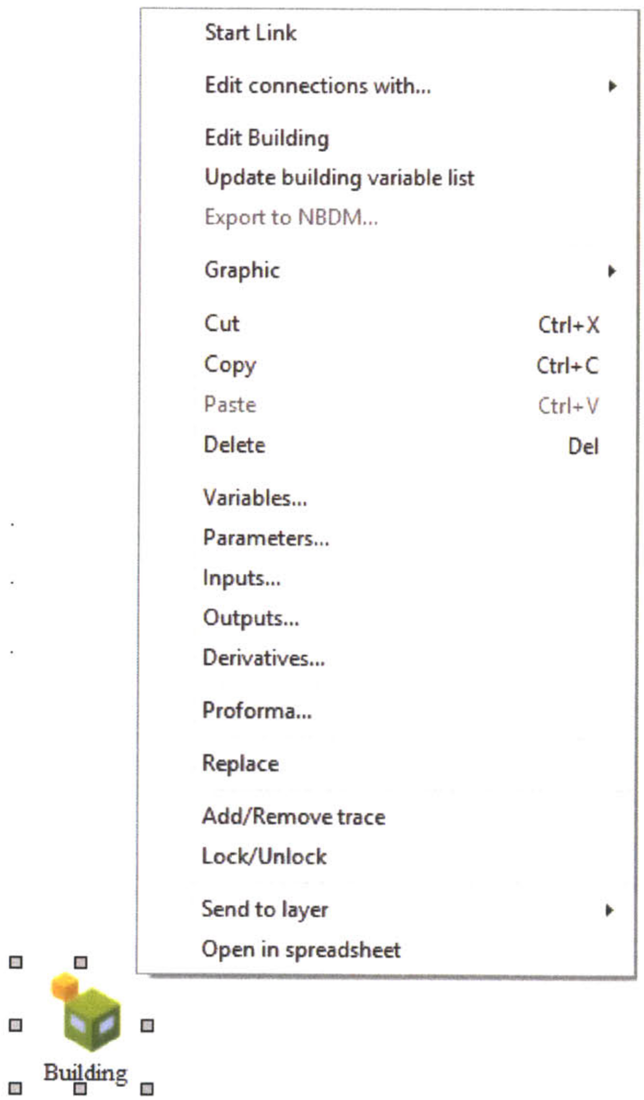


Figure 21: Building options

The second way is to open your building using the TRNBuild MFC Application. You can access this by navigating to your TRNSYS directory on your computer, double-clicking on the Building folder, and double-clicking the TRNBuild file. It should be easily recognizable, as the file icon is the same as the Building icon featured above. It is also labeled as an Application file. Then, navigate to the File drop down menu and click Open. A pop-up window will appear and prompt you to select your building file. Note that these files are

TRNBuild Building File or .b17 files, which are different from the files you open in the Simulation Studio, which are TRNSYS Studio Project or .tpf files.

The final way is to navigate to your building project folder and to right-click your building file directly. Then click the Open with option and choose to open the file with your TRNBuild MFC Application.

After you have opened your building file, you will find yourself in the TRNBuild Navigator (see Figure 22).

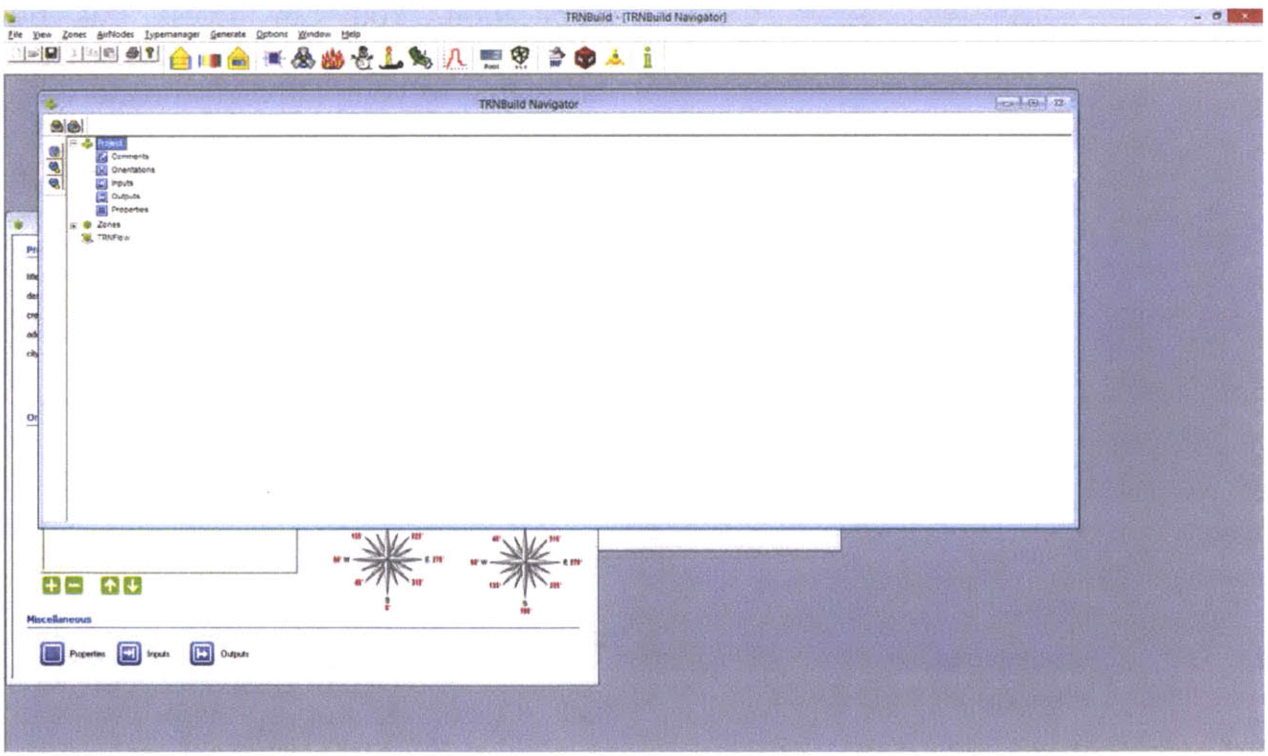


Figure 22: TRNBuild Navigator

If you are looking at the above screen you can begin to edit your building. You may want to start with the project initialization window (see Figure 23).

This window allows you to edit some general information about your project. You can specify project title, description, creator, address, and city under the Project header. Under Orientations you can define how surfaces in your project are oriented. Under Hemisphere you can define the orientation of the building itself.

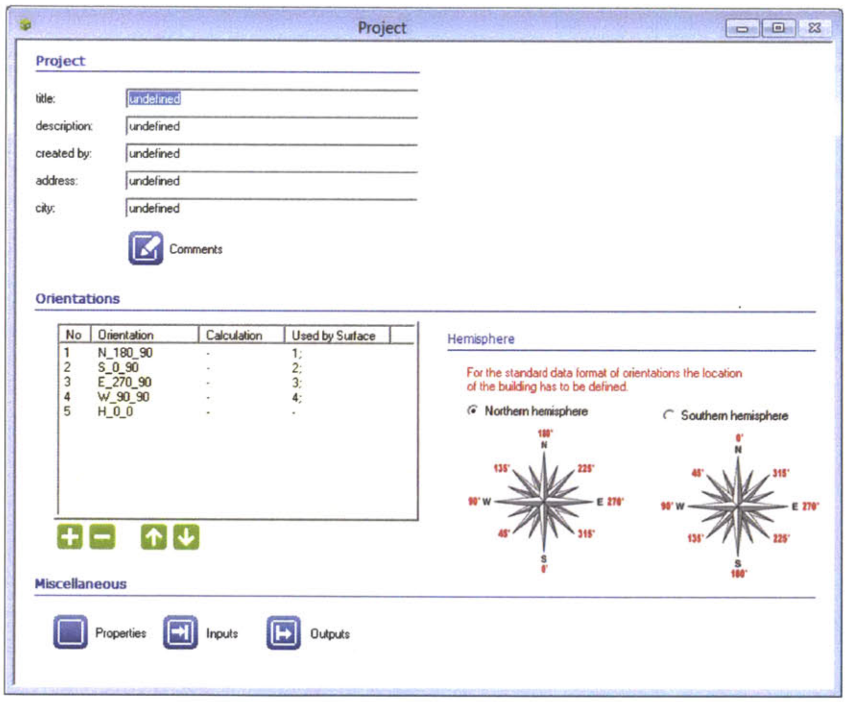


Figure 23: Project

There are three buttons under the Miscellaneous header. The Properties button gives you the option to edit various physical constants such as the density and pressure of air, as well as several parameters for internal calculations of heat transfer coefficients. You will, in most cases, not be changing the TRNBuild-supplied values. Only experienced TRNSYS users should even consider changing the default values. The Inputs button displays the TRNBuild-supplied inputs to your project, as well as allows you to view and edit any user-defined inputs. Similarly, user-defined inputs should only be altered by advanced TRNSYS users. The Outputs button shows you the outputs list, which will be an important aspect for designers. It allows you to specify all the various simulation outputs. Some examples are the temperature of an air node, the absolute humidity (humidity ratio) of an air node, and the sensible energy demand of an air node.

The next step is to become familiar with the Zone Window (below). This window can be accessed by clicking upon any of your zones in the TRNBuild Navigator. In order to add a new zone, you can click on the Zones drop-down menu and click Add Zone. Similarly, you can click on Delete Active Zone in this menu to delete a selected zone.

The Airnodes header indicates the airnode regimes you have specified for each zone. For the purposes of TRNBuild, an airnode is defined as a single, isolated volume of air. You can, if you choose, model several airnodes in a single thermal zone in order to create multi-airnode zones. Modeling a double façade or an atrium might necessitate multi-airnode zones, for example.

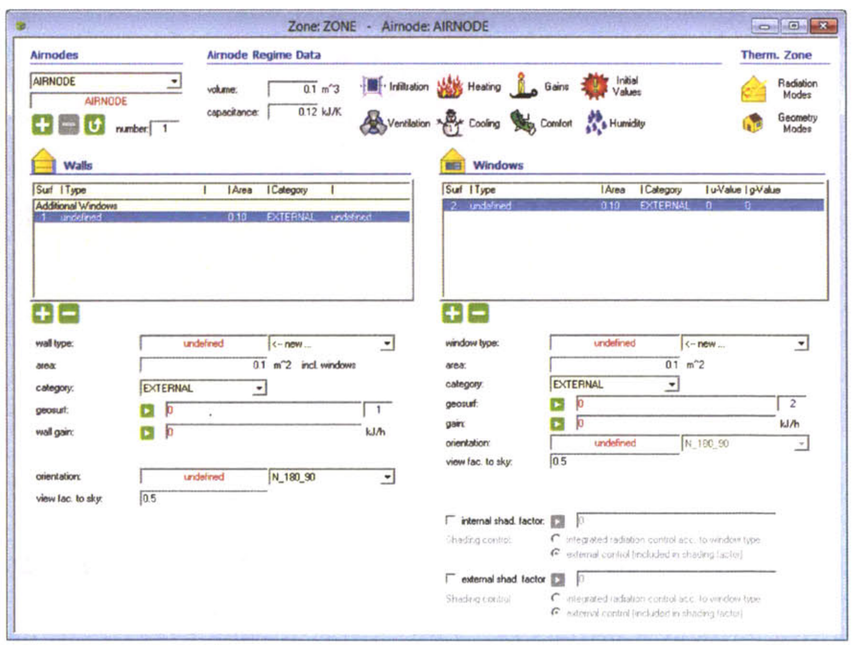


Figure 24: Zone - Airnode

There are four different kinds of required regime data you must take into account in the Zone Window. These are volume, capacitance, initial zone temperature and relative humidity, and humidity model.

Volume simply refers to the volume of air within the airnode. TRNBuild will automatically calculate the capacitance for you at a value of 1.2*volume. You also have to enter the initial zone temperature and relative humidity. These will differ depending on the temperature of air supplied to your space. For most typical HVAC systems, these values are 20°C and 50% relatively humidity. As far as the humidity model is concerned, we can just utilize the simple humidity model that is the default for TRNBuild for most modeling purposes. A detailed moisture capacitance model is simply unnecessary for the vast majority of designs.

One important thing to note about the TRNBuild interface is that each component of your building project can be referred to as a type. Wall, Layer, Window, Infiltration, Ventilation, Schedule, etc. are all examples of types. Furthermore, each type has a type manager associated with it. Type managers are used for adding new types, deleting existing types, or editing properties of existing types. The four edit buttons found on the bottom-right corner of each type manager (see Figure 25) are used to rename, delete, copy, and make new types, respectively. The remainder of this chapter will discuss the importance of these types in regards to your building projects.

Figure 25: RDCN

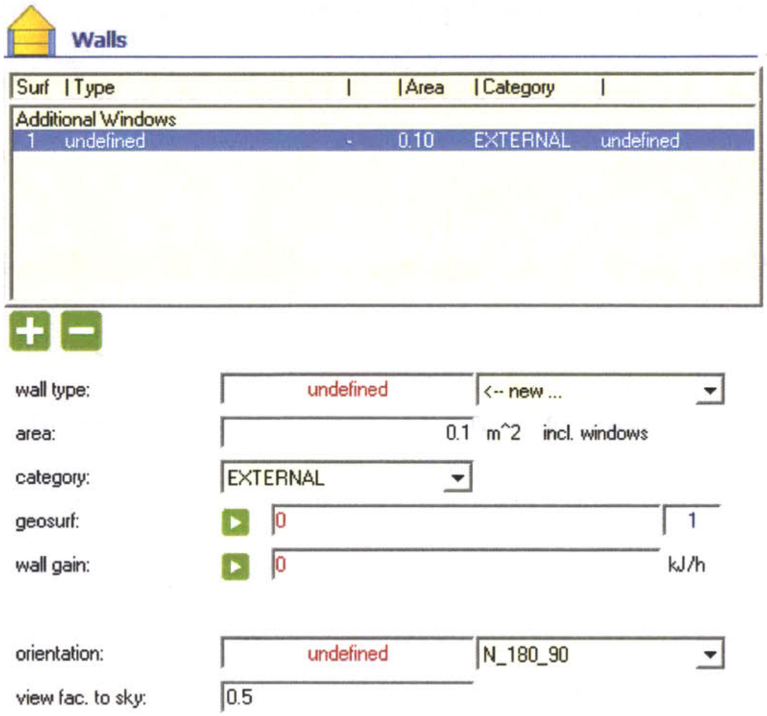


Figure 26: Walls

In the lower left of the Zone Window, users can add, edit, or delete a wall within an airnode. The upper window provides an overview of all defined walls. Below this window is the displayed definition of the selected wall. Clicking on a wall in the upper window allows the user to edit it. This window gives you the ability to define every aspect of each individual wall construction. Do note that every wall in your building project must be defined in order to ensure an accurate simulation. This is where having a CAD model of your building project to work with alongside your TRNSYS model becomes very useful. The plus button adds new walls and the minus button is used to delete selected walls.

This same process can be repeated to create all the windows in your building project (next page). Similar to the walls, your window constructions should be specified for each window. To access your window menu, click on any wall in your building project. You will then be able to define any windows within that specific wall construction.

The zone window also allows you to define any optional data such as infiltration, heating, gains, ventilation, cooling, and comfort. If you choose not to define any of this data yourself, TRNBuild will automatically use the data you filled in during the building creation process in Chapter 7, Building Modeling in TRNSYS. Therefore, it is advised to go through and specify each for every zone.

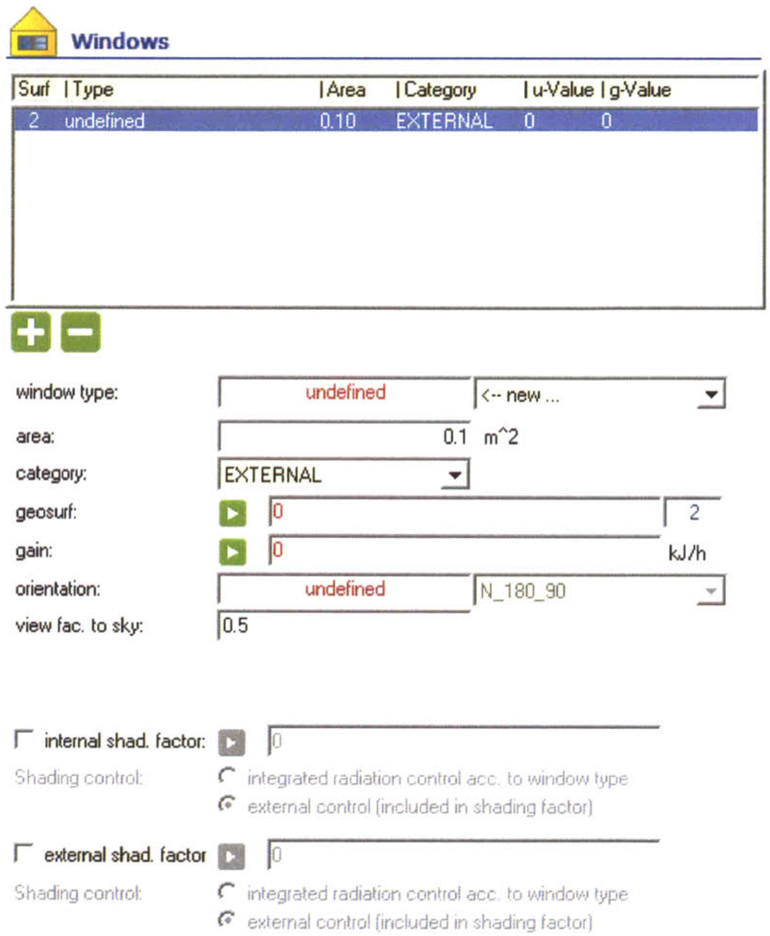


Figure 27: Windows

The Infiltration type (see Figure 28) can be used to specify an air flow from the outside of the zone into the zone. Infiltration is generally based off of wall construction. If you are unsure about what values to use for your zones, consult the ASHRAE

Fundamentals Handbook or DOE Commercial Reference Buildings. Then click new to define an infiltration for your zone and the check button to confirm your selection.

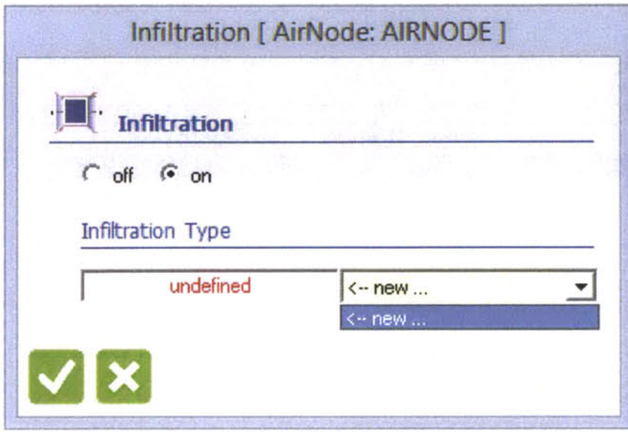


Figure 28: Infiltration

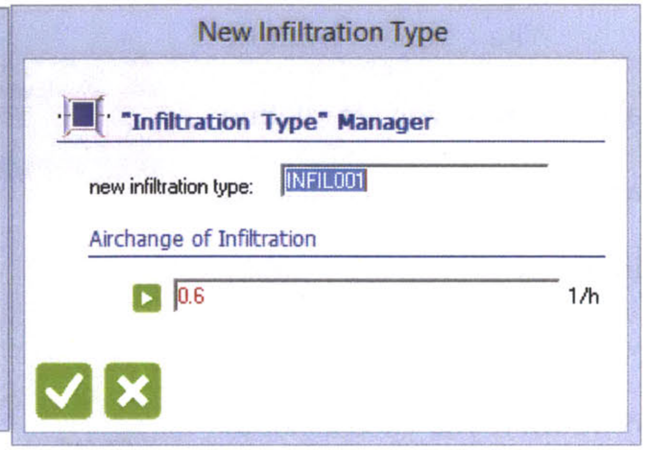


Figure 29: New Infiltration Type

Ventilation in TRNBuild is defined as air flow into the airnode from heating or cooling equipment. Ventilation is an optional setting and TRNBuild defaults it to off. However, when considering the viability of natural ventilation as opposed to mechanical ventilation, it is useful to turn ventilation on. To turn ventilation on, click on the Ventilation button in the Airnode Window (see Figure 30). You can use this dialog box to select, add, or delete ventilation types.

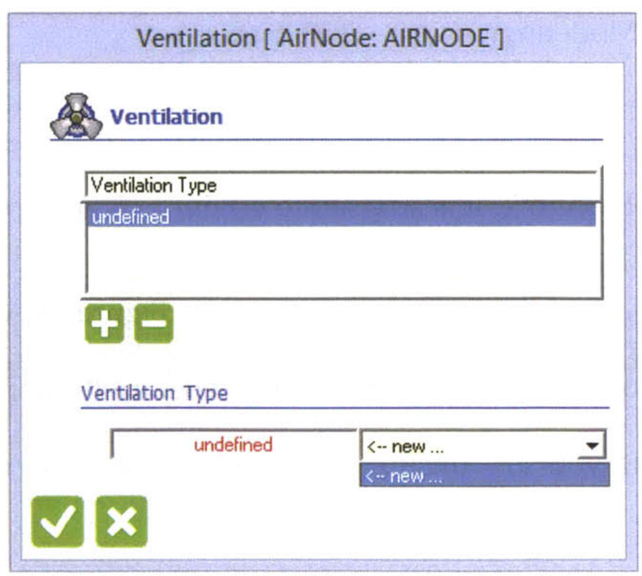


Figure 30: Ventilation

Upon clicking new, you will find yourself in the Ventilation Type Manager (see Figure 31). Here, you can specify the details for a new ventilation type. You have to establish the air change rate, temperature, and humidity of the air flow. These specifications should be easily accessible by anybody considering external ventilation systems in their building projects.

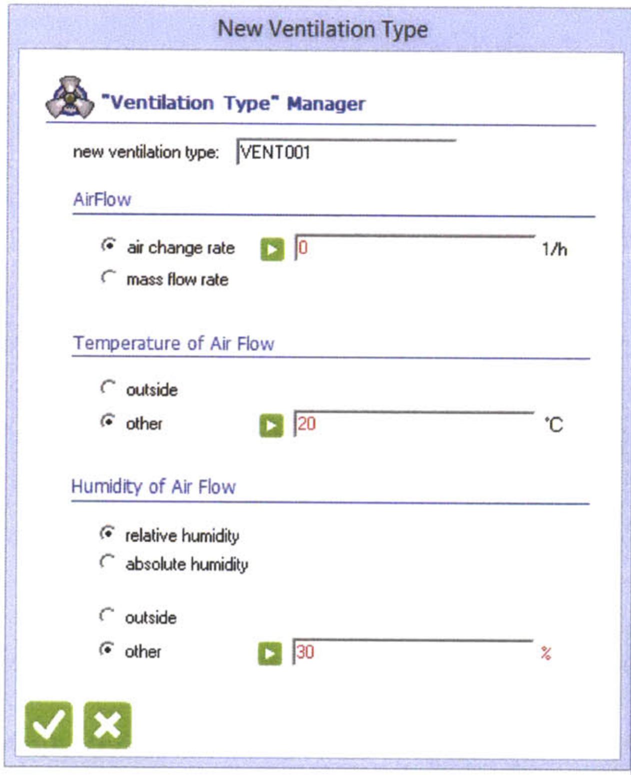


Figure 31: New Ventilation Type

The Heating button allows you to modify heating control for an airnode. Similar to the Ventilation Type Manager, the Heating Type Manager (see Figure 32) allows you to create, edit, or delete heating types. For heating types, you must specify a room setpoint temperature, the heating power, and air humidification if applicable. Selecting the unlimited option under Heating Power will cause TRNBuild to use as much heating power as necessary to maintain your setpoint temperature. The limited option will only apply as much heating power as is specified. The choice of which

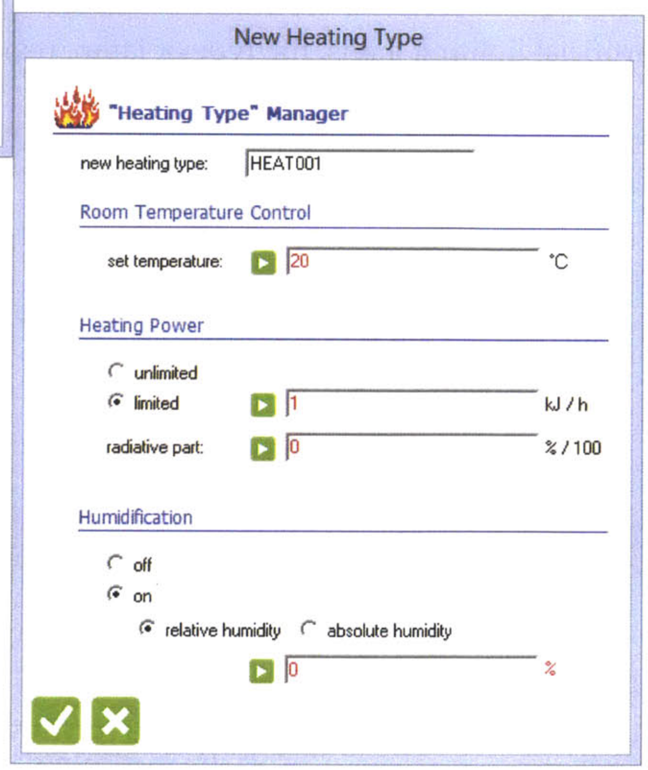


Figure 32: New Heating Type

option to use depends entirely on your heating system

The Cooling Manager (see Figure 33) functions almost identically to the Heating Manager. The particular values you need to use should also be specified by your cooling system.

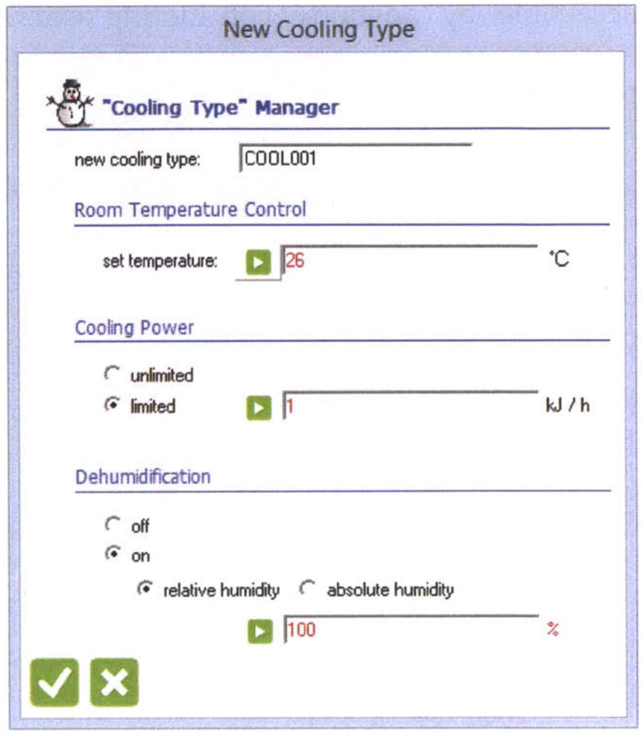


Figure 33: New Cooling Type

Internal gains can be defined by clicking the Gains button in the Zone Window. The Gains dialog box has very specific, predefined gain options that you can select from each menu. For people and computers, the scale refers to the number of people or computers. For artificial lighting gains, the type of lamp, related floor area, and convective part must be defined. Persons can also be added with varying levels of activity. All these types of gains can, and should often, be set on a schedule according to the operating hours of your building project. For design

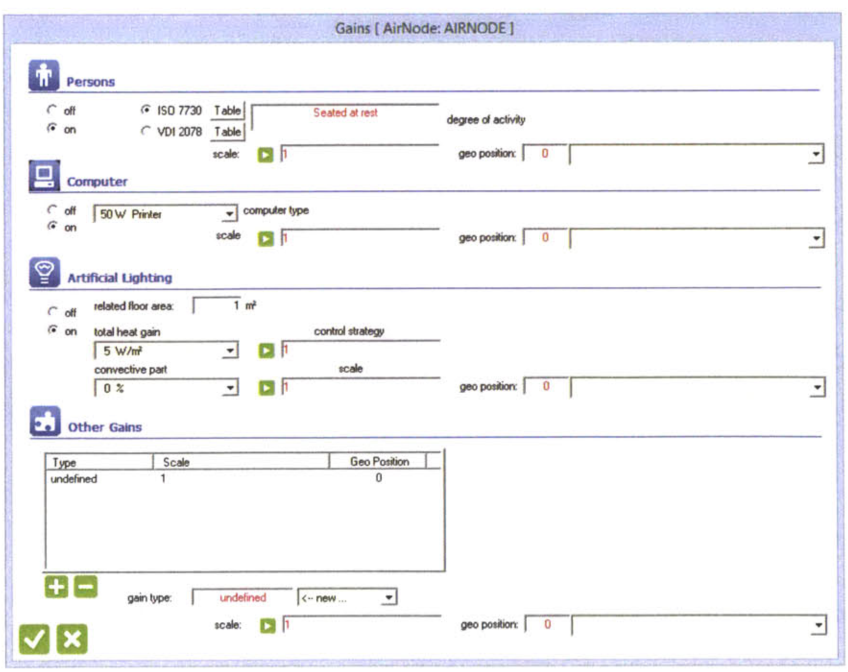
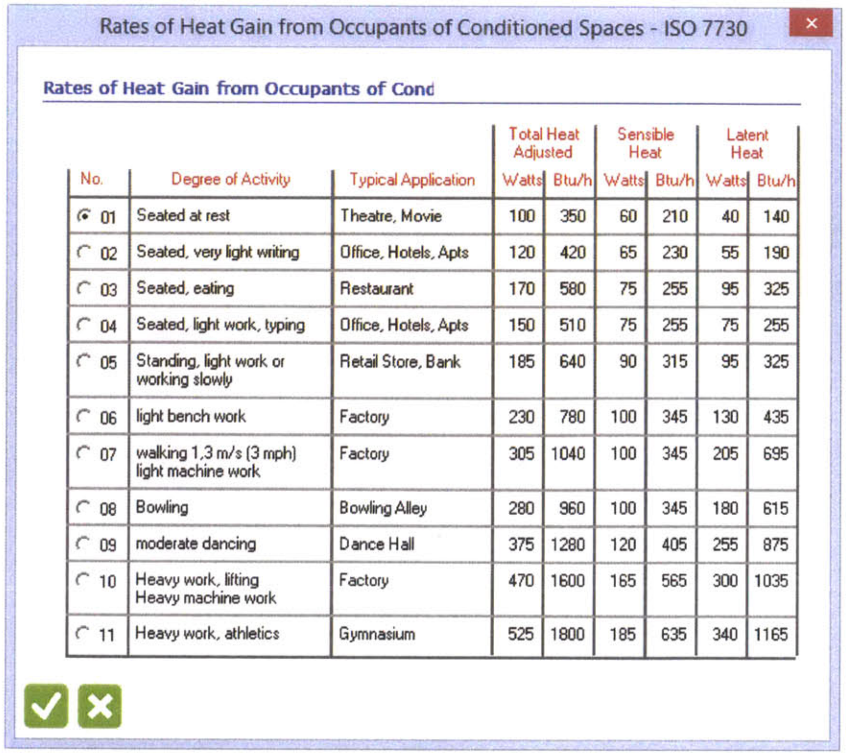


Figure 34: Gains

purposes, setting a schedule will be important, as each building generally has its own type of occupancy schedule. This will change from project to project based on the program and usage of the buildings.


Rates of Heat Gain from Occupants of Conditioned Spaces - ISO 7730

Rates of Heat Gain from Occupants of Cond

No.	Degree of Activity	Typical Application	Total Heat Adjusted Watts	Total Heat Adjusted Btu/h	Sensible Heat Watts	Sensible Heat Btu/h	Latent Heat Watts	Latent Heat Btu/h
01	Seated at rest	Theatre, Movie	100	350	60	210	40	140
02	Seated, very light writing	Office, Hotels, Apts	120	420	65	230	55	190
03	Seated, eating	Restaurant	170	580	75	255	95	325
04	Seated, light work, typing	Office, Hotels, Apts	150	510	75	255	75	255
05	Standing, light work or working slowly	Retail Store, Bank	185	640	90	315	95	325
06	light bench work	Factory	230	780	100	345	130	435
07	walking 1,3 m/s (3 mph) light machine work	Factory	305	1040	100	345	205	695
08	Bowling	Bowling Alley	280	960	100	345	180	615
09	moderate dancing	Dance Hall	375	1280	120	405	255	875
10	Heavy work, lifting Heavy machine work	Factory	470	1600	165	565	300	1035
11	Heavy work, athletics	Gymnasium	525	1800	185	635	340	1165

Figure 35: Rates of Heat Gain from Occupants of Conditioned Spaces – ISO 7730

Users can also add gains in addition to these predefined gains. A new gain type can be added by clicking new under Other Gains. This will direct you to the Gain Type Manager (see Figure 36). You must specify the radiative and convective power as well as the absolute humidity of the gain. Any new gain type definitions can also be saved for future modeling purposes.

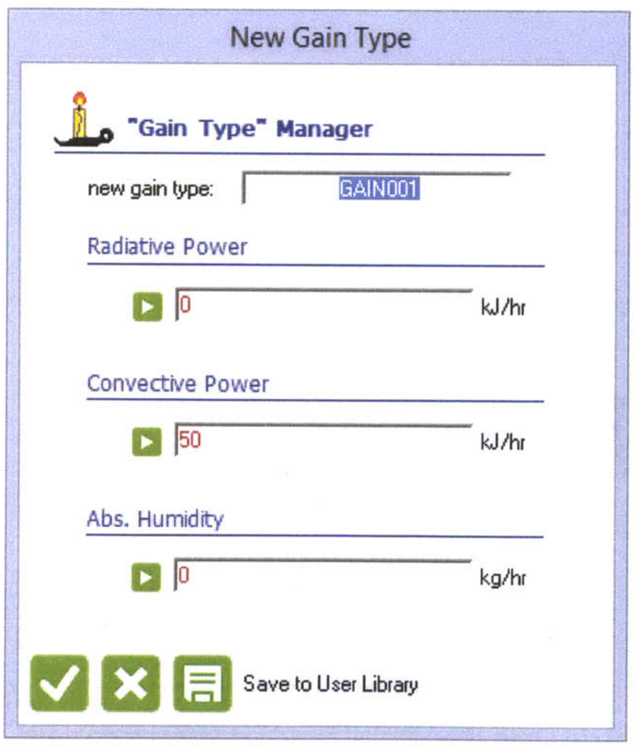


Figure 36: New Gain Type

Comfort is an optional setting for TRNBuild and its default is to be set off. Users can use the Comfort dialog box (see

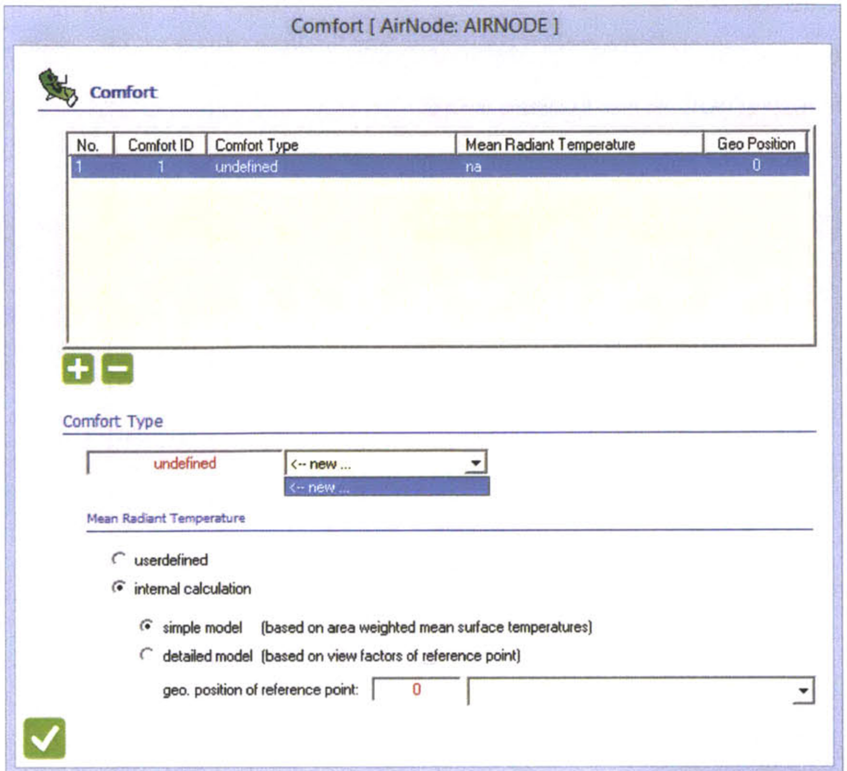


Figure 37: Comfort

Figure 37) in order to add, delete, and edit comfort types for their airnode. In order to initialize the comfort setting, you must select a model for defining the mean radiative temperature. These models can be either user-defined or an internal calculation, which can be further broken down into simple or detailed. I suggest a simple internal calculation for beginner TRNSYS users because it is calculated innately within the simulator.

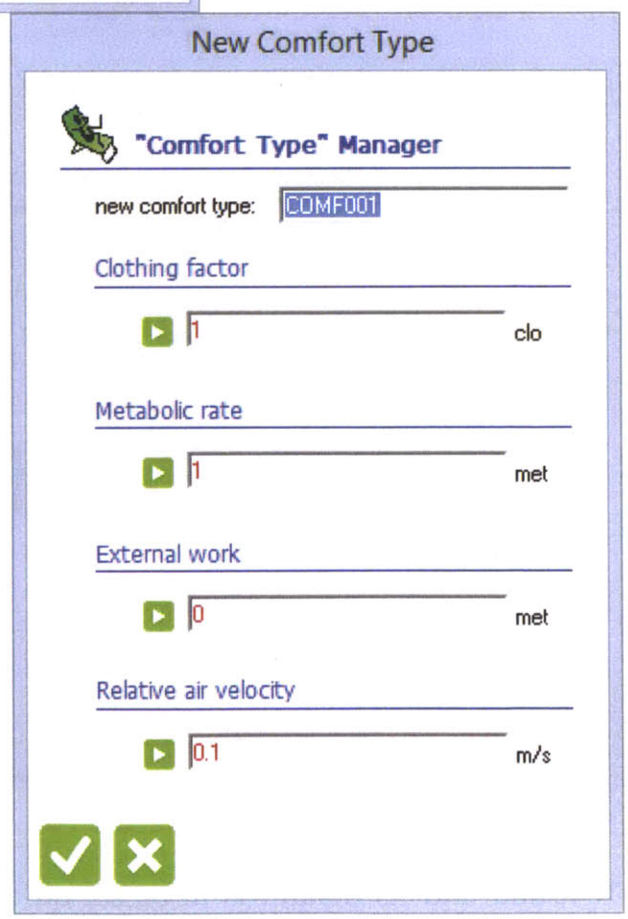


Figure 38: New Comfort Type

In order to create a new comfort type (see Figure 38), you must define the clothing factor, metabolic rate, external work, and relative air velocity for the comfort type. For those unfamiliar with clothing factors or metabolic rates, EN ISO 7730 can be consulted.[52] External work should typically be kept at 0 for beginner users. The relative air velocity is a figure that is individualized depending on the space in question.

9. MODELING BUILDING TYPOLOGIES

The first type was an office building, loosely modeled based on the Department of Energy (DOE) Medium Office reference building.[53] I chose not to model a specific office building, because I wanted my research to be generic enough to be applied. This form is standard as far as office buildings go, so this makes my research more pertinent to the general designer. I felt this would be more useful research than designing a specific Boston office.

As far as designing specifics are concerned, the Department of Energy specified a lot of the details of their design. However, I did take some liberties in my design. In the DOE reference office building, each floor has eight offices, four on one side of the building and four on the opposite side, separated by a central corridor. To make the model simpler, I combined the middle two of each set of offices on each side of the building. Because these offices are located between the corner offices, they experienced roughly the same thermal conditions. Thus, these offices can be approximated as a single zone.

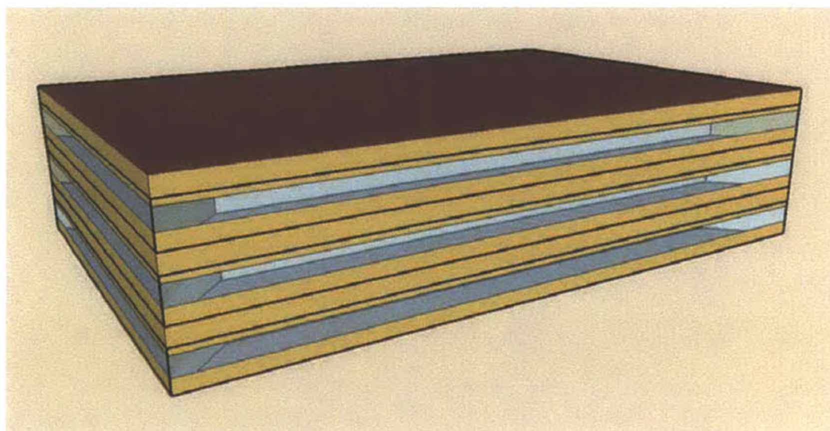


Figure 39[43]: DOE Medium Office reference building

The second was a residential building, loosely modeled based on my fraternity's (Sigma Alpha Epsilon) brownstone in the Back Bay. Our house lies on 165 Bay State

Road in Boston, Massachusetts, with a plain line of sight to the Charles River. It is nestled in a row of other dormitories and living groups. I chose to model the house because as a fraternity member, I have access to detailed information on the construction, layout, and program of the house. This will allow me to make informed design decisions. Though I was not involved in the design of the house, this is as close to that as possible. It is also a standard enough building type around Boston, such that people can relate to it.

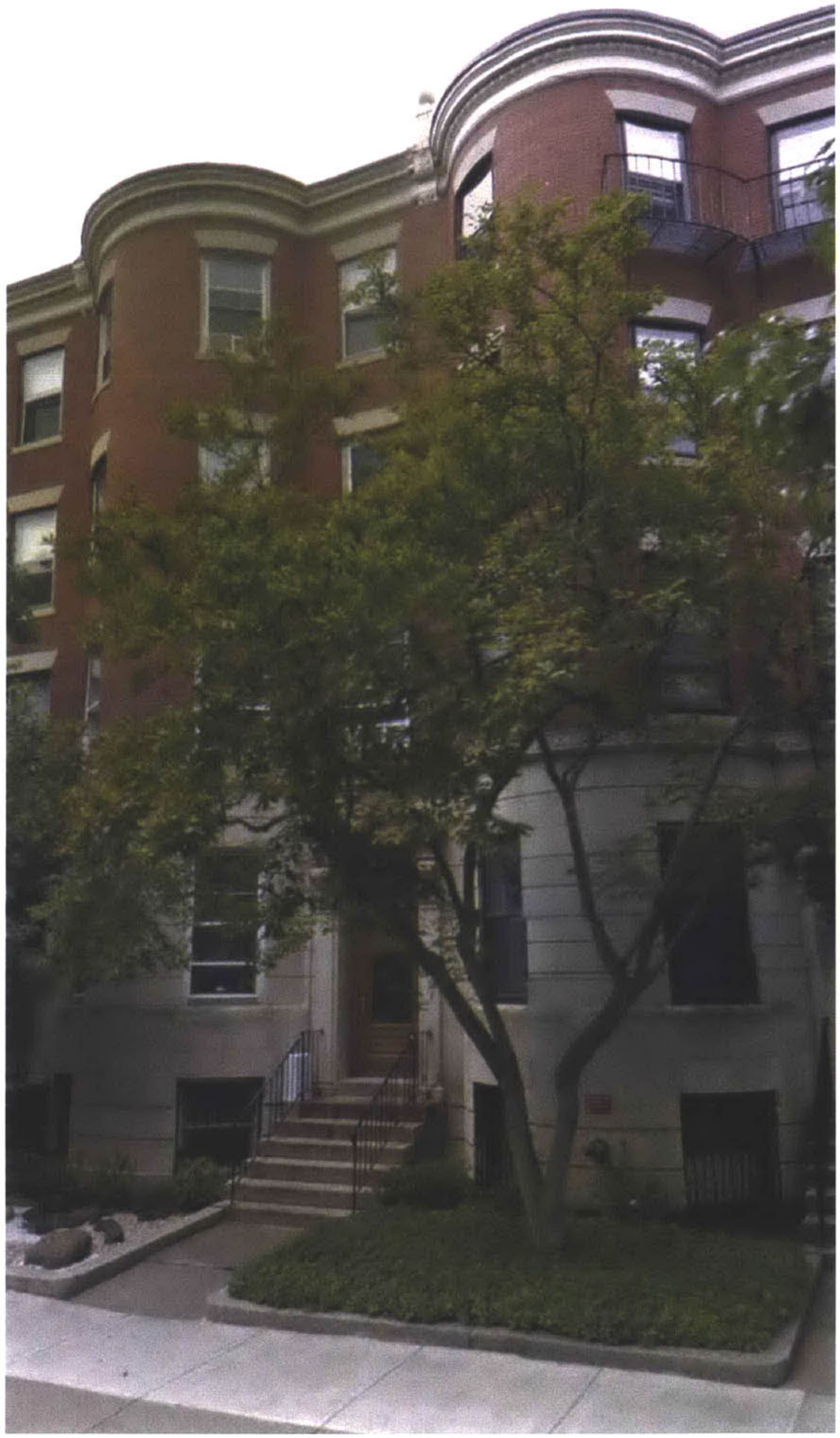


Figure 40: 165 Bay State Road

There are two sleeping areas on each side of the building separated by a central corridor. Based on the program of the space, it is reasonable to model the two separate sleeping areas on each side of the building as single zones. The thermal conditions in adjoining sleeping areas are similar enough such that we can save time and modeling effort by combining the two zones. This effort can instead be put towards interpreting simulation results, and using these interpretations to inform design decisions.

Along the same vein, I combined the two stairwells into a single stairwell within the central corridor by the same reasoning. Additionally, I simplified the geometry of the building. One important thing that I learned during my thesis research was that when using TRNSYS, it is important to simplify your model as much as possible. This will make it much easier to debug and run simulations, and will reduce modeling headaches in general. However, you must be careful not to oversimplify, as this will reduce the clarity of your work. Finding the balance between the two is a product of intuition and practice.

10. TRNFlow Interface

TRNFlow is a component of the existing TRNBuild graphical user interface (GUI) that functions such that air flow data for the model can be entered.[54] This allows user to make easy calculations of natural ventilation and other related air flow mechanisms such as passive night cooling and exhaust air shafts. Because it exists within the TRNBuild GUI, there are no new interfaces or programs to learn.

Below is the main TRNFlow interface (see Figure 42). Here you will define all the relevant information for your building project. In order to initialize this window, you must turn the State of TRNFlow from off to on. Then, you can begin to define airlinks. The types of airlinks are cracks, fans, straight ducts, flow controllers, large openings, and test data. Each airlink type has its own functions within your building. Essentially, which airlink types you use is entirely based upon your building's design. An example of an air link type manager is shown (see Figure 42).

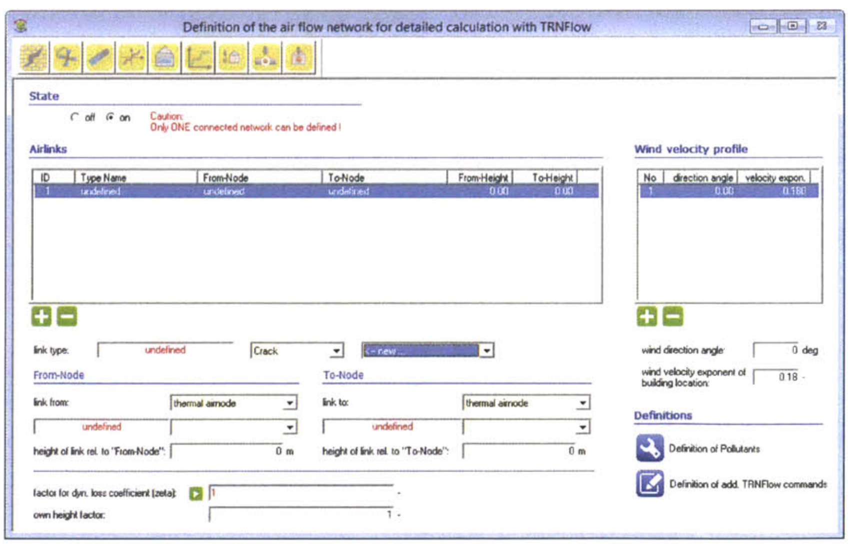


Figure 41: Definition of the air flow network for detailed calculation with TRNFLOW

Regardless of link type, you must specify which airnode your airlink is linking from and linking to. The node types are external, auxiliary, thermal, and constant pressure. Once again, as a designer, you will be the only person who can determine what type of node to assign to each airnode in your building. Typically, most naturally conditioned indoor spaces will be thermal airnodes and most external ventilation sources will be external airnodes. An example of an airnode manager is shown (see Figure 43).

The model-making process in TRNFlow is very similar to that of TRNBuild. The most valuable recommendation I can give to any designers

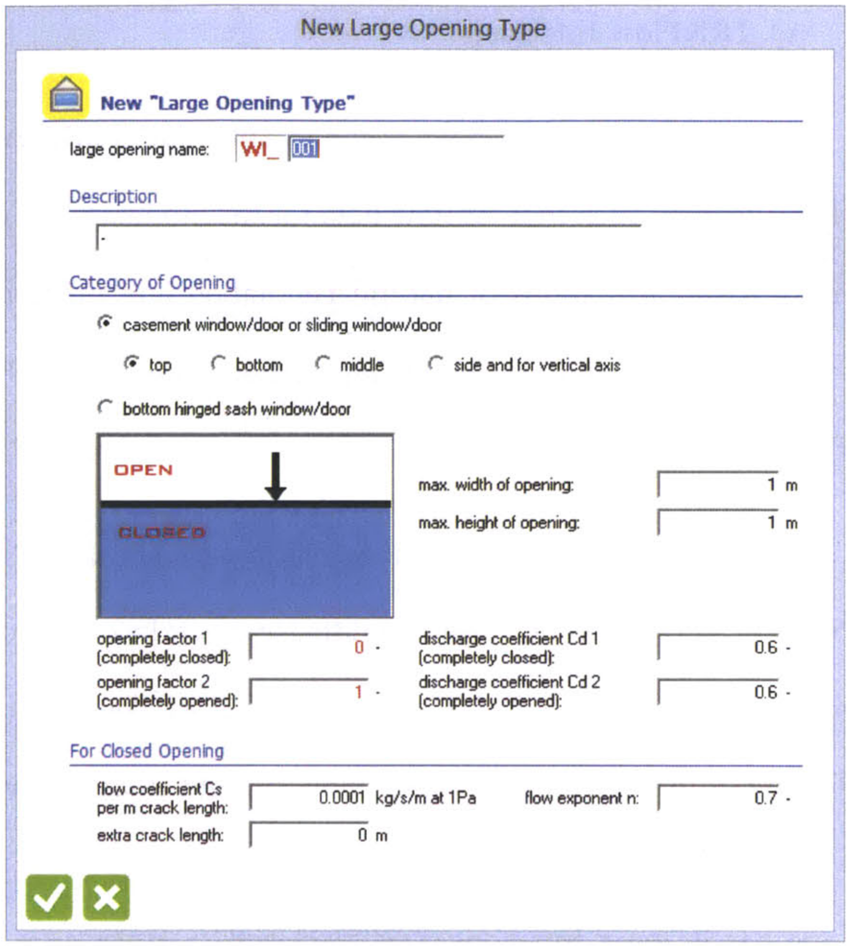


Figure 42: New Large Opening Type

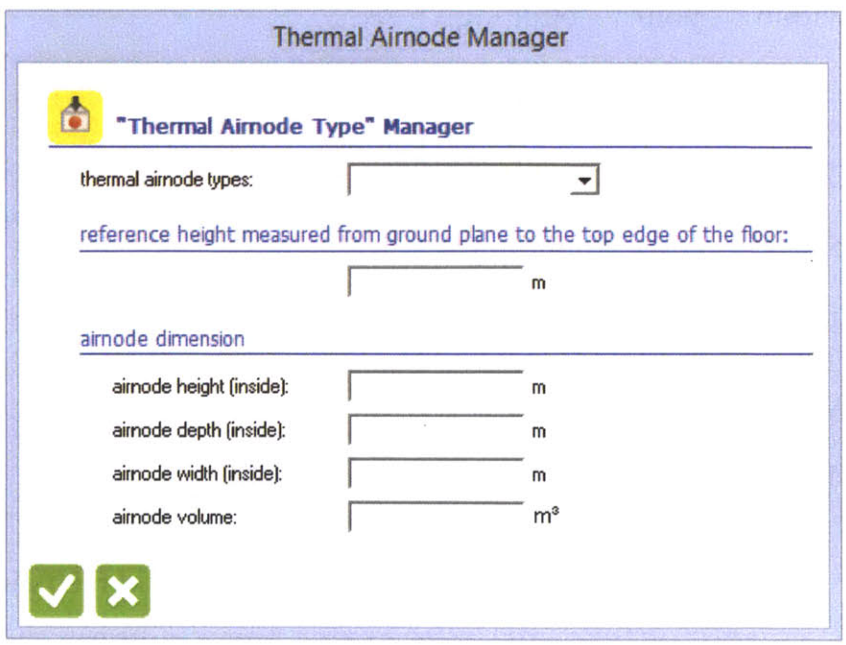


Figure 43: Thermal Airnode Manager

wishing to incorporate TRNFlow into their design is to be thorough and specific. The simulation process will be smoother and less painstaking if you are very deliberate and precise in your design decisions.

11. RESULTS

I initially modeled my buildings as standard, mechanically ventilated buildings to serve as a control. This exercise was more to familiarize myself with the modeling process using a more simplistic building. I ran a number of simulations to serve as a reference point, but I am much more interested in the results from the natural ventilation simulations. There is not much to be learned from the actual results of the simulations for the mechanically ventilated buildings, because this portion of my research was more of a confirmation that I could model properly in TRNSYS than it was an actual exploration of my topic. However, these models were also useful to come back to for verification purposes.

The real exploration begins when I run simulations for natural ventilation. I created new models of my building typologies that are fully naturally ventilated. I essentially modeled the buildings without any mechanical HVAC systems. Though this is obviously not practical for the entire year, I chose to do this in order to evaluate my buildings fully. For these types of simulations, I did not consider HVAC operating costs or energy expenditures because without an HVAC system, there is no such cost or expenditure.

I modeled my office building against the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) adaptive thermal comfort band. This band compares the prevailing monthly mean outdoor temperature to the indoor operative temperature in order to determine the appropriate range for acceptable thermal comfort conditions in occupant-controlled naturally conditioned spaces. However, there are a number of criteria that must be met in order for this assessment to be considered valid by ASHRAE. First and foremost, this method can only be used for naturally conditioned spaces strictly. This means that there cannot be any mechanical cooling or heating systems. Furthermore, occupants should be free to adapt their clothing, meaning the program of the space cannot limit them in this regard. Lastly, the prevailing mean outdoor temperature must be greater than 10° C and 33.5° C.

Immediately we can see that only four months of the year are acceptable for this analysis based on our climatic data of Boston (see Figure 44). These are the months from June to September. Of these months, August and September lie within the 80% acceptability limits, and June and July lie within the 90% acceptability limits. This means that 80% and 90%, respectively, of the occupants in the space are comfortable on average during this time period.

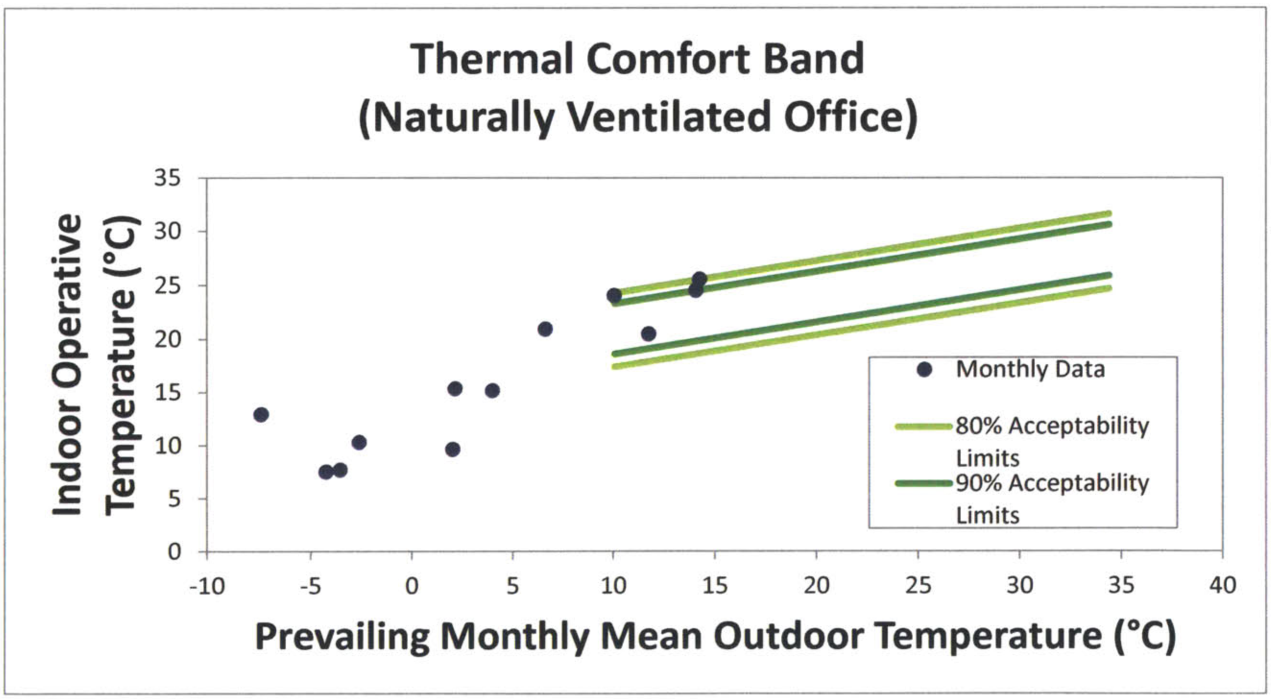


Figure 44: Thermal Comfort Band (Naturally Ventilated Office)

However, if we plot the same data for the naturally ventilated brownstone, we see a much different graph than that of the office (see Figure 45). The brownstone, as evidenced by the numbers, is unbearably hot during the summer months, despite all the windows being open. This data is consistent with my experiences living in the fraternity house during my summers as an undergraduate. It is insufferably hot in the SAE house in rooms without air conditioners.

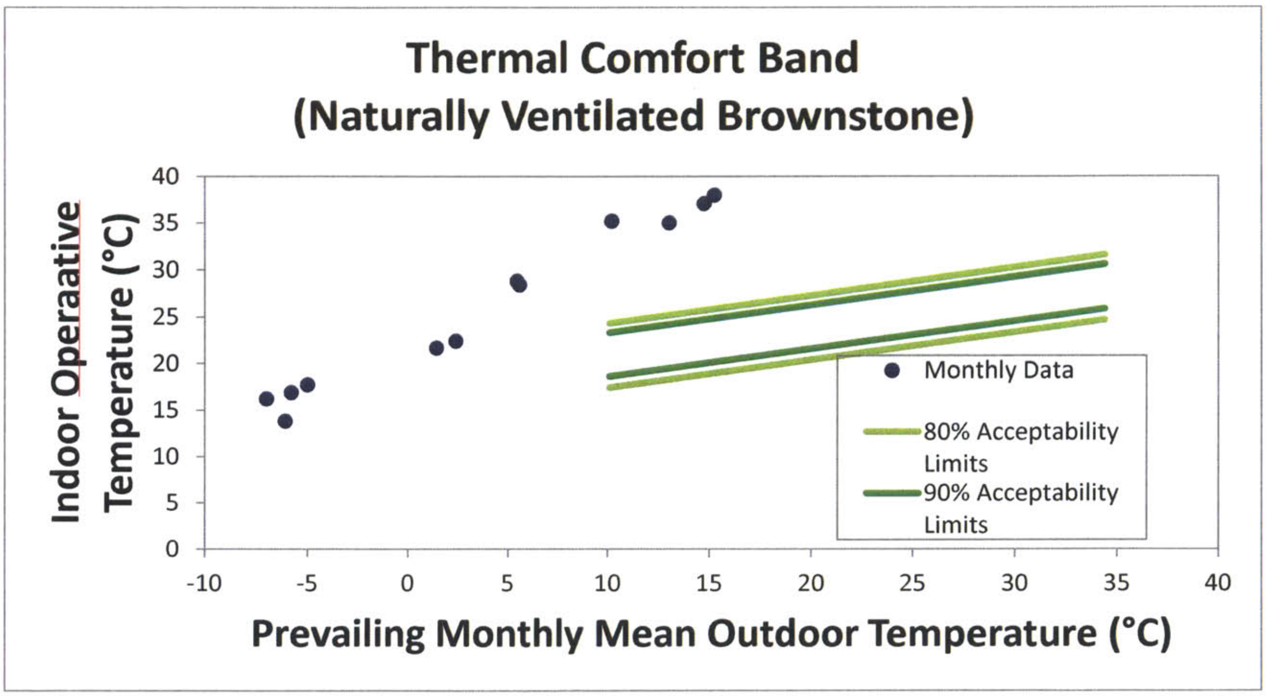


Figure 45: Thermal Comfort Band (Naturally Ventilated Brownstone)

To see a more detailed breakdown of what is going on during the summer months, I turn to the ASHRAE graphic comfort zone. This zone compares a building's indoor operative temperature to its humidity ratio. Based on this comparison, you can see whether or not a human is comfortable in your space. For the occupied summer months (those that exclude when the building is unoccupied), the naturally ventilated office is comfortable 83% of the time (see Figure 46).

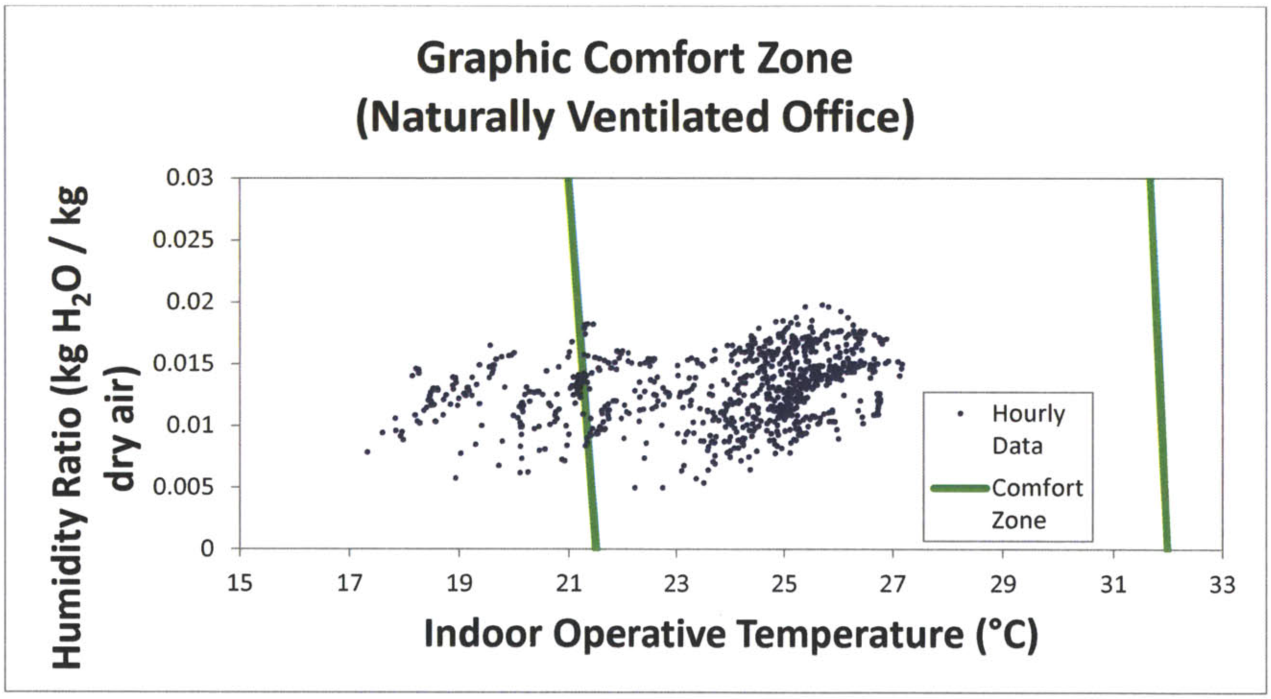


Figure 46: Graphic Comfort Zone (Naturally Ventilated Office)

Once again, however, the brownstone is a completely different story. During the summer months, occupants are never comfortable in the brownstone (see Figure 47). This may sound odd, because one would think that this should not be the case. Though it should not, the fact of the matter is that it is true. This holds very consistent with my experiences actually living in the house. As supported by the numbers, it is physically impossible for humans to be comfortable in the brownstone as it is currently designed.

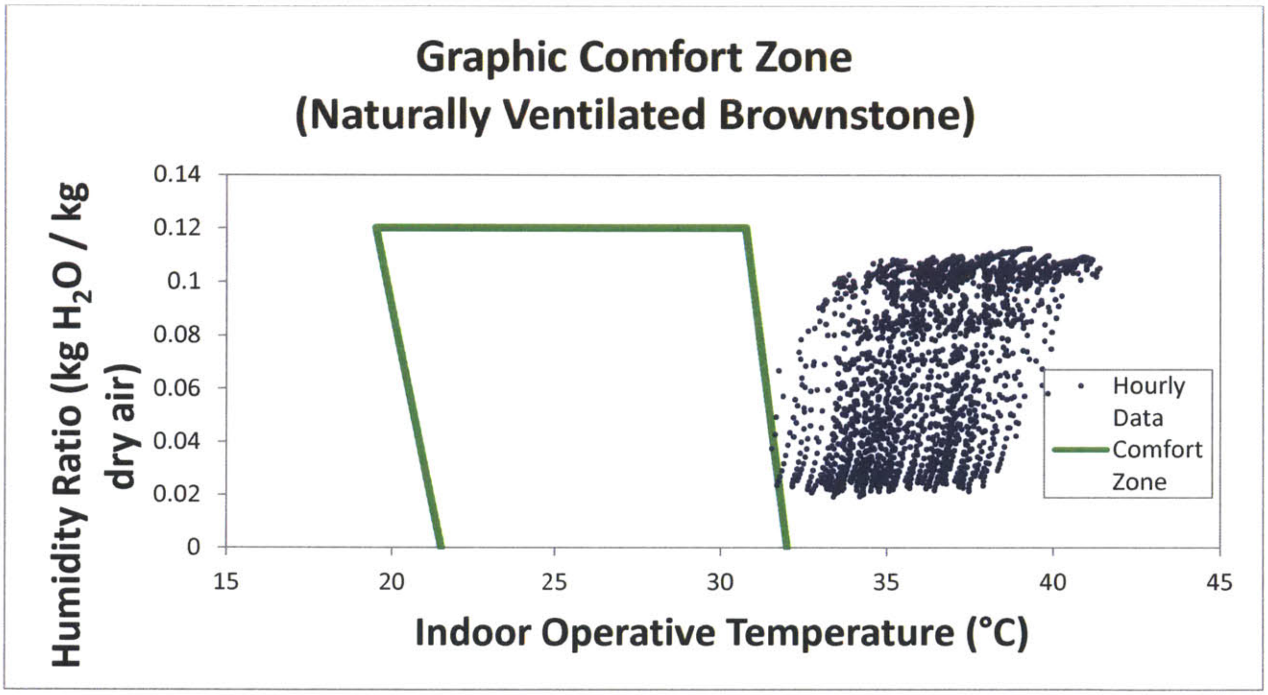


Figure 47: Graphic Comfort Zone (Naturally Ventilated Brownstone)

After performing an in-depth analysis of the brownstone (see Figure 48), I was able to come to several conclusions about the design of the brownstone in regards to natural ventilation. First of all, for the size of the space, the windows are much too small to promote proper wind-driven flow. Similarly, the egresses are not sufficiently sized or placed in order to allow wind as well. Additionally, buoyancy-driven flow is for all intents and purposes negligible in the brownstone. There is simply no exhaust point that would allow for it. With this information in mind, I proposed several solutions.

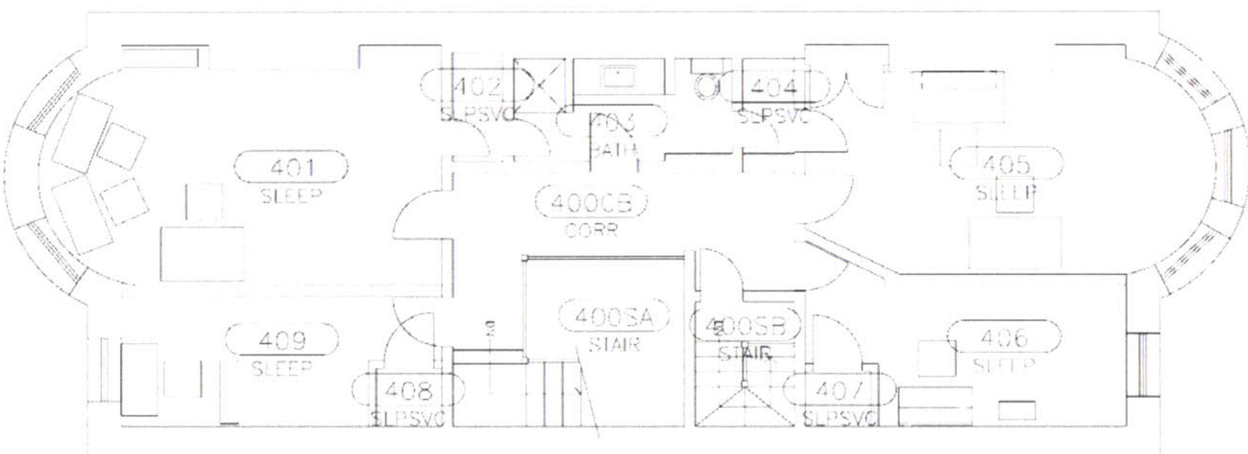


Figure 48[55]: 165 Bay State Road Plan

The first is to replace the typical casement windows found in most buildings with bottom hinged sash windows. This allows the building to keep its existing window framework while simultaneously doubling the amount of effective window area. Additionally, I altered the size of most doors in the house to accommodate more wind-driven flow. I then added a vented skylight system to the model. This not only allows an exhaust point for buoyancy-driven flow to travel up the large stairwell in the open-plan corridor, but also to allow some daylight into the space during the day. As the results will show, the added thermal gains from allowing more daylight into the space will not be significant enough to heat the space more than it is cooled from the new design improvements.

Below is the average indoor operative temperature for the modified brownstone plotted on the ASHRAE thermal comfort band. As you can see, from June to September, the monthly mean indoor operative temperatures for the brownstone are all within the 90% acceptability limits. This is quite evidently a vast improvement on the previous brownstone design from a thermal comfort standpoint, all with some relatively simple structural changes.

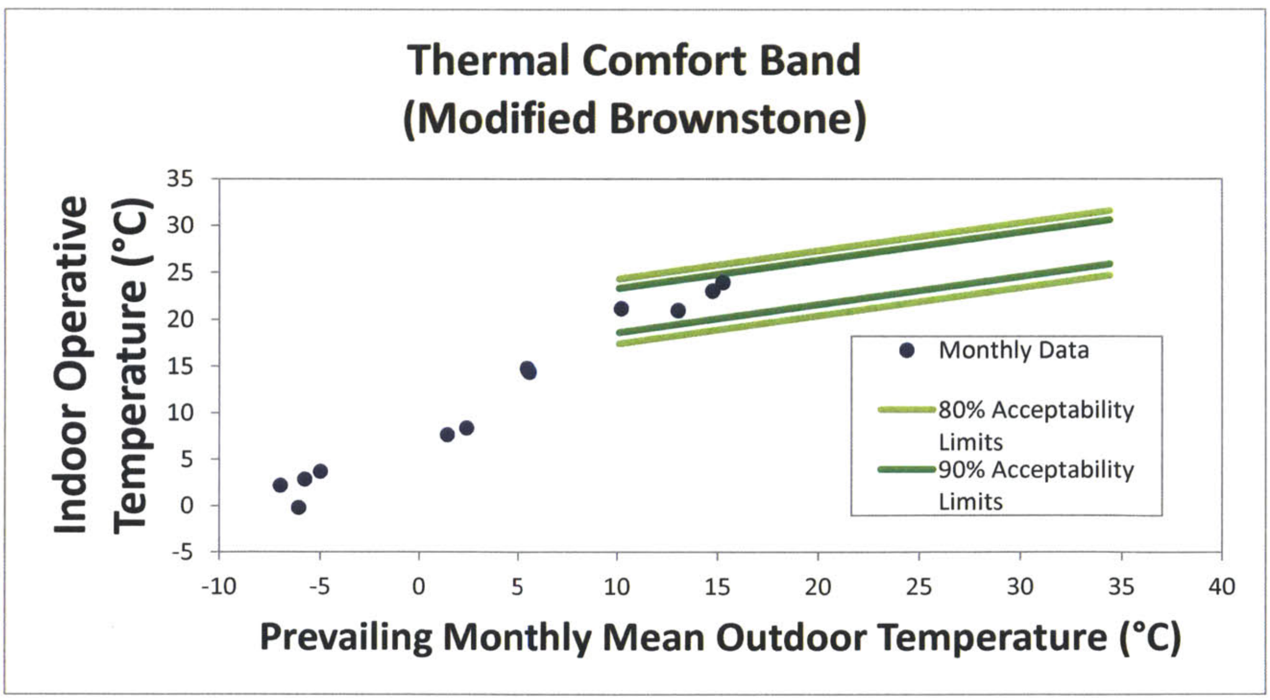


Figure 49: Thermal Comfort Band (Modified Brownstone)

I then plotted the indoor operative temperature against the humidity ratio as I did for my previous two buildings. We can again see that the occupied hours are largely within the graphic comfort zone. For the modified brownstone, occupants are comfortable 78% of the time. The other 22% of the time, the brownstone is actually now too cold. We now have the ability to close some of the windows in order to achieve comfort for all of the occupied hours. Considering that the brownstone was previously never comfortable, this is a very encouraging figure.

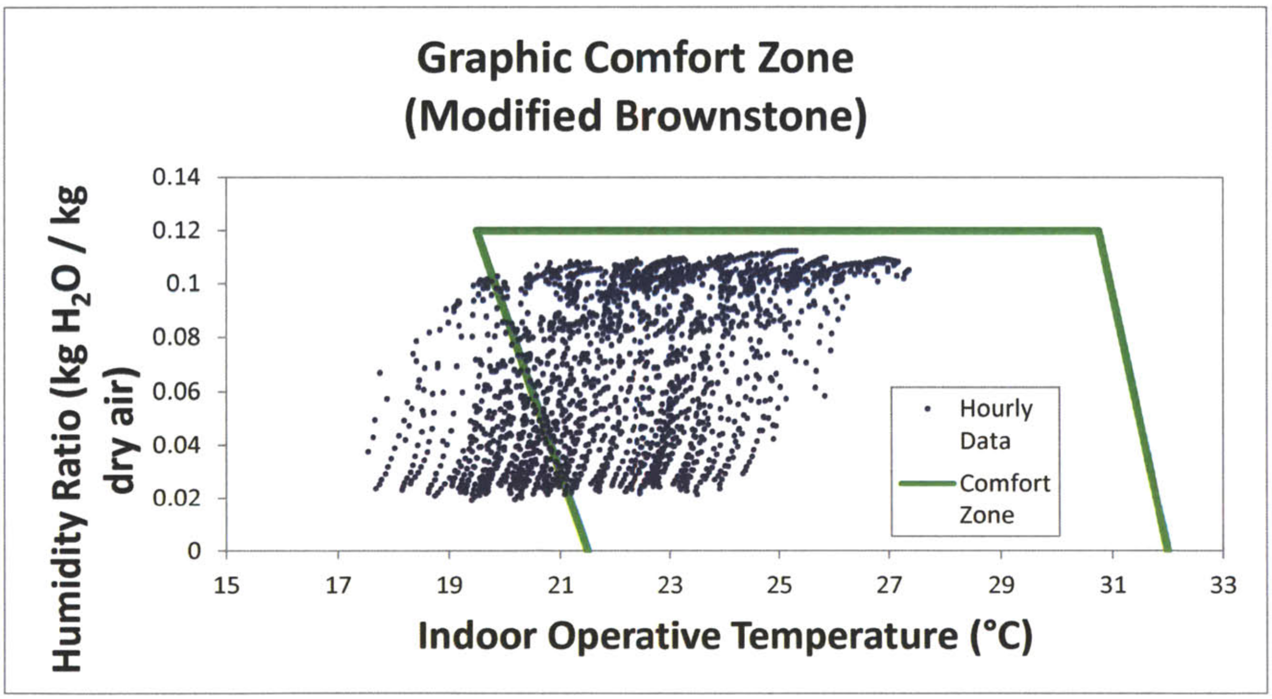


Figure 50: Graphic Comfort Zone (Modified Brownstone)

12. CONCLUSIONS

We are able to draw several conclusions from the success of my research. First and foremost, TRNSYS is quite obviously a useful simulation tool for the purposes of new design or for the redesign of pre-existing buildings. It allows you to run simulations in order to see quantitative effects of certain design changes prior to the changes going into effect. The ability to have this kind of foresight can be a powerful asset to any designer. Do note that the outputs a TRNSYS simulation can provide you with are not limited to those explored in my thesis project. The possibilities for utilizing technology in design are endless.

Furthermore, I believe that the ability of TRNSYS to connect design to data is a useful aspect that cannot be replicated by many other programs. Though there is still much work to be done in making programs such as TRNSYS more designer-friendly, my thesis can serve as a form of link between the more design-minded and the more technical-minded. With my clearly documented thesis research, running these TRNSYS simulations can be replicated by any designer using my iterative process. Results similar to mine can be easily achieved in a relatively straightforward way.

Eventually, we will be at the point where designers will be able to utilize such programs from the very beginning design stages. Until that point is reached, however, my work is not yet complete.

13. BIBLIOGRAPHY

1. United Nations Fund for Population Activities. Report on the United Nations Fund for Population Activities. [New York]: United Nations Fund for Population Activities., n.d. Print.
2. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision, http://esa.un.org/unup
3. "Overpopulation:." Effects of Overpopulation on the Environment and Society. n. pag., n.d. Web. 10 Dec. 2013.
4. CNN. Cable News Network, n.d. Web. 10 Dec. 2013.
5. Sonetti, G. Energy and Architecture - An Overview. Tech. N. pag: EDP Sciences, 2013. Print.
6. Annual Energy Review. Washington, DC: Energy Information Administration, Office of Energy Markets and End Use, U.S. Dept. of Energy, n.d. Print.
7. "Architecture 2030: Why?" Atom. n. pag, n.d. Web. 01 Nov. 2013.
8. U.S. Energy Information Administration Independent Statistics and Analysis. Washington, DC: U.S. Energy Information Administration, [2011]. Print.
9. Energy Information Administration Official Energy Statistics from the U.S. Government. [Washington, D.C.]: Energy Information Center, Dept. of Energy., n.d. Print
10. United States. Energy Information Administration. Energy Information Administration EIA : Eia.doe.gov : Official Energy Statistics from the U.S. Government. Washington, DC: Energy Information Administration, n.d. Print.
11. Perez-Lombard L., Ortiz J. et al., Energy and Buildings, 43 (2011) 255.
12. "IAQ Design Tools for Schools: Heating, Ventilation and Air-Conditioning (HVAC) Systems." EPA. Environmental Protection Agency, n.d. Web. 09 Dec. 2013.
13. Fundamentals volume of the ASHRAE Handbook, Atlanta, GA, USA, 2005
14. Designer's Guide to Ceiling-Based Room Air Diffusion, Rock and Zhu, ASHRAE, Inc., Atlanta, GA, USA, 2002
15. "IAQ Tools for Schools: Ventilation Energy: HVAC." EPA. Environmental Protection Agency, n.d. Web. 10 Dec. 2013.

16. Chen, Q. and Glicksman, L. (1999). Performance Evaluation and Development of Design Guidelines for Displacement Ventilation. Building Technology Program, Massachusetts Institute of Technology. Cambridge, MA.
17. Yudelson, Jerry. "Water and Energy Use in High-Performing Buildings." Environmental Design & Construction (2013): n. pag. Print.
18. Wood, Antony, and Ruba Salib. "Natural Ventilation in High-Rise Office Buildings." Taylor and Francis (2013): n. pag. Print.
19. "Why Energy Efficiency Upgrades." Better Buildings Neighborhood Program:. N.p., n.d. Web. 10 Dec. 2013.
20. "Buildings Energy Data Book." Buildings Energy Data Book. N.p., n.d. Web. 09 Dec. 2013.
21. "The Architectural Review." The Architectural Review 1205 (1997): n. pag. Print.
22. "Willis Carrier - The Invention That Changed The World - 1876-1902." Willis Carrier - The Invention That Changed The World - 1876-1902. N.p., n.d. Web. 10 Dec. 2013.
23. Kleiven, Tommy. Natural Ventilation in Buildings: Architectural Concepts, Consequences and Possiblities. Tech. N. pag: n. pag, 2003. Print.
24. McCutchan, Gordon C. Cooling by Natural Ventilation. Tech. Cambridge: Massachusetts Institute of Technology, 1950. Print.
25. Wigginton, M. and Harris, J. (2002) Intelligent Skins, Architectural Press, London.
26. Emmerich, Steven J., W. Stuart Dols, and James W. Axley. "Natural Ventilation Review and Plan for Design and Analysis Tools." National Institute of Standards and Technology (2001): n. pag. NISTIR. Web. 1 Nov. 2013.
27. Architectus. "Natural Ventilation." Sustainability. Architectus, 2013. Web. 19 Sept. 2013.
28. Linden, P. F. (1999). "The Fluid Mechanics of Natural Ventilation". Annual Review of Fluid Mechanics 31: 201-238.
29. "Natural Ventilation." Green Building Tech -. n.pag., n.d. Web. 10 Dec. 2013.
30. "Wind and Natural Ventilation Analysis." Vimeo. n.pag., n.d. Web. 10 Dec. 2013.
31. "Design Considerations for Naturally Ventilated Buildings." Design Considerations for Naturally Ventilated Buildings. n. pag., n.d. Web. 10 Dec. 2013.

32. "Commercial Inspection Tips: The Building Envelope - How Does It Stack Up?" December 2013. n.pag., n.d. Web. 10 Dec. 2013.
33. "File:Natural Ventilation High-rise Buildings.svg." - Wikimedia Commons. User:Fred the Oyster, 07 Apr. 2010. Web. 01 Nov. 2013.
34. Mendell, M. J., W. J. Fisk, et al. (1996). Elevated Symptom Prevalence Associated with Ventilation Type in Office Buildings. Epidemiology, 7 (6): 583-589.
35. Fisk, W. J. and A. H. Rosenfeld (1997). Estimates of Improved Productivity and Health from Better Indoor Environments. Indoor Air, 7: 158-172.
36. "Indoor Air Quality Scientific Findings Resource Bankhttp://www.iaqscience.lbl.gov/." Indoor Air Quality Scientific Findings Resource Bank : Health and Economic Impacts of Building Ventilation : Some Disadvantages of Increased Ventilation. n. pag., n.d. Web. 10 Dec. 2013.
37. "The Architects' Journal." The Architects' Journal December 1 (1994): n. pag. Print.
38. E. Gratia, A. De Herde, Is day natural ventilation still possible in the office buildings with a double-skin façade? Building and Environment 39 (4) (2004)
39. A.M. Jones, EDSL Ltd., TAS, Software package for the thermal analysis of buildings, 13/14 Cofferidge Close, Stony Stratford, Milton Keynes, Mk11 1BY, UK.
40. "Natural Ventilation for the Prevention of Airborne Contagion." PLOS Medicine:. N.p., n.d. Web. 10 Dec. 2013.
41. "Assessing Building Performance in Use 4: The Probe Occupant Surveys and Their Implications." Bordass and Leaman. N.p., n.d. Web. 13 Dec. 2013.
42. ROWE D., FORWOOD B., DINH C. and JULIAN W., Occupant Interaction with a Mixed Media Thermal Climate Control System Improves Comfort and Saves Energy, AIRAH meeting, Sydney , 1998
43. "Energy.gov." *Commercial Reference Buildings*. N.p., n.d. Web. 22 May 2014.
44. "Features." Suite of Tools -. N.p., n.d. Web. 23 Apr. 2014.
45. "CONTAM Overview - What Is CONTAM?" CONTAM Overview - What Is CONTAM? N.p., n.d. Web. 23 Apr. 2014.
46. "About CoolVent - CoolVent." CoolVent. N.p., n.d. Web. 23 Apr. 2014.
47. "CoolVent - The Natural Ventilation Simulation Tool by MIT." CoolVent. N.p., n.d. Web. 23 Apr. 2014.

48. "EnergyPlus." Building Technologies Office: Energy Simulation Software. N.p., n.d. Web. 23 Apr. 2014.
49. "TRNSYS - Official Website." TRNSYS - Official Website. N.p., n.d. Web. 23 Apr. 2014.
50. "TRNFlow – AIRFLOW SIMULATION IN BUILDINGS." TRANSSOLAR Software. N.p., n.d. Web. 23 Apr. 2014.
51. "Pricing & Ordering." Pricing Info -. N.p., n.d. Web. 23 Apr. 2014.
52. "Home." ISO 7730:2005. N.p., n.d. Web. 23 Apr. 2014.
53. "Energy.gov." Commercial Reference Buildings. N.p., n.d. Web. 23 Apr. 2014.
54. "TRNFlow – AIRFLOW SIMULATION IN BUILDINGS." TRANSSOLAR Software. N.p., n.d. Web. 21 May 2014.
55. "Mapping MIT Room by Room." *MIT Facilities*. N.p., n.d. Web. 22 May 2014.