Cooling multi-family residential units using natural ventilation in the Central U.S.

by

Roby Rai

B.Arch., Tribhuvan University, Nepal, 2011

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Architecture
College of Architecture, Planning and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2016

Approved by:

Major Professor
Michael D. Gibson

Copyright

Abstract

The use of Natural Ventilation (NV) to cool buildings in mixed climates can conserve significant cooling energy. In mixed climates it is particularly important during the fall and the spring, where appropriately designed buildings should use very little energy for heating or cooling. Natural ventilation is also important in residential buildings, where internal heat gain can be managed, making cooling by natural ventilation easier. Earlier investigations have clearly shown the economic, social, and health benefits of the use of NV in built environment. Studies have shown that increased airflow or air-speed during ventilation can bring a significant rise in comfort range which further reduces the cooling energy required to maintain comfort. The climatic data of the central United States (U.S.) shows that the availability of frequent high speed wind and favorable seasonal humidity conditions make natural ventilation feasible in late spring and early fall, where NV can offset most of the cooling demand for a home or multifamily residential unit, though it is not possible to maintain thermal comfort during the entire summer with NV alone.

In mixed climates, NV for multifamily residential units has not been investigated thoroughly. According to 2009 International Residential Code, multifamily residential buildings are typically designed to use a code minimum amount of operable or ventilating windows, 4% of the floor area being ventilated, while also using lightweight construction methods (such as wood framing) that is prone to fast thermal response during the overheated periods of the year. While climate may favor the use of NV in these building types, the sizing of windows and the building construction type limit the potential to save energy with NV.

This study hypothesized that the maximum benefits from NV in the climate of the central U.S. requires further optimization of window openings beyond the energy code minimum, and a

construction system incorporating mass that can slow thermal response during overheated periods. During the study, the climatic data of the central US was scrutinized to understand the most suitable time frames where NV could be applied in order to maintain indoor thermal comfort in various construction systems in residential buildings: mainly lightweight using wood framing, and heavier construction using concrete and masonry. The location of the housing unit, first level or second level, was also examined to account for the differences in thermal gains and losses as a result of ground coupling and additional heat gain from the roof. Further, computational fluid dynamics evaluated the comfort achieved with different ventilation areas. Change in comfort hours by using NV tested the practicability of the use of NV to maintain indoor thermal comfort for different scenarios. The study concluded with design recommendations for building orientation, operable window size, and construction type as these factors relate to thermal comfort and the optimization of multifamily residential buildings to utilize NV for energy savings in the U.S.

Table of Contents

List of Figures

List of Tables

Acknowledgements

This thesis would not have been possible without the guidance, motivation, and tireless effort of my major professor, Prof. Michael D. Gibson. I’d like to acknowledge his unwavering support and pedagogical expertise that guided me to the completion of this thesis.

Similarly, Prof. Gary J. Coates’ seminar classes stirred me to contemplate about the world energy scenario, sustainability and climate change, kindling my curiosity and awareness of energy efficiency, energy conservation, and sustainability.

I am thankful to all the thesis committee members: Prof. Michael D. Gibson, Prof. Gary J. Coates, and Prof. R. Todd Gabbard for their proper guidance and continuous support during the course of this study.

Lastly, I’d like to acknowledge the time, energy, and brainpower expensed by Abhisesh Lamsal, Avantika Gurung, and Shreejika Shrestha who assisted me tackle various problems during the course of this study.

Dedication

I would like to dedicate this achievement to my parents and sister.

Chapter 1 - Natural Ventilation for Cooling

Introduction

In recent decades, the most daunting task in front of the human civilization is to conserve energy, decrease exploitation of non-renewable resources, and reduce and repair environmental damages; requiring societal changes in the direction of sustainability, resilience, stability, security, and adaptation (James 2014). Sustainability creates and maintains the conditions for humans and the environment to co-exist while maintaining a productive harmony that can support today's as well as future's generations (U.S. EPA 2016). There has been economic boom and technological advancements since the start of industrial revolution. Fueling this progress is only possible with a supply of uninterrupted energy. Most sources of energy used today are exhaustible. The extensive use of renewable resources for energy generation has not materialized at a national scale until recently. According to an Energy Information Administration's (EIA) report in 2016, the use of renewable energy for electricity generation, in the United States (U.S.) alone, remains less than 13% of the total annual electricity generation (Martin and Jones 2016). In order to more fully utilize renewable energy in our society, we must change our energy consumption habits to scale more appropriately with renewable energy.

Residential buildings of the US are responsible for 30% of the total annual energy consumption, out of which, on average, 6% of the total energy is directed at air conditioning (AC) used to maintain indoor thermal comfort and air quality (EIA 2016a). The energy consumed by AC in residential buildings can rise to as high as 25% of the annual energy consumption in states with a high cooling demand like Florida, Texas, and Arizona (EIA 2016b). Electricity demand in many states peaks during the cooling season, further straining electricity infrastructure and furthering reliance on concentrated sources of energy from fossil fuels. It would be a great achievement towards sustainability to reduce heat gain and cooling loads in residential buildings, so that indoor thermal comfort could be attained with using less energy and renewable energy sources. Passive design techniques are an important method of maintaining indoor thermal comfort and reducing cooling loads using less energy (Santamouris and Asimakopoulos 1996, p. 35).

Natural ventilation, which is totally powered by wind, has been in practice since the start of civilization, whereas mechanical systems have only existed for 150 years, and in residential buildings for much less time (Etheridge 2011, p. 30). Mechanical systems may be the only way to maintain thermal comfort in buildings in extreme conditions. However, the increasing reliance on mechanical systems over natural ventilation is a serious issue warranting contemplation. The use of natural ventilation should be prioritized over mechanical systems where possible because it conserves energy and natural resources, maintains indoor air quality, and reduces environmental impacts (Li and Heiselberg 2003, p. 3). Long before the invention of Heating Ventilation and Air Conditioning (HVAC), people in tropical and arid environments around the world, such as Egypt, thrived with natural ventilation only, providing evidence that if designed and operated properly, natural ventilation can provide thermal comfort (Fathy 1986).

In the climate of the Central U.S., natural ventilation can be designed and integrated to offset most of the summer cooling demand for multi-family residential buildings. While helping to conserve energy, natural ventilation also offers benefits to building occupants’ health in several dimensions. Prevailing building codes mandate the use of ventilation windows; Section R303 of the International Residential Code (IRC) of 2012 advises that residential buildings must have a minimum opening area equivalent to 4% of the total floor area being ventilated. However, the application of building codes comes with limitations. There should be adjustments made in practice when natural ventilation is integrated, in order to recognize unique geographic, climatic, and site-specific environmental conditions; this is true for the central U.S. where natural ventilation practice should recognize these factors. Apart from the codes, choices regarding the building construction system, orientation, and use of external shading devices, can contribute to further reducing the cooling load of residential buildings, and broadening the impact of natural ventilation for a specific building.

This study will consider climatic conditions of the state of Kansas, one of Central U.S. states, to evaluate the impact of the ventilation areas specified by IRC code for cross ventilation, a type of natural ventilation, to cool residential buildings. The study will consider possible modifications to practice that may be useful for a unique climatic condition of Kansas. Furthermore, the effects of building orientation, the use of external shading devices, and the ratio of window area to overall exterior wall area (commonly known as window-wall-ratio or WWR), on indoor summertime thermal comfort will be examined. The role of different construction systems incorporating mass to maintain indoor thermal comfort will also be demonstrated. In the process of this study, it is anticipated that a combination of ventilation area, reduction of solar gains through appropriate orientation and shading, and incorporation of mass in construction will suit the climatic conditions of Kansas best for cross ventilation in the cooling season. Such recommendations would potentially decrease the use of HVAC in multi-family housing, conserving energy and contributing to sustainability.

The Energy Scenario

On average, a fifth of the total electricity consumed by residential buildings in the US is used in air conditioning. In the year of 2015, natural gas, crude oil, and coal produced nearly 67% of the total energy in the U.S., which is graphically represented in Figure 1-1 . These sources are the primary producers of green-house-gases (GHGs) which traps solar radiation inside the earth's atmosphere and raises global temperature. Global warming has become an alarming problem that, if unchecked, will slowly alter the balance of ecosystems, or even threaten the existence of many sensitive organisms. Therefore, we can state that the relationship between energy usage and environmental balance are closely linked.

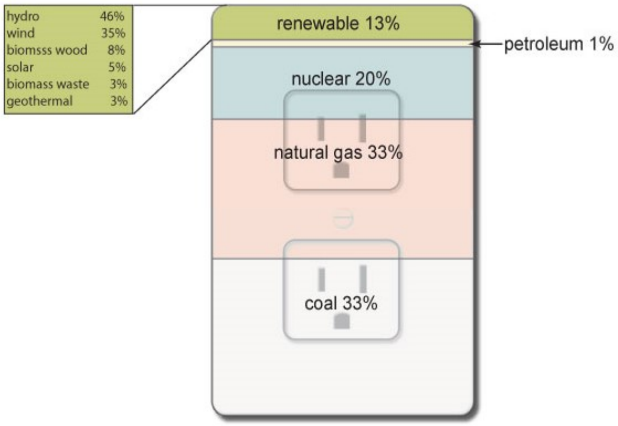


Figure 1-1 Sources of U.S. electricity generation, 2015

Source: (EIA 2016a)

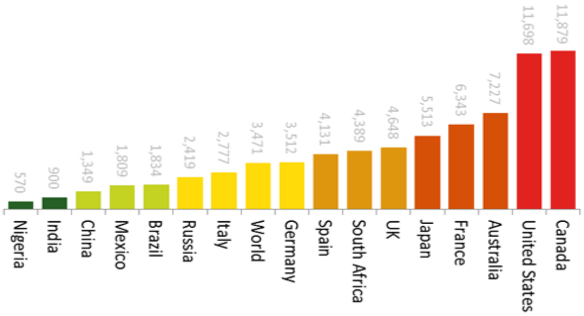


Figure 1-2 Household Electricity Consumption (kWh/year)

Source: Enerdata via World Energy Council

Most of the developed countries like Canada, the US, Australia have relatively high per capita energy consumption. These countries could make interventions to restore environmental balance and lead the world as energy conserving nations. If commitments are made to reduce energy consumption, a priority could be given to research and development of more efficient mechanical systems, and increase the production of energy from renewable energy sources.

Implementing passive building design, and improving occupant behavior can conserve energy as well. Switching to renewable energy as the primary energy source around the globe is important environmentally. Similarly, the Intergovernmental Panel for Climate Change (IPCC) assessment report aptly points out the environmental benefits of embracing passive design techniques in building construction (Intergovernmental Panel on Climate Change 2015). Passive design strategies utilize freely available energy source to provide comfort instead of consuming nonrenewable resources (Bainbridge and Haggard 2011, p. 4). Daylighting, natural ventilation, and solar power are among the most common passive design strategies.

Energy conservation and energy efficiency date back to the oil embargo of the 1970s, which blatantly exposed the finite nature of many energy sources. During the 1980s, initial efforts to conserve energy in buildings by emphasizing energy efficiency backfired, when increased insulation and building tightness led to increased dependency on mechanical systems and resulted in sick building syndrome (SBS) and other building related sicknesses for occupants. After several amendments through the 1990s, the importance of balancing energy efficiency with ventilation and indoor environmental quality was finally become understood (Santamouris and Allard 1998). Santamouris and Allard state, while designing energy-conscious buildings, the balance of two aspects are to be considered:

- A suitable building envelope possessing good thermal performance, and incorporates the use of appropriate heating, cooling, daylighting techniques.
- A good indoor climate offering thermal comfort, effective ventilation, and good indoor quality

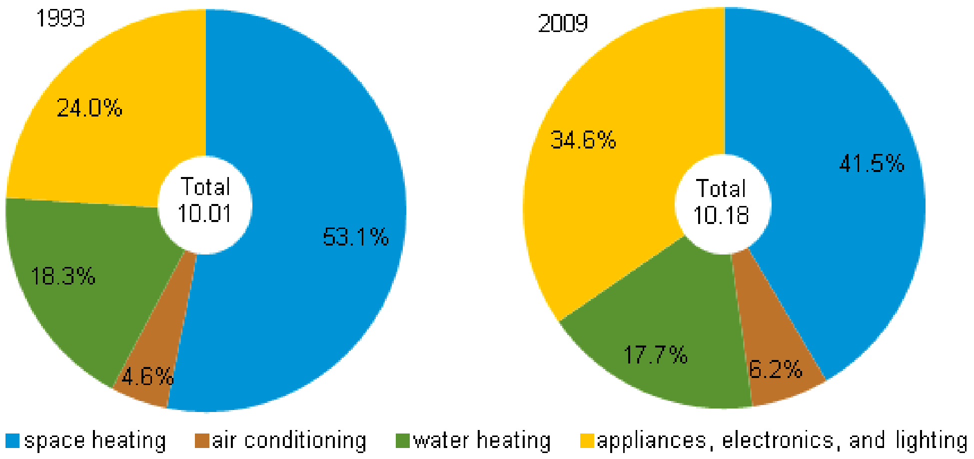


Figure 1-3 Energy Consumption in homes by end uses (Quadrillion Btu and Percent)

Source: (EIA 2016b)

Thus it is important to achieve energy conservation in buildings while also maintaining comfort and healthy indoor environment. To achieve such conservation, the building envelope along with techniques of cooling, heating and daylighting are important aspects to be considered. In recent decades, advancements in building technologies have resulted in energy conservation (see Figure 1-3), where energy consumption for HVAC has dropped from 74% of the total energy in 1993 to 66% of the total energy in 2009, though the total energy consumption has increased slightly (EIA 2016b). It is clear from the Figure 1-3 that with all of the technological advancements, homes in 2009 were using 2% more energy than in 1993 and cooling and lighting energy use is increasing.

Energy codes in the U.S. are getting increasingly stringent, mandating prescriptive energy efficiency measures, such as minimum insulation levels, that are further aligned with climate regions. It is necessary to understand building science and systems to design buildings that meet such energy codes. Building performance can be optimized by a combination of passive strategies that address the building envelope, and higher efficiency thermal control systems; in combination, these measures reduce energy usage (Gensler 2016). For reducing mechanical cooling energy, one important passive strategy is the use of natural ventilation for cooling and fresh air.

Natural Ventilation

Deliberate introduction of outdoor air into a building is known as ventilation. It can be of two types: natural and mechanical. The introduction of outdoor air into the building through windows, doors, stacks, and other apertures in building envelop is natural ventilation, a process that uses natural wind-driven forces or thermal buoyancy to drive flow (Etheridge 2011). Fresh, ventilating air from the outside replaces air inside the building, exhausting internal heat gain and diluting pollutants that can affect indoor environmental quality. Inlets and outlets for natural ventilation can be placed in accordance to the desired pattern of air flow inside a building. A condition where inlets and outlets are placed on opposite sides of a building, with outdoor wind driving air flow, is known as cross ventilation, a strategy known to be the most effective individual natural ventilation strategy (DeKay and Brown 2013).

According to Santamouris and Allard (1998), the use of natural ventilation during the daytime has three objectives:

- Cooling of the indoor environment by exhausting heat gains and replacing interior air, as long as the outdoor temperature is lower than the indoor.
- Cooling of the building envelope.
- Direct cooling of the human body by physiological (evaporative, and convective) cooling

Natural ventilation is possible as a result of naturally created pressure differentials on the two exterior environments at the inlets and outlets. The processes involved in natural ventilation can be divided into two fundamental steps. The first step is the passage of outdoor air through inlets into the building. The second step is the motion of the flowing air inside the building before being exhausted to the outdoors. The first priority is given to the pattern and magnitude of the air involved in the envelop flow rate. The next priority is given to achieving satisfactory internal air motion while the air is circulating inside the building (Etheridge 2011). The optimum pattern and magnitude can be achieved depending on the temperature and speed of the air inside building, and the resultant perception of satisfaction among the occupants inside that building. Similarly, satisfaction due to internal air motion is related to the amount of flow or turbulence of the air flow, which is perceived by occupants and directly relates to the satisfaction and comfort.

Natural ventilation has limitations in its application, because it can be used for cooling during overheated periods only when temperature and humidity levels fall below the threshold of comfort. Thus high humidity and temperature make some climates unfavorable for the applicability of natural ventilation for cooling or even for indoor air quality, given modern comfort criteria (Santamouris and Wouters 2006). However, there are ways that natural ventilation can be combined with other forms of low-energy cooling systems to make it useful in challenging climatic conditions as well. Such systems are called hybrid systems (Etheridge 2011).

The most obvious aspect of incorporating natural ventilation in designing buildings is reduced capital cost and lower operation cost. Yet studies have shown that occupants prefer to have control over their environment, hence showing a preference to be connected to their external environment rather than isolated from it, as they might be in buildings with absolute HVAC control (Etheridge 2011). From the perspective of occupants’ health, buildings served only by mechanical HVAC, with or without humidification, have consistently led to 20-200% higher incidences of Sick Building Syndrome (SBS) symptoms compared to buildings that are naturally ventilated (ASHRAE 2013). The benefits of using natural ventilation make it desirable over exclusive HVAC control in places where the weather and climate permit.

Adaptive Thermal Comfort

The idea of thermal comfort must be understood prior to comprehending the concept of adaptive thermal comfort. According to the American Standard of Heating, Refrigeration, and Air-Conditioning (ASHRAE), thermal comfort is a state where the indoor thermal environment and occupants' personal factors combine to provide an acceptable comfort for at least 80% of occupants. This acceptability is equivalent to the satisfaction of the occupants, achieved when a thermal sensation of 'slightly warm', neutral, or 'slightly cool' is observed among the occupants (ASHRAE 2013).

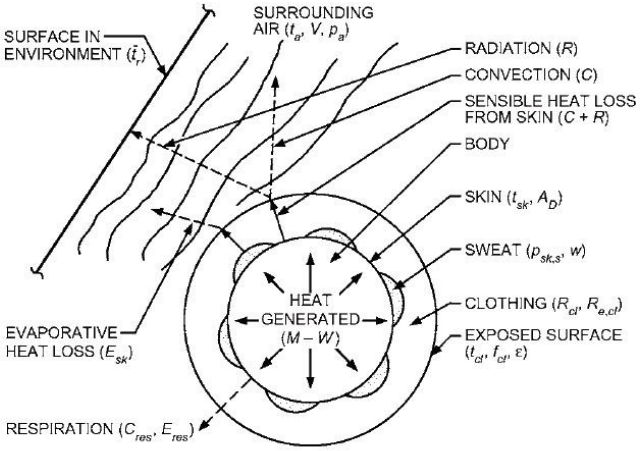


Figure 1-4 Heat Balance of Human Body for Thermal Comfort

Source: (ASHRAE 2013)

ASHRAE standard 55 follows the heat balance model of the human body where thermal sensation is subject to four environmental, two personal, and a number of psychological factors. Temperature, thermal radiation, humidity, and air speed are the four environmental factors, whereas activity level and clothing are the two personal factors (ASHRAE 2013). This heat balance model is shown in Figure 1-4.

Researchers concerned with passive building design criticize ASHRAE standard 55 however. The basic human capability of changing 'personal factors' and 'environmental factors' to achieve thermal comfort has been neglected by the standard. Occupants can open or close windows, change posture, change clothing, and turn on task/ambient cooling or heating to adapt a slightly uncomfortable environment and turn it into one that is acceptable (de Dear and Brager 2002, pp. 549-561). By ignoring the potential for users to adapt to their environments, ASHRAE standard 55 recognizes thermal comfort in a very limited manner. An alternative model for comfort is provided by the Adaptive Thermal Comfort model, which recognizes the ability of occupants to change and adapt to slightly uncomfortable environments.

Robinson et al. (1943, pp. 175-176) identified the adaptive nature of human comfort in their study. Subjects constantly exposed to a high degree of temperature showed 50%, improvement in acclimatization upon continuous exposure to a warmer climate for 3 day; acclimatization increased to 95% after a week. The investigation further asserted that acclimatization once induced could be maintained by a weekly exposure to the similar environment. But, if not exposed to such conditions, acclimatization to overheated conditions diminished slowly over a period of 2 to 3 weeks (ASHRAE 2013).

Similarly, de Dear and Brager (1998, pp. 83-96) illustrated the adaptive nature of human comfort in their study where it became evident that people habituated to living in air-conditioned environments have a higher expectation for homogeneity and cooler temperatures. In these conditions, subjects had a lower tolerance to temperature deviation from the standard thermal comfort conditions. On the other hand, people living or working in naturally ventilated buildings proved to be more accepting of deviation from standard thermal comfort conditions. Occupants from naturally ventilated buildings expect higher peak temperatures at the upper reaches of the comfort range, typically as high as 81 °F/27 °C, due to their ability to operate windows, and naturally-driven air flow in the indoor environment (Clements-Croome 2002). These occupants were more accustomed to the daily natural variations of wind and temperature, suggesting that occupants of naturally ventilated buildings establish their own thermal perception, leading to a wider range of preference and tolerance than that standardized in ASHRAE standard 55.

The adaptive nature of human comfort can be utilized in favor to conserve energy especially in cooling buildings. De Dear and Brager (1998, pp. 83-96) were able to graphically present an estimate of energy savings in their study, shown in Figure 1-5, when the adaptive comfort standard was used for building operation rather than the ASHRAE standard 55 comfort model. In the figure, darker regions show more differences between set-point temperatures. Consequently, a range of energy savings are possible in such areas by switching to the adaptive comfort standard.

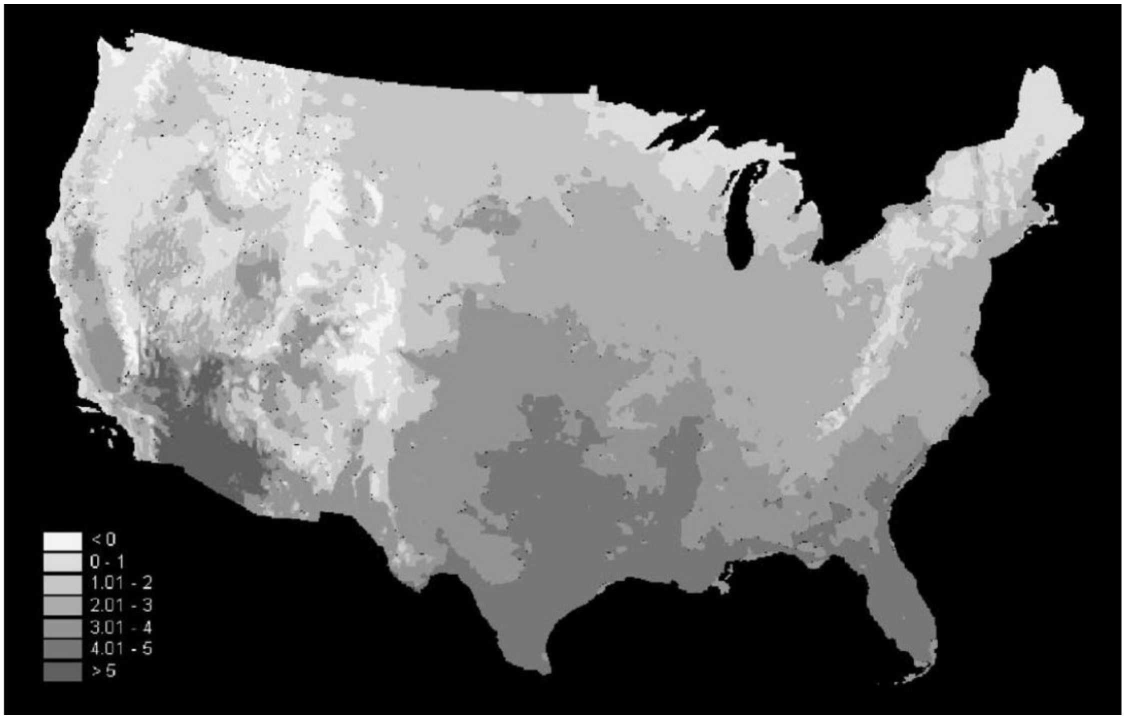


Figure 1-5 Comparison of recommended indoor comfort temperatures, upper limits vs ASHRAE Standard 55

Source: (de Dear and Brager 2002, pp. 549-561)

The adaptive comfort model can be abstracted with the help of the psychrometric chart, which is based on the physical and thermodynamic properties of air across a given climate and time interval. In a bioclimatic design approach, it is a preliminary process to interpret available climatic data. This helps to understand the existing climatic problems and potentials, determining available strategic solutions and relating climate to human comfort requirements (Szokolay 2008, p. 53). An in-depth understanding of the psychrometric chart is useful to determine suitable strategies that will aid energy efficiency for a particular climate.

As suggested by Santamouris and Allard (1998), it is of the utmost importance to consider adaptive thermal comfort along with an optimized building envelope, effective ventilation, and good indoor air quality, in order to achieve desirable indoor thermal comfort with maximum energy conservation in any building design. The use of natural ventilation to power effective ventilation will reduce energy consumption. Similarly, other smart design considerations can provide good indoor thermal comfort, conserve energy as well as slow the impact of global warming by reducing the production of greenhouses gasses associated with air conditioning.

Chapter 2 - Natural Ventilation: Science and Architecture

Cross-Ventilation

Physical Processes

Natural forces, particularly, wind pressure and stack effect, drive the process of natural ventilation and are responsible for the pattern and direction of the air flow through and around buildings. Whenever wind is incident on the exterior surfaces of a building, a positive pressure is developed on the windward side and a negative pressure is developed on the leeward side. This pressure differential, along with the existing pressure differentials inside buildings, become the driving force of natural ventilation(Khan, Su, and Riffat 2008, 1586-1604).

Natural ventilation can be wind-driven, buoyancy-driven, or a combination of both. This study is focused on cross-ventilation, a type of wind-driven natural ventilation. Cross-ventilation is a special case in natural ventilation where a space is connected to the outside air with inlets and outlets. These inlets and outlets are strategically placed in zones of positive pressure and negative pressure respectively (Melaragno 1982, p. 332). Increasing the size of such inlets and outlets increases the magnitude of cross-ventilation through a room. Inlets should be placed in high pressure zones, while outlets should be placed in the low pressure zone in order to achieve the most effective cross-ventilation (DeKay and Brown 2001, p. 182).

Cooling

Cooling or heating occurs when there is heat transfer between two objects at different temperature. Such transfer is possible by any of three models: conduction, convection, and radiation. The process of heat transfer from molecule to molecule within the same or between different objects in contact is called conduction. Warming of one end of an iron bar while the other end is heated is an example of conduction. It is usually the only mode of heat transfer within solid objects. Convection is the process of heat transfer by motion of a gas or liquid, a movement of rising warmer and less dense fluid and sinking cold and denser fluid which simultaneously transfers heat. Water boiling in a pot is an example of convection. Radiation is the transfer of heat between objects that are far apart. This transfer is possible due to electromagnetic waves. The earth receiving heat from sun is an example of radiation (Mehta, Scarborough, and Armpriest 2010, p. 104). Only in the presence of air is natural ventilation possible. Convection and radiation are the causes of heat transfer in natural ventilation as air can be treated as a fluid.

Natural ventilation aids in the reduction of cooling load in a building by exhausting warm indoor air and replacing it with cooler outdoor air. Similarly, the moving air during natural ventilation contacts the human body to extract heat from the occupant's body by the process of convection, radiation, and perspiration, effectively increasing the comfort range by reinforcing the perception of comfort at increasingly higher temperatures. This further increases thermal comfort for the occupants(Santamouris and Wouters 2006, p. 220).

The size of the inlets and the outlets, the magnitude of the wind, and the direction of the wind with respect to the ventilation openings all affect the cooling capacity of natural ventilation (DeKay and Brown 2001, p. 182). These parameters can be used to quantify the amount of air flowing from outside environment into an enclosure, which is known as the ventilation rate or air flow rate. There are various measurement units to describe the rate of natural ventilation: the ones used mostly are the volume flow rate, mass flow rate, air change rate, and per occupant air flow rate. The differential pressure between the inlet and the outlet also affect the air flow rate. Similarly, larger inlets and outlets, and wind approximately normal to the inlets help achieve maximum rate of ventilation (DeKay and Brown 2001, p. 182).

The cooling in an enclosure due to natural ventilation is proportional to the air flow rate of the ventilation. The indoor higher-temperature air is replaced by fresh lower-temperature outdoor air that reduces the heat content of the indoor air, lowering its temperature. Due to the laws of thermodynamics, natural ventilation results in sensible cooling only when the indoor temperature is higher than the outdoor temperature. The rate at which the indoor heat is removed, (E_v), according to Etheridge (2011), can be quantified as:

$$E_v = \rho c_p Q \Delta T$$

where,

ρ = density of air

c_p = specific heat of air

Q = volume flow rate

ΔT = difference in internal and external temperature

Similarly, increased air movement during natural ventilation accelerates the rate of convection, while also increasing evaporation from occupants' skin to induce a physiological cooling effect. This physiological cooling due to natural ventilation can be estimated by an equation proposed by Szokolay (2008):

$$dT = 6v_e - 1.6v_e^2$$

where,

dT = apparent cooling effect due air movement, in Kelvin. It will determine the physiological cooling caused by elevated indoor air speed during use of natural ventilation.

v_e = effective air speed = air speed at the body surface – 0.2 m/s

n.b. this expression is for an effective air speed of up to 2m/s only.

This equation implies that a higher air speed results in a higher cooling effect on the body. Coincidently, standards from ASHRAE do not recommend air speeds more than 0.2 m/s, while Szokolay claims that air speed up to 2 m/s (10 times the ASHRAE limits) under overheated conditions are practical (Santamouris and Wouters 2006; Szokolay 2008). The effective cooling due to air movement according to this model is shown in Table 2-1.

v_e	0.25	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4	1.6	1.8	2
dT (k)	0.30	0.58	1.14	1.66	2.14	2.60	3.02	3.42	3.78	4.40	4.90	5.26	5.50	5.62

Table 2-1 Cooling effect due to elevated air speed, Szokolay's model of cooling

Comfort

The effectiveness of the use of natural ventilation to cooling indoors can be determined by studying the indoor temperature during the use of natural ventilation. The indoor temperature is dependent of three different kinds of temperature measures: ambient or dry bulb temperature (T_{db}), mean radiant temperature (T_r), and operative temperature (T_{op}).

Ambient or dry bulb temperature is the temperature of the air that surrounds the occupant. Mean radiant temperature is the area-weighted average of surrounding surfaces in the environment, which are perceived by occupants because of heat lost or gained to those surfaces. Similarly, operative temperature is the temperature equivalent where the perception of mean radiant temperature and ambient temperature are combined (ASHRAE, HVAC APP SI HDBK 2015).

While determining the statistical likelihood of indoor thermal comfort, the operative temperature is the most significant of all other factors. It can be compared to a standard temperature of adaptive thermal comfort for a particular location suggested by ASHRAE's adaptive comfort model (Prajongsan and Sharples 2012, p. 109).

Climate

The potential to use natural ventilation is highly dependent on climate, with different aspects of climate that directly affect the use of natural ventilation in any given location. Natural ventilation can be used independently to cool indoor environments when the outdoor temperature and relative humidity are within comfort range. Natural ventilation for cooling is recommended in mild climatic conditions. However, there are other forms of natural ventilation, usually night ventilation, that can be effective in hotter climates with high diurnal temperature changes (Santamouris and Wouters 2006, p. 219).

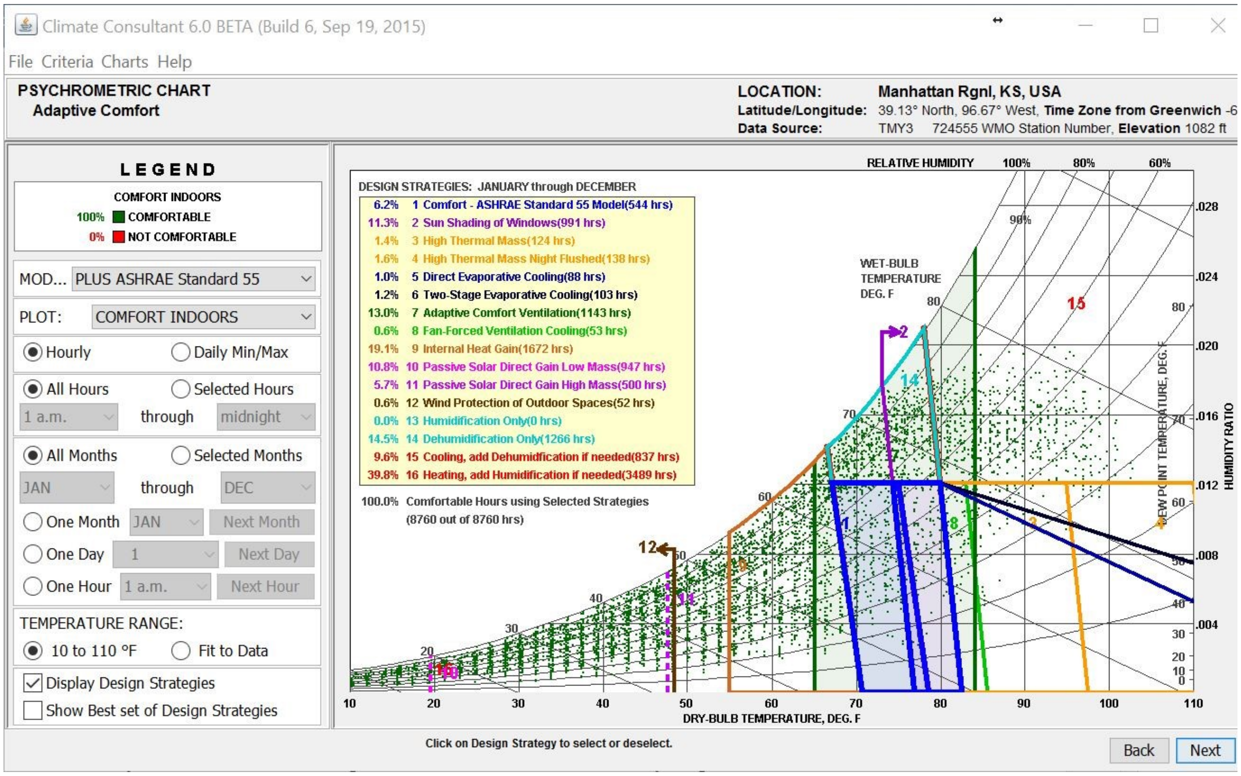
The maximum outdoor temperature within which daytime natural ventilation can be utilized for cooling is 32°C (89.6°F), but there should be an indoor wind speed of 2 m/s (Givoni 1994, p. 6). The diurnal temperature variation, the variation of maximum and minimum temperature in a day, is equally important while determining the use of night time natural ventilation. A minimum diurnal drop of 6°C-8°C is preferred for an effective night time ventilation in a building with a good thermal mass (de Saulles 2009).

Relative humidity in the range of 30%-60% is suitable to utilize natural ventilation for cooling (Szokolay 2008, p. 18). High humidity makes evaporation from human skin less efficient, and also affects respiration. Increased air speed can decrease skin moisture by evaporative cooling, increasing the thermal comfort range simultaneously (Berglund 1998, p. 35). Low relative humidity causes discomfort due to drying of the mouth, throat, and nose (Szokolay 2008, p. 18).

Wind is another climatic aspect which influences natural ventilation and can be a deciding factor in cooling and maintaining thermal comfort. Proper fenestration design and appropriate wind speed can induce suitable indoor air speed that can effectively counter indoor heat gains and prompt physiological cooling of the occupants to increase the thermal comfort range. Cross ventilation, the simplest and most direct form of natural ventilation, is dependent on natural wind.

Understanding the climate of a location is important in designing a climate responsive and passive building. Climate Consultant 6.0 is an example of software that generates graphical information from different components of climatic data in a format that is easy to understand and apply in decision-making when designing a building. The output information of climate consultant is obtained by processing an energy-plus weather (EPW) file, which has climatic data of a typical meteorological year (TMY) that represents a statistically average year of climate for the location of the data set (Wikipedia.org 2014). The outputs of climate consultant not only help understand climate, but in turn help to design energy efficient, sustainable buildings (Milne, Liggett, and Al-Shaali 2007, 466).

Climate Consultant provides a psychrometric chart as an output which shows design strategies for all hours of a year. A snapshot of Climate Consultant's window is shown in Figure 2-1, which says for the given climate (Manhattan, Kansas) a total of 544 hours of comfort is possible according to the ASHRAE Standard 55 model, with an increase of 1143 hours of comfort possible by adaptive comfort ventilation in a year. These analysis help understand the climate of a specific region in much more detail without cumbersome calculations.



PSYCHROMETRIC CHART
Adaptive Comfort

LOCATION: **Manhattan Rgnl, KS, USA**
Latitude/Longitude: 39.13° North, 96.67° West, **Time Zone from Greenwich** -6
Data Source: TMY3 724555 WMO Station Number, **Elevation** 1082 ft

COMFORT INDOORS
100% 🟩 COMFORTABLE
0% 🟥 NOT COMFORTABLE

MOD... PLUS ASHRAE Standard 55
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Selected Hours
1 a.m. through midnight
● All Months ○ Selected Months
JAN through DEC
○ One Month JAN Next Month
○ One Day 1 Next Day
○ One Hour 1 a.m. Next Hour
TEMPERATURE RANGE:
● 10 to 110 °F ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

DESIGN STRATEGIES: JANUARY through DECEMBER

6.2%	1 Comfort - ASHRAE Standard 55 Model(544 hrs)
11.3%	2 Sun Shading of Windows(991 hrs)
1.4%	3 High Thermal Mass(124 hrs)
1.6%	4 High Thermal Mass Night Flushed(138 hrs)
1.0%	5 Direct Evaporative Cooling(88 hrs)
1.2%	6 Two-Stage Evaporative Cooling(103 hrs)
13.0%	7 Adaptive Comfort Ventilation(1143 hrs)
0.6%	8 Fan-Forced Ventilation Cooling(53 hrs)
19.1%	9 Internal Heat Gain(1672 hrs)
10.8%	10 Passive Solar Direct Gain Low Mass(947 hrs)
5.7%	11 Passive Solar Direct Gain High Mass(500 hrs)
0.6%	12 Wind Protection of Outdoor Spaces(52 hrs)
0.0%	13 Humidification Only(0 hrs)
14.5%	14 Dehumidification Only(1266 hrs)
9.6%	15 Cooling, add Dehumidfication if needed(837 hrs)
39.8%	16 Heating, add Humidification if needed(3489 hrs)

100.0% Comfortable Hours using Selected Strategies
(8760 out of 8760 hrs)

Click on Design Strategy to select or deselect.

Figure 2-1 Psychrometric Chart from Climate Consultant 6.0 for Manhattan, KS

Building Features

Building Plan and Orientation

Buildings that have deep plans are not preferred for cross ventilation implementation design and use. The problem with deep plan buildings are that the innermost areas are unreachable to wind-driven outdoor air circulation and flow. The case is similar for daylighting in such buildings. If a building is big enough, and an elongated plan is not desired or possible, a central open courtyard or atrium can help incorporate natural ventilation effectively (Etheridge 2011).

Equator facing windows admit solar radiation that heats the indoor environment. Simple horizontal overhangs can control solar radiation in the summer or fall when the sun is high in the sky. Horizontal sun from the east and the west produces glare while contributing to heat gain. Sun from the east and west cannot be blocked by simple overhangs and therefore requires vertical fins, landscaping, and other measures to protect the building interior from heat gain and glare. (Bainbridge and Haggard 2011, p. 13) Therefore, proper building orientation is important to reduce heat gain which reduces cooling loads as a whole during the summer.

Internal Heat Gains

Internal heat gains warm up the building, increasing its temperature, and, when temperatures reach the threshold of the comfort zone, must be offset by cooling from conditioned air or exchanged with cooler, outdoor air when exterior conditions permit. It is therefore advised to reduce internal heat gains to a magnitude that can be easily overcome using outdoor, naturally ventilated air. Furthermore, the evaporative cooling of occupants can be achieved with relatively higher speed of air (Etheridge 2011).

On the other hand, smaller skin-dominated residential buildings usually have higher external heat gains than internal gains, primarily due to solar radiation, which makes up most of the cooling load. Summer solar gain can be reduced by proper building and window orientation. Moreover, the equator-facing windows can be provided with overhangs or shading devices to reduce overheating during late spring, summer, and fall. Exterior shading devices are more efficient than interior curtains or blinds because solar radiation is prevented from entering the building (Bainbridge and Haggard 2011, pp. 86-90).

Shape of Building and Surrounding Environment

The shape of a building affects the effectiveness of natural ventilation. Every building has a characteristic surface pressure distribution. These pressure differentials impact the flow of air, in turn influencing the effectiveness of natural ventilation. A simple diagram (Figure 2-2) showing an isolated building versus densely packed buildings can help understand the point (Etheridge 2011).

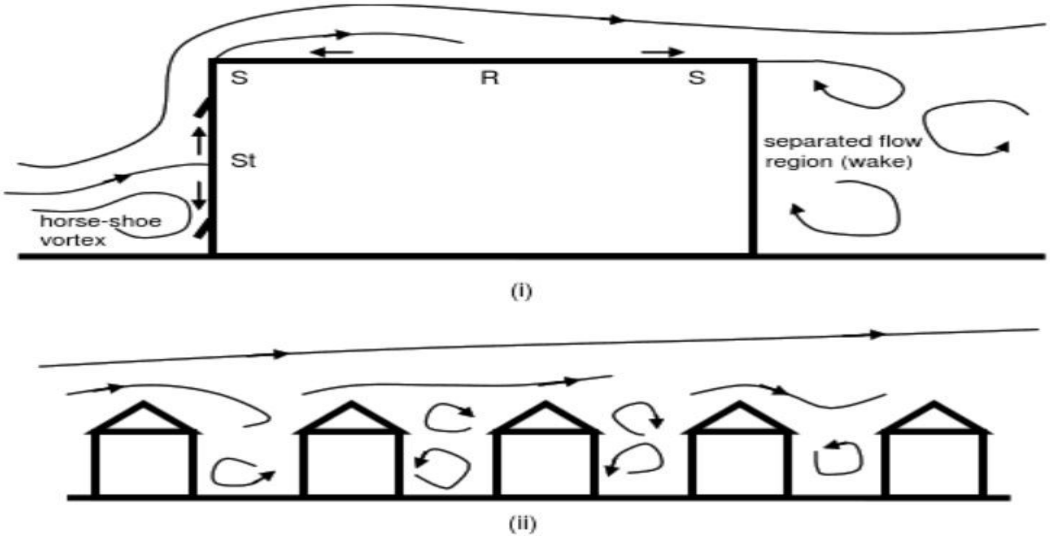


Figure 2-2 (i)Effect of wind in isolated building and (ii) densely packed buildings

Source: (Etheridge 2011)

The surrounding environment may present limited options for manipulation when designing for natural ventilation. Considerations must be given to the prevailing wind direction while designing for natural ventilation. The orientation of a building must be in relation to the prevailing wind to get the most effective natural ventilation. In other case, the varying magnitude and direction of wind can be a problem, which can be accommodated by introducing an automatic control system (Etheridge 2011).

Sites with noise and air pollution brings another challenge to natural ventilation. Not much can be done to neutralize outdoor pollutants, but few techniques such as underground ducts (earth tubes) and top-down ventilation can be options in such cases. Moreover, it is advisable not to place openings in the direction of pollution sources (Etheridge 2011).

Building Envelope

Proper sizing and positioning of the openings for natural ventilation should be done in concert with factors such as internal heat gain through the openings, thermal storage, etc. using the appropriate integration techniques (not covered in the scope of this study). However, the relation of openings and resultant air speed is of interest in this study.

Ventilation rates in a partitioned building are dependent on these parameters: windward and leeward opening areas along with internal openings (Chu, Chiu, and Wang 2010, 667-673). While understanding the air flow in relation to opening areas, Santamouris and Allard (1998) were able to calculate the resultant average speed of wind in reference to inlet and outlet size. They are shown in Table 2-2 through Table 2-5.

INLET AND OUTLET PARALLEL TO EACH OTHER

Conditions for Perpendicular Winds	V-Avg (%)
W-inlet/W-wall =1/3 & W-outlet/W-wall=1/3	35
W-inlet/W-wall =1/3 & W-outlet/W-wall=2/3	39
W-inlet/W-wall =1/3 & W-outlet/W-wall=1	44
W-inlet/W-wall =2/3 & W-outlet/W-wall=1/3	34
W-inlet/W-wall =2/3 & W-outlet/W-wall=2/3	37
W-inlet/W-wall =2/3 & W-outlet/W-wall=1	35
W-inlet/W-wall =1 & W-outlet/W-wall=1/3	32
W-inlet/W-wall =1 & W-outlet/W-wall=2/3	36
W-inlet/W-wall =1 & W-outlet/W-wall=1	47

Table 2-2Role of size of openings in cross ventilation, Perpendicular wind, Inlet and Outlet Parallel to each other

Source: (Santamouris and Allard 1998)

Conditions for Oblique to inlet Winds	V-Avg (%)
W-inlet/W-wall =1/3 & W-outlet/W-wall=1/3	42
W-inlet/W-wall =1/3 & W-outlet/W-wall=2/3	40
W-inlet/W-wall =1/3 & W-outlet/W-wall=1	44
W-inlet/W-wall =2/3 & W-outlet/W-wall=1/3	43
W-inlet/W-wall =2/3 & W-outlet/W-wall=2/3	51
W-inlet/W-wall =2/3 & W-outlet/W-wall=1	59
W-inlet/W-wall =1 & W-outlet/W-wall=1/3	41
W-inlet/W-wall =1 & W-outlet/W-wall=2/3	62
W-inlet/W-wall =1 & W-outlet/W-wall=1	65

Table 2-3 2Role of size of openings in cross ventilation, Oblique wind, Inlet and Outlet Parallel to each other

Source: (Santamouris and Allard 1998)

INLET AND OUTLET PERPENDICULAR TO EACH OTHER

Effect of inlet & outlet sized in cross-ventilated spaces; openings on adjacent walls; wind perpendicular to inlet

Conditions for Perpendicular to inlet Winds	V-Avg (%)
W-inlet/W-wall =1/3 & W-outlet/W-wall=1/3	45
W-inlet/W-wall =1/3 & W-outlet/W-wall=2/3	39
W-inlet/W-wall =1/3 & W-outlet/W-wall=1	51
W-inlet/W-wall =2/3 & W-outlet/W-wall=1/3	51
W-inlet/W-wall =1 & W-outlet/W-wall=1/3	50

Table 2-4 2Role of size of openings in cross ventilation, Perpendicular wind, Inlet and Outlet perpendicular to each other

Source: (Santamouris and Allard 1998)

Conditions for Oblique to inlet Winds	V-Avg (%)
W-inlet/W-wall =1/3 & W-outlet/W-wall=1/3	37
W-inlet/W-wall =1/3 & W-outlet/W-wall=2/3	40
W-inlet/W-wall =1/3 & W-outlet/W-wall=1	45
W-inlet/W-wall =2/3 & W-outlet/W-wall=1/3	36
W-inlet/W-wall =1 & W-outlet/W-wall=1/3	37

Table 2-5 2Role of size of openings in cross ventilation, Oblique wind, Inlet and Outlet perpendicular to each other

Source: (Santamouris and Allard 1998)

The tables show that varying areas of inlets and outlets reduce the speed of air flow inside the building to as low as 32% of the exterior wind speed. Similarly, the maximum amount of air flow that can be transferred is 65% of the exterior wind speed. Ventilation rates reach the maximum value when the opening ratio of outlet to inlet is uniform, regardless of internal opening configuration. Smaller inlet windows compared to outlets also provide higher inlet speeds. Similarly, smaller outlet windows compared to inlets provide more uniform air flow (Chu, Chiu, and Wang 2010, 667-673).

Windows that are wide or horizontal are preferred to square or vertical windows. Such wide windows are able to collect wind over a wider range to generate more airflow. They are highly preferred in areas where the prevailing wind is fluctuating in pattern and intensity(ASHRAE 2013).

Inlet openings should be unobstructed by indoor partitions as much as possible. If partitions are required, they should be split to redirect airflow but never should restrict the air flow between inlet and outlet (ASHRAE 2013). Internal partitions reduce the change of external and internal pressure, making the peak ventilation rate of a partitioned building always smaller in magnitude than that possible for a building with an open plan (Chu, Chiu, and Wang 2010, 667-673).

These studies are able to show that the speed of wind can be managed in a limited range. Operable window with adjustable aperture sizes in both inlets and outlets can thus be used in windy conditions. It is impractical to expect occupants to understand these relationships with precision, however, and maintain the most optimum inlet to outlet ratio although occupants can learn simple practices to improve and manage ventilation over time.

To sum up all the above mentioned building features, Rosenbaum (1999) concludes the following points to manage the air flow rate of natural ventilation through the building envelope:

- Irregularly shaped or spread-out buildings can enhance cross-ventilation.
- In orienting buildings and ventilation openings, a slight deviation from the perpendicular direction of wind is desirable for effective natural ventilation.
- The size of inlet and outlet should be more or less equal.
- Windows that are more horizontal are more effective in cross-ventilating than the vertical ones.

Window Wall Ratio (WWR)

Window-wall ratio is the percentage of exterior walls covered by windows. It is calculated as the ratio of wall fenestration area and total exterior, above-grade wall surface area (Deru and Torcellini 2005). It plays an important role in the consumption of heating and cooling energy in buildings. During the cooling season, it is commonly known that higher WWR may contribute to higher solar gain during daytime. Due to lower thermal resistances of windows compared to wall, a larger aggregate rate of heat transfer can be expected for a building envelope with a higher WWR (Su and Zhang 2010, p. 198).

The ASHRAE standard 90.1 recommends a maximum of 40% WWR (Institute 2013, p. 77). However, the solar heat gains through higher WWR (combined with the increased heat losses from glazing in the wintertime) suggests the most suitable WWRs lie in between 20%-30% although lower WWRs will compromise the energy-saving potential of daylighting (Sullivan, Lee, and Selkowitz 1992, pp. 10-11). Maximum energy conservation can be obtained in this range of WWR.

Construction Type

Building construction type directly impacts energy conservation and thermal comfort. Residential buildings are built using predominantly lightweight construction systems such as wood framing, but may also be built with heavier construction systems that incorporate thermal masss. Buildings may also use a mix of lightweight and heavy construction system as well. The International Council for Energy Conservation (the authors of International Energy Conservation Code) specifies a minimum thermal resistance components according to construction type (Institute 2013, p. 77). These thermal resistances have been adopted in the International

Residential Code (2012, p. 481) to prescribe the insulation level of each envelope components according to types of construction and U.S. climate zone, and can be seen in Table 2-6.

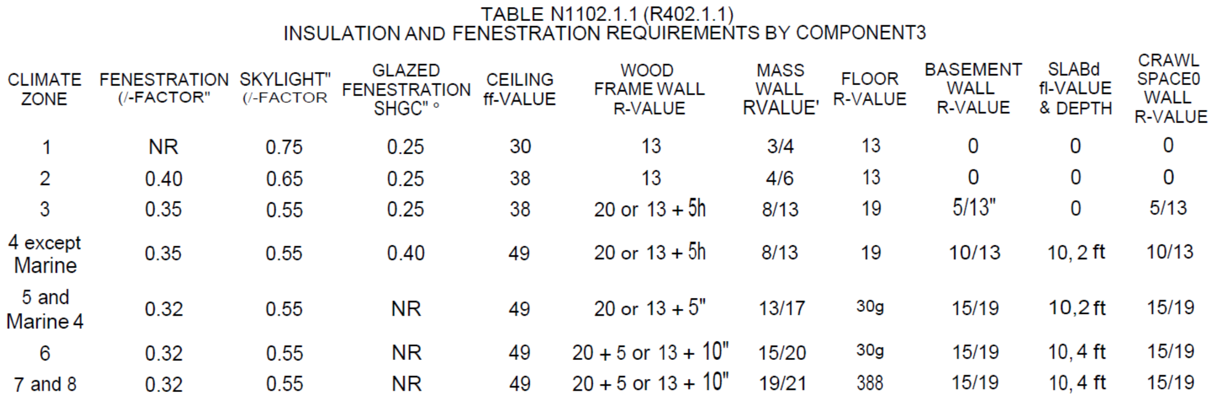


TABLE N1102.1.1 (R402.1.1)
INSULATION AND FENESTRATION REQUIREMENTS BY COMPONENT3

CLIMATE ZONE	FENESTRATION (/-FACTOR"	SKYLIGHT" (/-FACTOR	GLAZED FENESTRATION SHGC" °	CEILING ff-VALUE	WOOD FRAME WALL R-VALUE	MASS WALL RVALUE'	FLOOR R-VALUE	BASEMENT WALL R-VALUE	SLABd fl-VALUE & DEPTH	CRAWL SPACE0 WALL R-VALUE
1	NR	0.75	0.25	30	13	3/4	13	0	0	0
2	0.40	0.65	0.25	38	13	4/6	13	0	0	0
3	0.35	0.55	0.25	38	20 or 13 + 5h	8/13	19	5/13"	0	5/13
4 except Marine	0.35	0.55	0.40	49	20 or 13 + 5h	8/13	19	10/13	10, 2 ft	10/13
5 and Marine 4	0.32	0.55	NR	49	20 or 13 + 5"	13/17	30g	15/19	10,2 ft	15/19
6	0.32	0.55	NR	49	20 + 5 or 13 + 10"	15/20	30g	15/19	10, 4 ft	15/19
7 and 8	0.32	0.55	NR	49	20 + 5 or 13 + 10"	19/21	388	15/19	10, 4 ft	15/19

Table 2-6 Insulation and fenestration requirements by component

Heat Balance

The human body, electrical equipment, and direct solar gain are some direct sources of heat gain in a residential building. Table 2-7 shows the different appliances in house that contribute to internal heat gain, directly heating the indoor air. As the specific heat of air is low, small increases in heat can increase air temperature significantly.

End Use/Appliances	Energy Use in kWh/year	Energy Use in BTU/hr	% Internal Gain Conversion	Internal Heat Gain BTU/hr
Interior Lighting	1975	769	100	769
Refrigerator	687	268	100	268
TV	621	242	100	242
Oven/Range	440	171	80	137
Ceiling Fan	332	129	Very Low	0
Exterior Lighting	195	76	0	0
Cloth Washer	69	27	30	8
Cloth Dryer	941	367	15	55
Dishwasher	165	65	60	39
Residual	Varies	Varies	90	Varies
Occupant* (per person)				400

Table 2-7 Energy Use and Internal Heat Gains for national average home (1900 sft, 2.8 bedrooms

Source: (Parker, Fairey, and Hendron 2010, pp. 43-44)

The heated interior air can be replaced by cooler air from outside to maintain thermal comfort. If the temperature difference is significant and substantial wind speed is present, the pressure differential will drive the cool air inward easily. In an attempt to minimize the rise of air temperature of indoor air during summer, shading devices for the windows are important, as admitted solar radiation can account for a large increase in interior temperature.

While solar gain and internal heat gains can heat indoor air, an appropriate flow of exterior air can offset the heat gains. The amount of air flow rate is highly dependent on the outdoor air speed and the ventilating aperture's size. The relation of ventilation apertures to natural ventilation in practice is explained by DeKay and Brown (2013). Figure 2-3 shows the required size of openings, as a percentage of floor area, to remove heat from buildings in cross-ventilation. It is assumed that the temperature difference of outdoor air to the indoor environment is 3°F. Design wind speed can be selected on the vertical axis. Moving horizontally to meet the

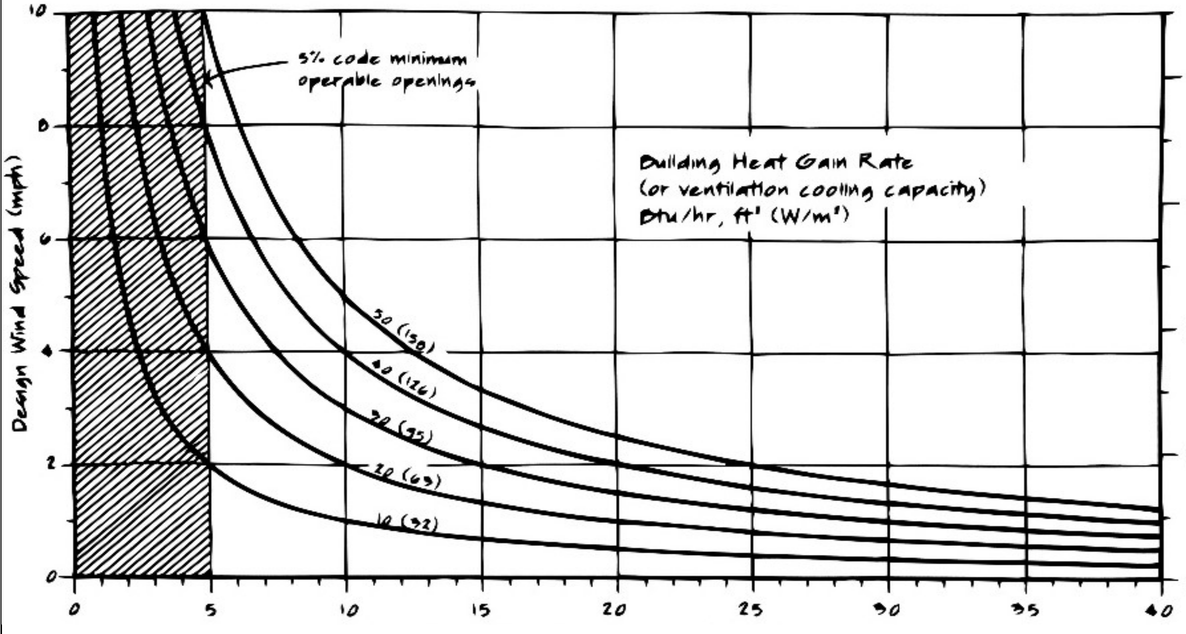


Figure 2-3 Size of openings for cross ventilation

Source: (DeKay and Brown 2013, p. 213)

curve that matches the building's heat gain, then vertically downward to meet horizontal axis, identifies the size of the inlet in areas as a percentage of floor area.

Hybrid Ventilation

The use of natural ventilation for cooling is limited to environmental factors, primarily by temperature, humidity, and wind. Mild climates can easily utilize natural ventilation but when the environment is hot and humid, or hot and arid, different techniques can be combined with natural ventilation to offer thermal comfort (Santamouris and Wouters 2006, p. 119). Evaporative cooling, swamp cooling, and ambient/task cooling are some of the ways to make natural ventilation feasible in arid environments. Similarly, desiccant cooling and ambient/task cooling can be adopted to maintain thermal comfort in humid conditions.

In hot climates, the use of mechanical ventilation with natural ventilation can provide cooling and improve indoor air quality for buildings. In this case the building's systems can switch readily between natural and mechanical ventilation modes to maintain thermal comfort; such as system is referred to as a hybrid ventilation system, and can switch modes at different seasons or even at different times of day, as exterior conditions change (Heiselberg 2002, p. 10).

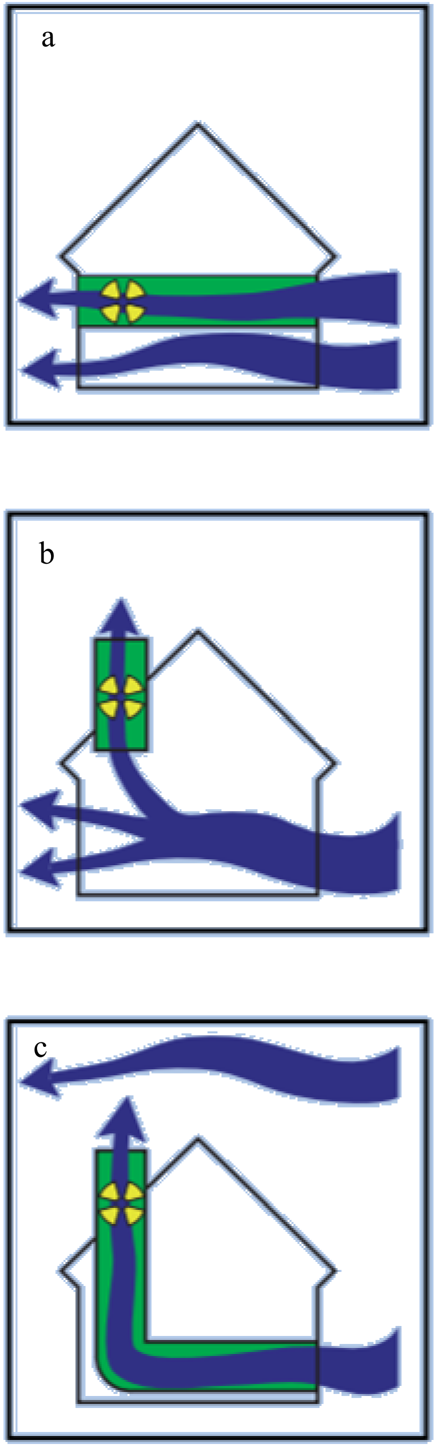


Figure 2-4 Three principles of hybrid ventilation

Source: (Heiselberg 2002, p. 17)

Principally, there are three types of hybrid ventilation system as shown in Figure 2-4: (a) Natural and mechanical ventilation, (b) Fan-assisted natural ventilation, and (c) Stack and wind assisted mechanical ventilation.

Chapter 3 - Methodology

The study was focused on the climate of the central U.S. State of Kansas, which was chosen as the location for study. Further focus was required to undergo this investigation. A two multi-family residential building was selected at Kansas State University, located in Manhattan, Kansas. These apartments were built in 1957 (Kansas State University 2016). Expansions and renovation works have been continuously carried out over the last 10 years on this complex of 14 stand-alone apartment buildings, although eventual replacement of the complex in the near future is planned.

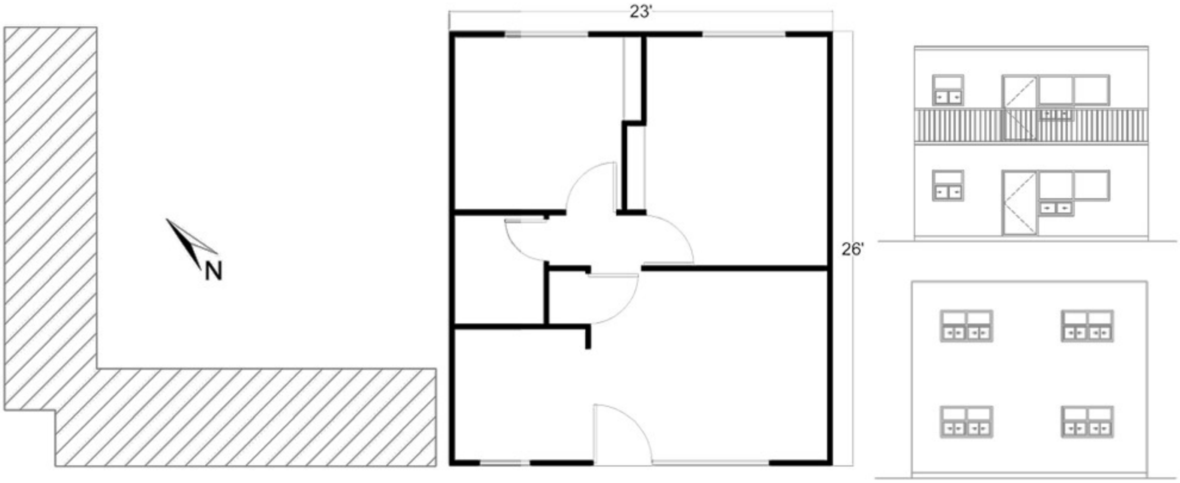


Figure 3-1From L-R: Building, two-bedroom apartment unit, front elevation (top), back elevation

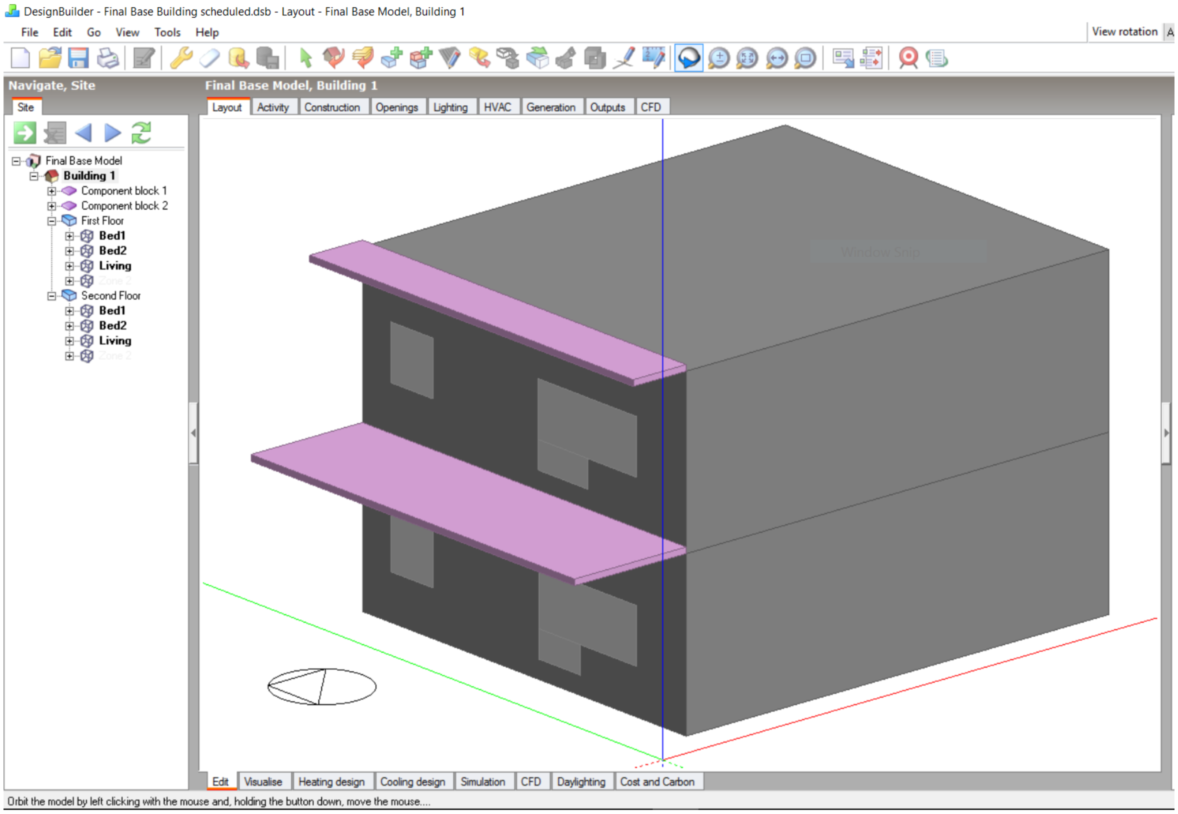
Refer to Appendix A - for details and clear drawings

Each building is oriented 45° to any of the cardinal directions. A typical residence building has a number of two-bedroom apartments, and four single-bedroom apartments on each wing of each floor for a total of 16 single-bedroom apartments and 8 two-bedroom apartments in one building. A two-bedroom apartment is approximately 600 square feet (ft^2). It has a WWR of approximately 15% and an aperture opening percentage of 25% of the total window area. The operable window area is equivalent to 2% of the area being ventilated, omitting the closet and the bathroom.

Climatic appropriateness is necessary to be able to incorporate natural ventilation in building design. The initial analysis step was to determine the suitability of the Manhattan, Kansas climate for the use of natural ventilation. Climate Consultant 6 was fed the climatic data file of Manhattan Regional Airport, which then yielded various infographics of temperature, humidity, and wind speed and direction. It also calculated the monthly maximum adaptive comfort temperature (T_{com}) following the rule of ASHRAE standard 55 with either 80% or 90%, acceptability to the occupants. The obtained T_{com} was adopted for this study, used later in determining the effectiveness of various other models of natural ventilation for cooling.

The climatic data file of Manhattan Regional Airport was obtained from the National Renewable Energy Laboratory's (NREL) website. This file contained hourly climatic data for a typical meteorological year, in chronological sequence. Evaluating comfort trends in hourly data can be cumbersome, because temperatures move significantly from hour to hour and day to day, making meaningful trends difficult to identify. For this reason, an abstraction process was used to organize the data into manageable chunks according to a model described by Prajongsan and Pimolsiri (2012). In this model, the days of each month were reduced to four sessions of six hours, and average climatic variables for each session were calculated. These hours for each session were 1 am – 6 am (First Session, S1), 7 am – 12 pm (Second Session, S2), 1 pm – 6 pm (Third Session, S3), and 7 pm – 12 am (Fourth Session S4). This mining process was carried out by running a custom-tailored program, written using a programming language called Python. It can be found in the Appendix E -

The ability to simulate the operative temperature and other environmental data was possible through the software Energy Plus, which is a whole building energy simulation tool developed with the support from the US Department of Energy (USDOE). The environmental parameters used in this study were outdoor dry bulb temperature, wind speed, wind direction, operative temperature, solar gain, gain due to occupancy and lighting, and natural ventilation. DesignBuilder, a graphic user interface (GUI) incorporating Energy Plus was selected to carry out further investigation. DesignBuilder is a user-friendly interface offering a meteorological database and a sophisticated modelling environment. This tool can evaluate solar energy supply, heating and cooling demand for all seasons, and total energy consumption. Further, the average indoor temperature and surface temperature throughout a typical year can also be simulated (Tronchin and Fabbri 2008, p. 1178).



Orbit the model by left clicking with the mouse and, holding the button down, move the mouse....

Figure 3-2 Existing apartment modelled in Design Builder

Two, two-bedroom apartments units, one on each floor, were modeled in Design Builder. This base model (M_0) can be seen in Figure 3-2. Different rooms were assigned different lighting and occupancy schedules, which was then kept constant throughout the study. Heat transfer through party walls to adjust apartments were not part of the study, and these walls were assigned as adiabatic walls. The building assemblies, composed of layers of specific materials, were then assigned; though different combinations of assemblies would be used during the study to understand the effect of construction systems on cooling. The assembly that did not change in all the models was the glazing used in windows. All of these data are reported in Appendix D - .

A brief table listing schedules of occupancy and lighting are shown in Table 3-1.Similarly, the material layers and thermal resistance of the various construction systems used are listed in Table 3-2.

The base building (M_0) was assigned the IRC prescribed lightweight construction profile. It was then simulated to the obtain operative temperature (T_{op}) along with various other environmental parameters for every hour of each month studied. These results were then processed in the python program to obtain averages of all the sessions (S1, S2, S3, and S4) of each month. The average T_{op} obtained from each session of each month was then adjusted for physiological cooling, using Szokolay's model, corresponding to the average air speed for the corresponding sessions and months. This adjusted temperature was termed adjusted operative temperature (T_{adj}). The results from the base building was used comparison against the results of simulations carried out on variations of the base building. Each variation went through the same calculation process to obtain results.

S.N.	Type	Room	Days	Schedule	% Use
1	Occupancy	Living Room	All week	12 am - 7 am	0
				7 am - 4 pm	50
				4 pm - 6 pm	66
				6 pm - 10 pm	100
				10 pm - 11 pm	66
				11 pm - 12 am	0
		Bedrooms	All week	12 am - 7 am	100
				7 am - 8 am	50
				8 am - 9 pm	25
				9 am - 10 pm	0
				10 pm - 11 pm	25
				11 pm - 12 am	75
2	Lighting	Living Room	All week	12 am- 4 pm	0
				4 pm - 11 pm	100
				11 pm - 12 am	0
		Bedrooms	All week	12 am - 7 pm	0
				7 pm - 11 pm	33
				11 pm - 12 am	0

Table 3-1 Schedules showing occupancy and lighting in living and bedrooms

An open window under different magnitudes of outdoor air velocity will result in particular indoor air speed, influenced also by various environmental factors as well. The indoor air speed at a level of 2.5 feet above the floor was calculated using the software Autodesk CFD. The building was modelled and boundary conditions for the CFD analysis were set, which are reported in Appendix B - .

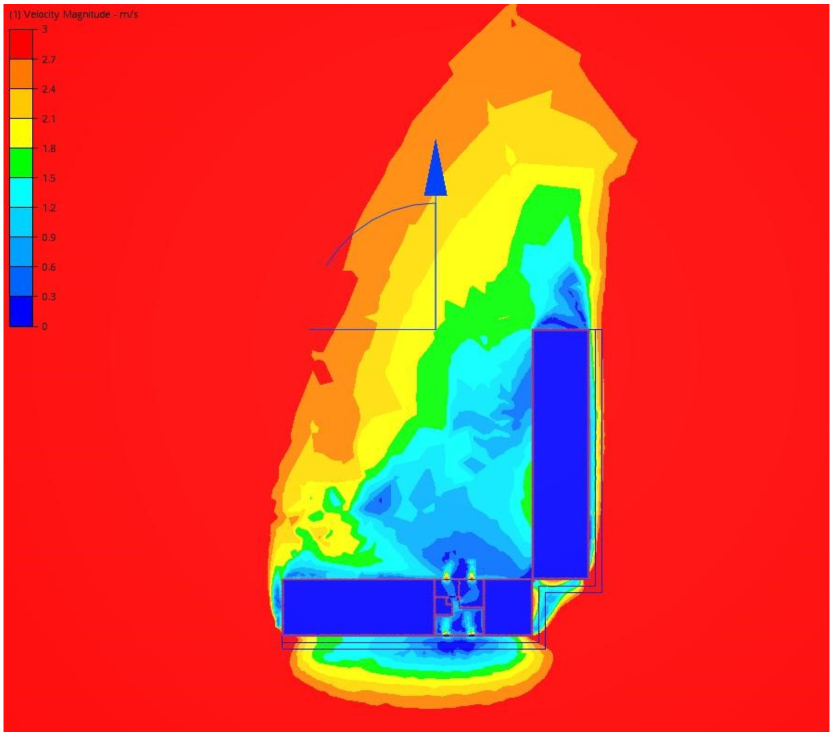


Figure 3-3 CFD image showing the apartment building with 4m/s outside air

Figure 3-3 shows an example of a CFD result. The base building (M_0), with a ventilation area at 2.5% of occupied area, and a modified building (M_{IRC}), with a ventilation area of 4% of the occupied area, were compared; individual tests varied the outdoor air speeds (1 m/s, 2 m/s, 3 m/s, 4 m/s, 5 m/s, and 6 m/s) to obtain a respective indoor air speed, assuming all of the operable windows are open. The indoor air speed was then tallied in Table 2-1 to obtain corresponding physiological cooling due to that air speed. The M_{IRC} model was designed to have the same window area as that of the M_0 model, with an equal ventilating area at each of the four windows.

S.N.	Construction Type	Parts	Layers (Outer to Inner)	Thickness (inches)	Total Thickness (inches)	R-Value (ft^2-^oF-hr/Btu
1	Lightweight	External Wall	Stucco	0.75	10.19	17
			Gypsum Board	0.625		
			R-21 Fiberglass batt 2X6 inch (5.5-inch cavity)	4.19		
			Wood 2X4 at R-1.25/inch	4		
			Gypsym Plasterboard	0.625		
		Internal Wall	Gypsum Plasterboard	0.5	5	4
			Air Gap	4		
			Gypsum Plasterboard	0.5		
		Ground Floor	Hard Wood	0.75	12.75	5
			Concrete	6		
			Compacted Earth	6		
		Internal Floor	Plywood	0.75	12.75	4
			Air Gap	11.25		
			Plywood	0.75		
		Roof	Rubber	0.2	13.95	49
			XPS Polystyrene	3		
			Plywood (Lightweight)	0.75		
			R-30 Fiberglass batt 2X6 in (5.5-inch cavity)	9.5		
			Gypsum Plasterboard	0.5		
2	Heavy Mass	External Wall	Stucco	0.75	11.25	17
			XPS	2		
			Concrete	8		
			Gypsym Plasterboard	0.5		
		Internal Wall	Same as Lightweight			
		Ground Floor	Same as Lightweight			
		Internal Floor	Concrete	4	4	2
		Roof	Same as Lightweight			
3	Medium Mass	External Wall	Same as Lightweight			
		Internal Wall	Same as Lightweight			
		Ground Floor	Same as Lightweight			
		Internal Floor	Same as Heavy Mass			
		Roof	Same as Lightweight			

Table 3-2 Construction system details

The orientation of a building is crucial in providing thermal comfort. The base building (M_0) was next oriented to eight possible directions, on an interval of 45°, and compared to see which orientation was the most efficient to maintain thermal comfort. Similarly, the model M_0, which lacked external shading devices, experienced significant solar gain during the summer. A one-meter-long shading device was added to all the windows for uniform outputs in every simulation. The length of the external shading devices was chosen to ensure a significant change in operative temperature due to shading. This modified model was simulated to obtain respective operative temperatures as it was rotated in 45-degree increments to eight different orientations.

The IRC prescribed minimum operable window area for multi-family residences is equivalent to 4% of the area being ventilated. Given the high wind and unique climate of Kansas, the IRC stipulated operable window area might be more than sufficient. In order to study this assertion, the base model (M_0) was modified by increasing the operable window area and adding shading devices in a revised model (M_{IRC}). The total area of windows in the base model was 65 square feet, out of which a total of 12 square feet was operable. The model was modified such that the area of the operable window was now modified to be 20 square feet, 4% of the area being ventilated, maintaining the total window area constant. Four window systems, 2 on each side, were provided with 3' x 1.7' operable windows. The operative temperature was obtained in DesignBuilder while the indoor air speed was calculated from CFD simulations, with the results tallied according to Szokolay's physiological cooling model to produce an adjusted operative temperature (T_{adj}) that considered cooling due to indoor air speed. This result was compared to the result of model M_0.

The construction type of the model M_0, which was of lightweight construction, was then modified to heavy mass construction (M_{0hvy}) with the shading devices. The properties of envelope assemblies complied with the IRC 2012 code, listed in Table 2-6. Similarly, M_{IRC} was also modified to get M_{IRChvy}. The models M_{0hvy} and M_{IRChvy} maintained the schedules, WWR, window glazing type, and simulation criteria as M_0. The details of the assembly constructions are reported in Appendix D - . M_0, M_{0hvy}, M_{IRC}, and M_{IRChvy} were all compared for thermal comfort by determining their respective T_{adj}. The pattern of improvement in adjusted operative temperature due to these changes were studied.

The effect of WWR on indoor thermal comfort was tested next. Model M_0 was modified by removing all the existing windows and adding new windows with shading devices such that the new models would have a WWR of 0%, 4%, 10%, 20%, and 30%. These new models were named M_{w0}, M_{w4}, M_{w10}, M_{w20}, and M_{w30} respectively. The windows were placed in a manner such that the two windows on front and the rear sides were of equal size and similar configuration for efficient natural ventilation. A Design Builder model, elevations, and window configuration for the M_{w20} is shown in Figure 3-4. The results from these five models along with M_0 were compared to see the effect of WWR on operative temperature and thermal comfort.

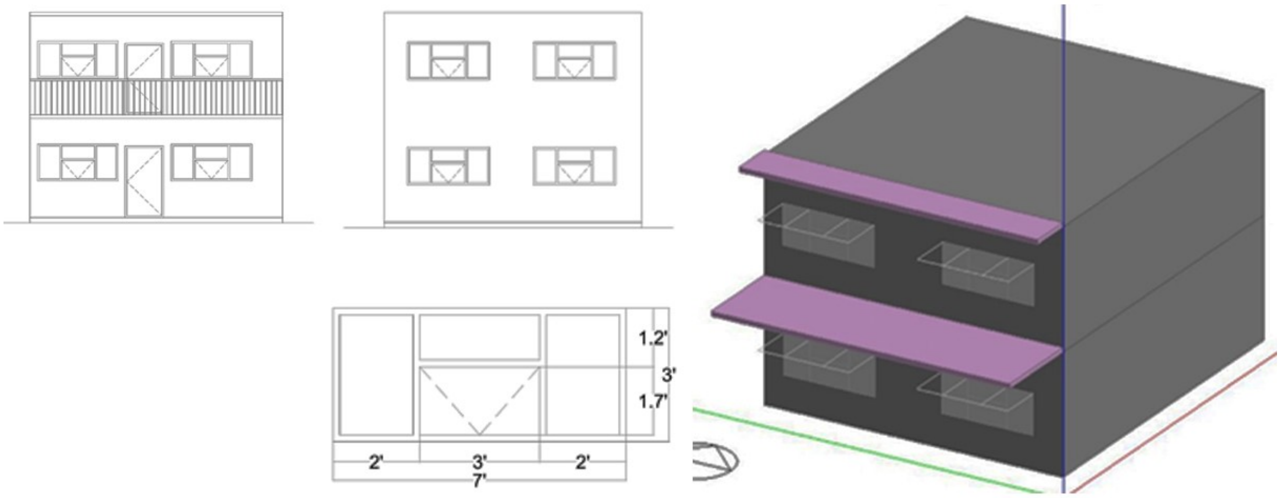


Figure 3-4 Details for WWR 20% model L-R: Front Elevation, Rear Elevation (Top), Window Detail (Botton), and 3D design builder model, refer to Appendix A - for detail and clear drawings

The list of different models used in this study has been itemized in Table 3-3.

Lastly, the percentage of comfort hours in each of the M_{IRC}, M_{0hvy}, M_{IRChvy}, and WWR models were compared with the data of the base model, M_0. Any increase in the comfort hour percentage in any of the modified models compared to the base model, M_0, indicated the benefits of use of natural ventilation for cooling along with that particular strategy.

S. N	Model Name	Details
1	**M_0**	The existing apartment; NE oriented (45°); unshaded; Lightweight
2	**M_{IRC}**	The existing apartment but with different operable window area = 20 sft. and a meter long shading devices
3	**M_{0hvy}**	M_0 which has heavy mass construction and a meter long shading devices
4	**M_{IRChvy}**	M_{IRC} which has heavy mass construction and a meter-long shading devices
5	**$M_{w\#}$**	M_0 with WWR equivalent to #; 4 equal sized windows with a meter long shading devices, 2 on each exterior walls; Constant operable window area in all models, four 3' X 1.7' operable windows

Table 3-3 Different models used in the study

S.N.	Symbol	Meaning
1	**T_{db}**	Outdoor dry bulb temperature
2	**T_{op}**	Indoor operative temperature
3	**T_{com}**	Maximum adaptive comfort temperature
4	**T_{adj}**	Adjusted operative temperature, which accounts physiological cooling due to elevate indoor air speed

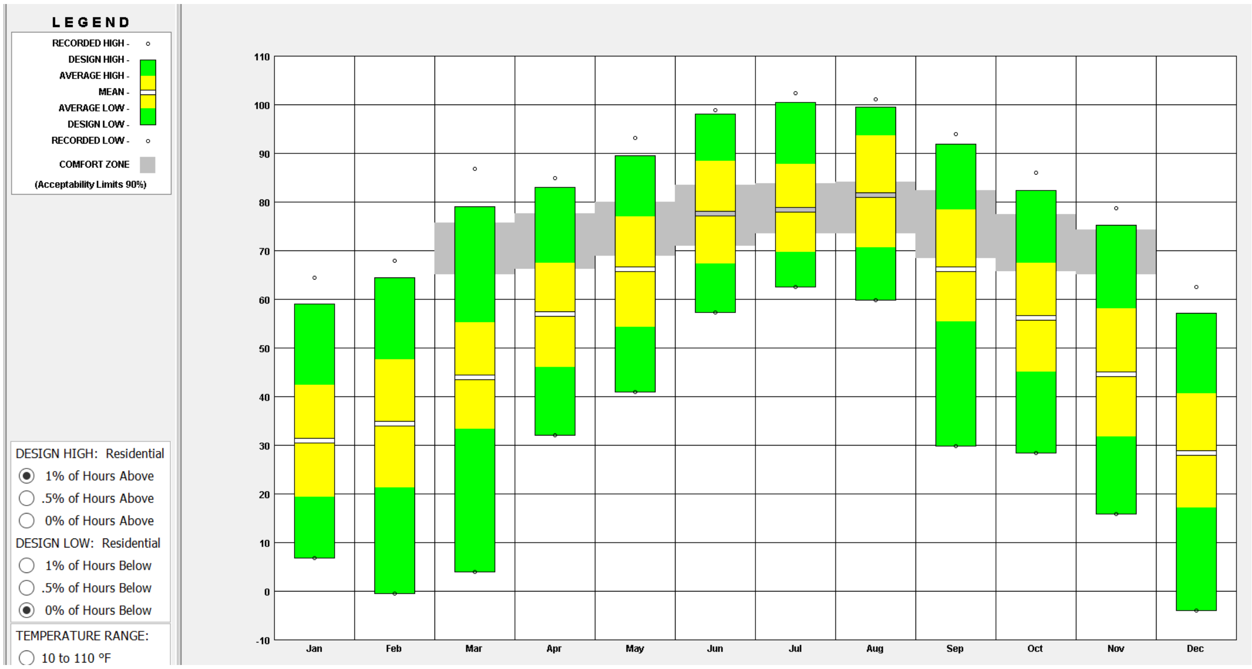
Table 3-4 Different temperatures and their symbol

For easy visualization of tables from here on, cells containing temperatures up to 1 °F higher than maximum comfort temperature will be bold faced and lightly highlighted while temperature higher than that will be bold faced and dark highlighted, signifying discomfort.

Chapter 4 - Results and Discussions

Climate Analysis

The climatic appropriateness was determined from the infographic outputs of Climate Consultant 6. The average high temperature for each months of a year showed that the months of May, June, July, August, and September are most appropriate for natural ventilation for cooling. Although the mean temperature for all those months lies in the comfort range as shown in Figure 4-1 , the average temperature of different sessions from Figure 4-2 showed that they occasionally rise beyond the thermal comfort range.



DESIGN HIGH: Residential
● 1% of Hours Above
○ .5% of Hours Above
○ 0% of Hours Above
DESIGN LOW: Residential
○ 1% of Hours Below
○ .5% of Hours Below
● 0% of Hours Below
TEMPERATURE RANGE:
○ 10 to 110 °F

Figure 4-1Adaptive comfort model with monthly average high and mean temperature, Climate Consultant 6

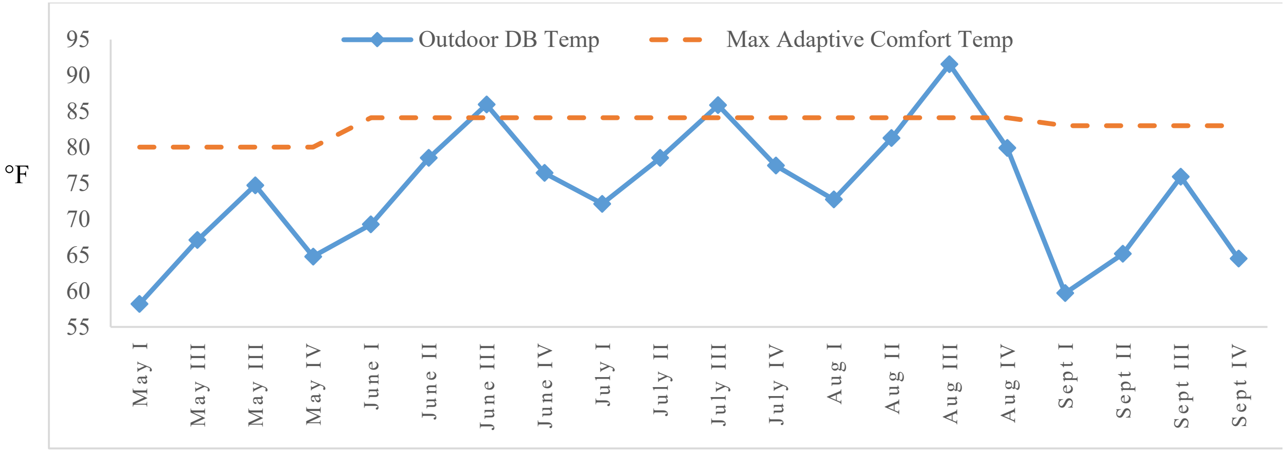


Figure 4-2 Session-wise outdoor average dry bulb temperature

The mean, average high, and design high temperature for the months of May, June, July, August, and September as suggested by Climate Consultant 6 is shown in Table 4-1. May and September have similar outdoor dry bulb temperature, and wind pattern for each sessionand may be treated as similar; thus data for the month of May was omitted for ease. The maximum outdoor temperature within which daytime natural ventilation can be utilized for cooling is 32°C (89.6°F), but with this maximum temperature, there should be an indoor wind speed of 2 m/s (Givoni 1994, p. 6). In agreement to this fact, the months of June, July, August and September were studied for effectiveness of natural ventilation. The month of August showed an average high of 94°F, mostly due to the temperature of Aug III session corresponding to late afternoon. In the remaining sessions and months, the temperatures were well within range to utilize natural ventilation.

Months	Mean °F (°C)	Average High °F (°C)	Design High °F (°C)	Max. Adaptive Comfort Temperature °F (°C)
May	67 (19)	76 (24)	**90 (32)**	80 (27)
June	78 (26)	**89 (32)**	**98 (37)**	84 (29)
July	79 (26)	**88 (31)**	**101 (38)**	84 (29)
August	82 (28)	**94 (34)**	**100(38)**	84 (29)
September	66 (19)	79 (24)	**92 (33)**	83 (28)

Table 4-1Mean, average high, design high temperature, and maximum adaptive comfort temperature for various months, Climate Consultant 6

Months	Mean (miles/hour)	Average High (miles/hour)
June	9.6	16.2
July	5.6	12.1
August	8.1	14.9
September	7.7	15

Table 4-2 Mean, and average high outdoor air speed, Climate Consultant 6

Elevated indoor air speed, as high as 2 m/s, is suitable in very hot conditions as discussed earlier. The outdoor air speed for different months is shown in Table 4-2. Different outdoor air speeds result in different indoor air speed, affected by the orientation of building and operable window area. There are other environmental factors that affect air speed, but for the purposes of this study a constant wind speed was presumed in calculating indoor air speed. The resultant indoor air speed for different outdoor air speed in the studied M_0 and M_{IRC} is shown in Table 4-3. Any air speed above 2 m/s creates discomfort, though the discomfort percentage is low for outdoor air speed up to 6 m/s. As seen in Table 4-2, the average high air speed may rise far beyond 6m/s, though discomfort is limited to living room, where the air initially enters; these averages are shown for the M_0 model, and M_{IRC} in Figure 4-3. It is evident that the M_{IRC} model is more effective in maintaining thermal comfort during higher outdoor air speed than the base building.

Floor Level/Outdoor Air Speed		1 m/s	2 m/s	3 m/s	4 m/s	5 m/s	6 m/s
Base Building	First	0.2 m/s	0.3 m/s	0.4 m/s	0.6 m/s	0.7 m/s	0.8 m/s
	Second	0.2 m/s	0.3 m/s	0.4 m/s	0.7 m/s	0.7 m/s	0.8 m/s
IRC model	First	0.2 m/s	0.3 m/s	0.6 m/s	0.7 m/s	0.9 m/s	1.1 m/s
	Second	0.2 m/s	0.3 m/s	0.5 m/s	0.7 m/s	0.8 m/s	1.0 m/s

Table 4-3 Resultant average indoor air speed for different average outdoor air speed, CFD analysis

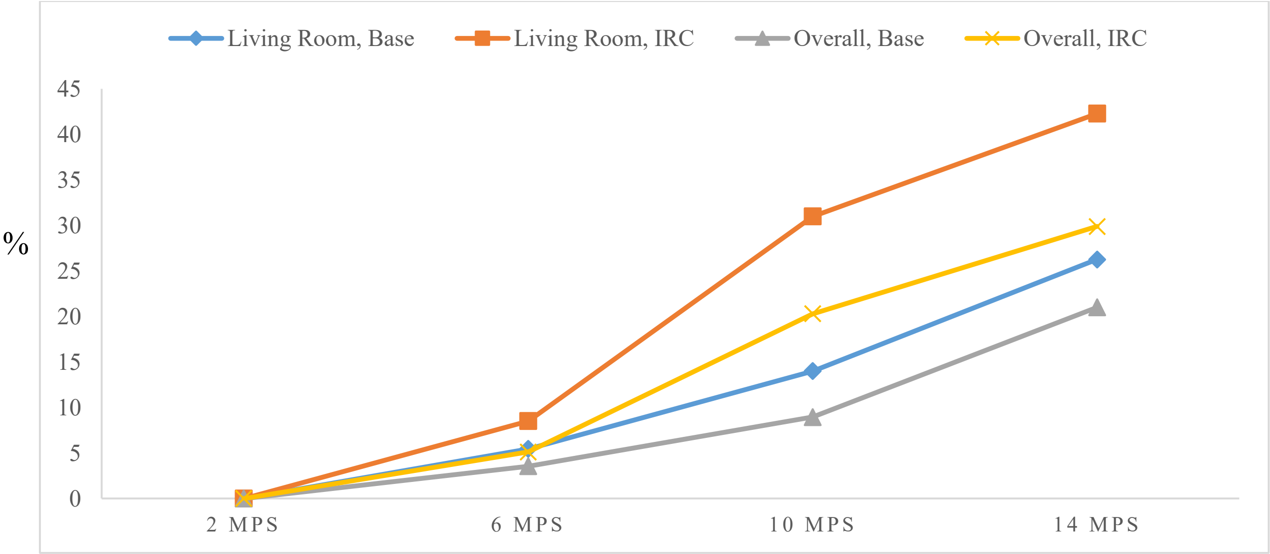


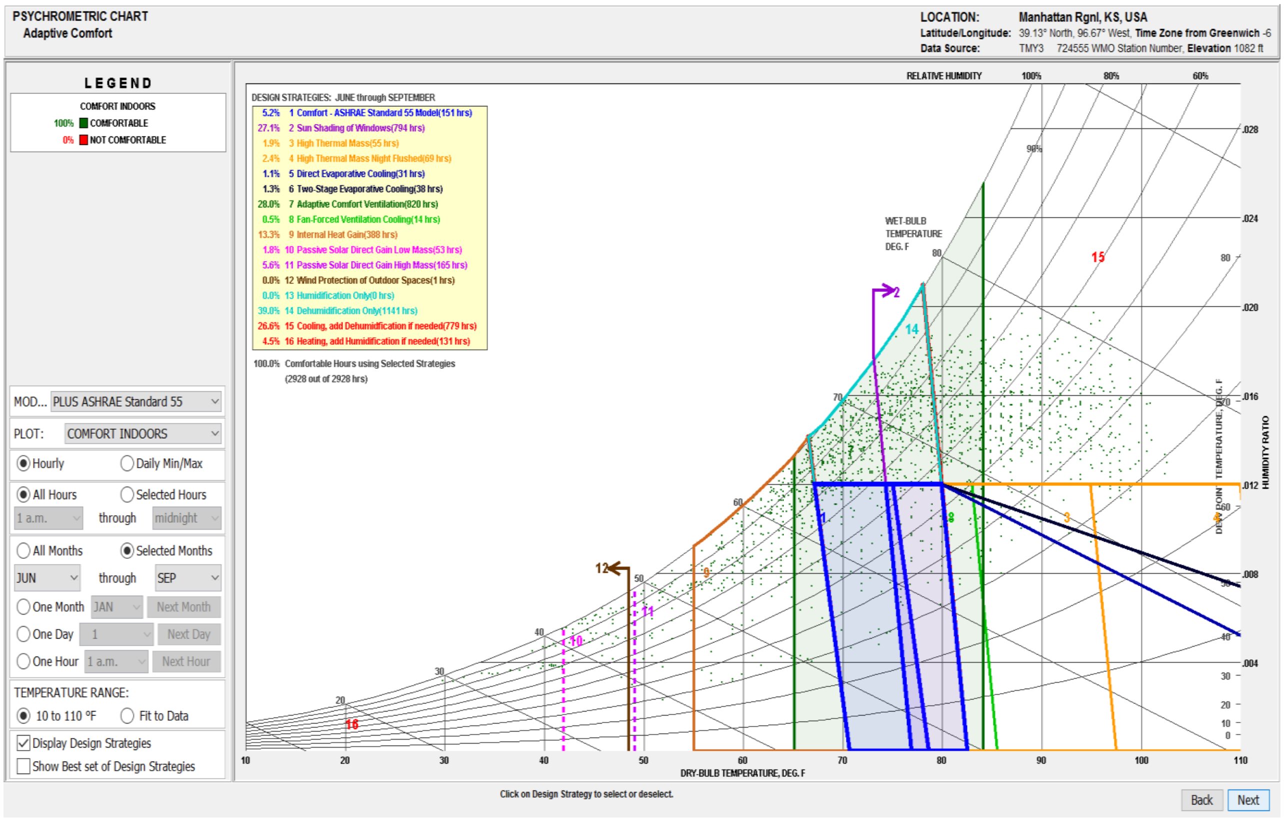
Figure 4-3 Percentage of discomfort (>2 m/s indoor air speed) in base and IRC model

The humidity level during different months is shown in Table 4-4. Relative humidity in the range of 30%-60% is suitable to utilize natural ventilation for cooling (Szokolay 2008, p. 18). The outdoor temperature rises during the daytime while decreases during night. The relative humidity behaves opposite to the outdoor temperature during these cycles. Humidity is low during daytime, dropping to its lowest value around noon. Early morning hours have the highest humidity. Since, the relative humidity decreases to the comfort range during the hottest period of the day, humidity cycles for the studied climate are suitable for natural ventilation. When natural humidity is high, temperatures drop to well within the comfort range, and ventilation may continue through nighttime.

Months	Maximum Humidity (%)	Time	Minimum Humidity (%)	Time
June	87	5:00 AM	50	2:00 PM
July	93	6:00 AM	63	2:00 PM
August	87	6:00 AM	47	2:00 PM
September	90	6:00 AM	51	2:00 PM

Table 4-4 Maximum and minimum relative humidity, Climate Consultant 6

The psychrometric chart shown in Figure 4-4 shows that the use of natural ventilation for adaptive thermal comfort can aid in 820 (28%) additional hours of comfort out of 2928 hours during the months of June-September. The use of natural ventilation will increase comfort hours due to the physiological cooling offered by elevated indoor air speed while using natural ventilation.



PSYCHROMETRIC CHART
Adaptive Comfort

LOCATION: **Manhattan Rgnl, KS, USA**
Latitude/Longitude: 39.13° North, 96.67° West, **Time Zone from Greenwich** -6
Data Source: TMY3 724555 WMO Station Number, **Elevation** 1082 ft

LEGEND

COMFORT INDOORS
100% 🟩 COMFORTABLE
0% 🟥 NOT COMFORTABLE

DESIGN STRATEGIES: JUNE through SEPTEMBER

- 5.2% 1 Comfort - ASHRAE Standard 55 Model(151 hrs)
- 27.1% 2 Sun Shading of Windows(794 hrs)
- 1.9% 3 High Thermal Mass(55 hrs)
- 2.4% 4 High Thermal Mass Night Flushed(69 hrs)
- 1.1% 5 Direct Evaporative Cooling(31 hrs)
- 1.3% 6 Two-Stage Evaporative Cooling(38 hrs)
- 28.0% 7 Adaptive Comfort Ventilation(820 hrs)
- 0.5% 8 Fan-Forced Ventilation Cooling(14 hrs)
- 13.3% 9 Internal Heat Gain(388 hrs)
- 1.8% 10 Passive Solar Direct Gain Low Mass(53 hrs)
- 5.6% 11 Passive Solar Direct Gain High Mass(165 hrs)
- 0.0% 12 Wind Protection of Outdoor Spaces(1 hrs)
- 0.0% 13 Humidification Only(0 hrs)
- 39.0% 14 Dehumidification Only(1141 hrs)
- 26.6% 15 Cooling, add Dehumidification if needed(779 hrs)
- 4.5% 16 Heating, add Humidification if needed(131 hrs)

100.0% Comfortable Hours using Selected Strategies
(2928 out of 2928 hrs)

MOD... PLUS ASHRAE Standard 55
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Selected Hours
1 a.m. through midnight
○ All Months ● Selected Months
JUN through SEP
○ One Month JAN Next Month
○ One Day 1 Next Day
○ One Hour 1 a.m. Next Hour
TEMPERATURE RANGE:
● 10 to 110 °F ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

Click on Design Strategy to select or deselect.

Figure 4-4 Psychrometric chart showing design strategies for adaptive thermal comfort, Climate Consultant 6

Base Model Result

The existing apartment, base model (M_0), had 3 sessions of uncomfortable outdoor dry bulb temperature. The operative temperature (T_{op}) in the interior was found to be uncomfortable in the August III session for the first floor. On the other hand, the second floor operative temperature was found to be uncomfortable in the June III, July III, July IV, August II, August III, and August IV sessions. Outdoor air combined with indoor air speed, when utilized in the form of natural ventilation, results in a different adjusted operative temperature to represent the effects of physiological cooling. The adjusted operative temperature (T_{adj}) for the first floor showed that the use of natural ventilation maintained thermal comfort in all sessions. The second floor, however, had uncomfortable T_{adj} in July III, August III, and August IV sessions. The difference between the upper and lower floors may be attributed to the upper floor shielding the lower floor from heat gain, while the increased heat gains of the upper floor resulted in warmer operative temperatures. The first floor also has ground contact through a partially uninsulated slab, resulting in lower operative temperatures on that level.

Months-Quarters	Outside Dry Bulb Temp T_{db} (°F)	Operative Temperature T_{op} (°F)		Wind Direction (°)	Wind Speed (m/s)	Indoor air velocity (m/s)	Cooling due to air speed (K)	Adjusted Operative Temperature T_{adj} (°F)	
		First Floor	Second Floor					First Floor	Second Floor
June I	69.3	75.3	77.7	122.5	3.0	0.4	1.1	73.3	75.7
June II	78.5	77.5	80.9	157.2	4.0	0.6	2.1	73.7	77.1
June III	**85.9**	82.0	**87.5**	157.6	6.0	0.8	3.0	76.6	82.1
June IV	76.4	79.8	82.8	129.4	4.0	0.6	2.1	76.0	79.0
July I	72.1	78.1	81.7	97.0	2.0	0.3	0.6	77.0	80.6
July II	78.5	78.9	82.9	122.7	3.0	0.4	1.1	76.9	80.9
July III	**85.9**	82.7	**88.7**	139.6	3.0	0.4	1.1	80.7	**86.7**
July IV	77.5	81.3	**85.5**	93.4	2.0	0.3	0.6	80.2	**84.4**
Aug I	72.7	78.7	82.2	126.3	2.0	0.3	0.6	77.6	81.1
Aug II	81.3	81.0	**85.4**	150.4	4.0	0.6	2.1	77.2	81.6
Aug III	**91.5**	**86.0**	**92.9**	165.1	5.0	0.7	2.6	81.3	**88.2**
Aug IV	79.9	83.7	**88.0**	144.4	3.0	0.4	1.1	81.7	**86.0**
Sept I	59.7	70.8	71.7	109.0	2.0	0.3	0.6	69.7	70.6
Sept II	65.2	71.8	73.0	136.1	4.0	0.6	2.1	68.1	69.2
Sept III	75.9	76.2	79.5	162.1	5.0	0.7	2.6	71.5	74.8
Sept IV	64.5	72.9	74.5	121.0	3.0	0.4	1.1	70.9	72.5

Table 4-5 Calculation of operative and adjusted operative temperature of existing building

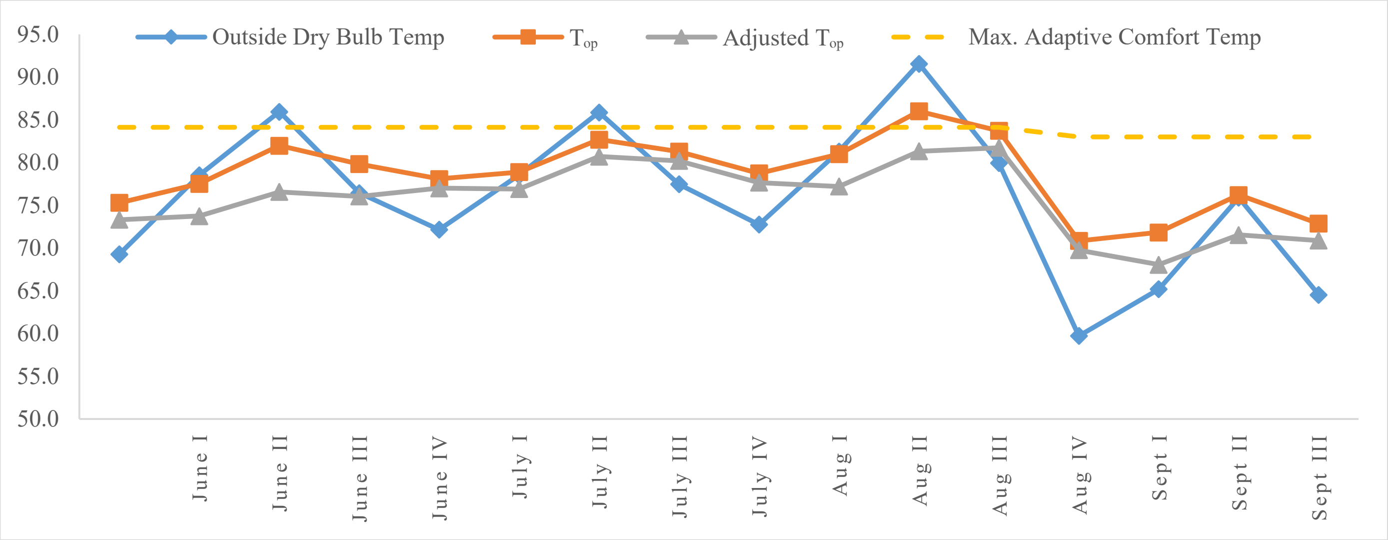


Figure 4-5 First floor adjusted operative temperature due to use of natural ventilation

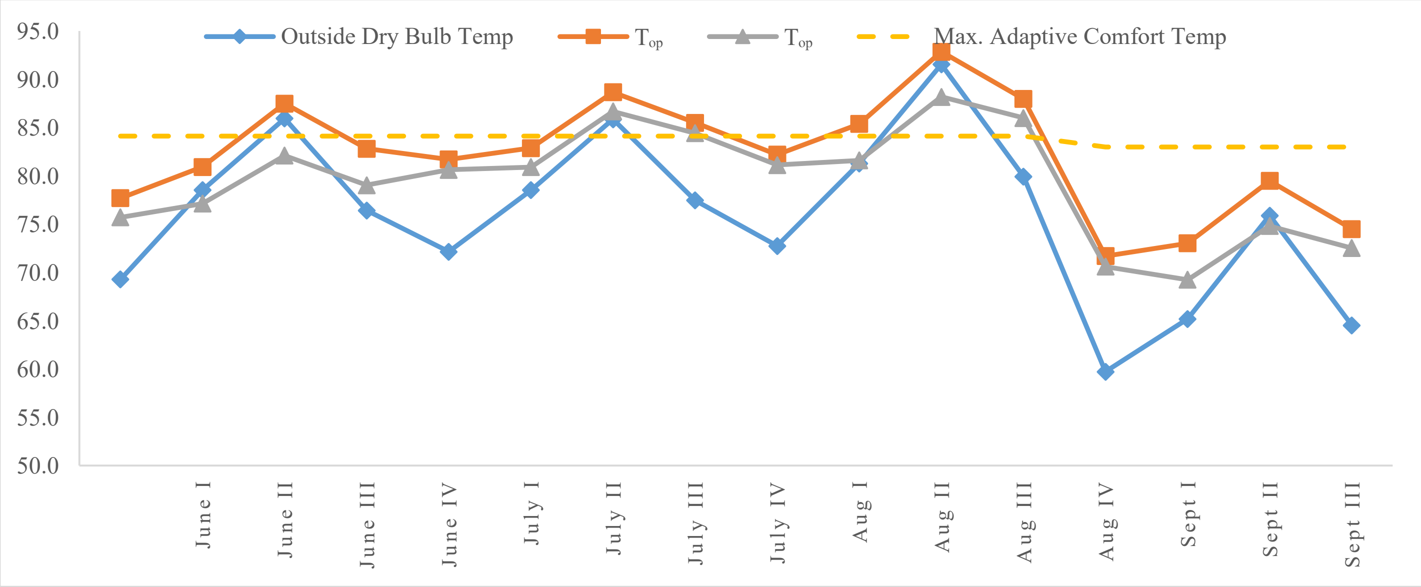


Figure 4-6 Second floor adjusted operative temperature due to use of natural ventilation

Cooling due to elevated air speed is visualized in Figure 4-5 and Figure 4-6. It is, however, important to note that thermal comfort was only achieved due to significant outdoor air speed. If there is very low outdoor air speed, it is unlikely that thermal comfort could be maintained in many sessions. The session of July III maintained thermal comfort if the outdoor air speed was 4m/s. Similarly, the session of August III only maintained thermal comfort if the outdoor average air speed is above 2 m/s.

The orientation and the use of exterior shading devices are important in mitigating solar radiation entering a building (Bainbridge and Haggard 2011, pp. 86-90). To understand the effects of orientation and external shading devices the base building's performance was analyzed for different orientations with and without exterior shading devices. The results showed that the south orientation was the most efficient. The use of external shading was very effective in lowering the direct solar gain, thus lowering the operative temperature. The base building is, however, oriented North-East (45°), demanded by the shape of the building, which is L-Shaped. If the building was oriented to the South (270°), the other wing, which can be ±90°, would gain more solar heat and perform worse. Such a condition would continue with many other orientations, with one wing performing well and the other performing poorly. The existing building, on the other hand, is oriented at 45° angle so that each wing either oriented at 135° or 315° performs equally as the other wing in order to maintain a moderate temperature. Yet it can be emphasized that a single wing, not being L-shaped, could be oriented south with proper shading devices and perform the best at maintaining thermal comfort and implementing natural ventilation.

Quarters	T_{db} (°F)	Operative Temperature T_{op} (°F)																															
		0°/E				45°/NE::Base				90°/N				135°/NW				180°/W				225°/SW				270°/S				315°/SE			
		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded		Unshaded		Shaded	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
June I	69.3	76.0	78.6	74.7	77.4	75.3	77.7	74.4	76.9	74.6	77.1	73.9	76.5	75.6	78.1	74.4	77.1	76.1	78.7	74.7	77.4	75.1	77.6	74.4	76.9	74.2	76.7	73.9	76.5	75.1	77.7	74.4	77.0
June II	78.5	78.8	82.7	76.0	79.2	77.5	80.9	75.4	78.3	75.7	78.7	74.7	77.5	77.3	81.2	75.8	79.0	78.2	82.6	76.2	79.5	76.4	80.3	75.2	78.3	75.2	78.2	74.7	77.5	77.5	81.0	75.7	78.8
June III	**85.9**	82.9	**88.9**	79.4	**84.3**	82.0	**87.5**	78.9	83.7	80.5	**85.7**	78.3	82.9	82.2	**87.7**	79.2	84.0	82.8	**88.6**	79.4	**84.2**	80.7	**86.1**	78.8	83.5	79.0	83.9	78.1	82.7	81.1	**86.8**	79.0	83.9
June IV	76.4	80.8	**84.4**	78.6	82.2	79.8	82.8	78.2	81.5	78.6	81.9	77.3	80.8	80.1	83.3	78.2	81.6	80.9	**84.2**	78.6	82.1	79.5	82.5	78.1	81.4	77.8	81.3	77.3	80.7	79.3	82.9	78.0	81.6
July I	72.1	78.6	82.3	77.2	80.9	78.1	81.7	76.9	80.5	76.9	80.3	76.1	79.6	78.1	81.5	76.8	80.3	78.9	82.5	77.2	80.9	77.9	81.5	76.9	80.5	76.3	79.7	76.0	79.5	77.4	80.9	76.6	80.1
July II	78.5	79.9	**84.2**	77.3	81.0	78.9	82.9	76.7	80.3	76.8	80.4	75.8	79.1	78.5	82.7	76.9	80.6	79.5	**84.3**	77.4	81.3	77.8	82.3	76.6	80.3	76.2	79.7	75.7	79.0	78.3	82.3	76.8	80.3
July III	**85.9**	83.4	**89.7**	80.1	**85.2**	82.7	**88.7**	79.6	**84.7**	81.0	**86.5**	78.7	83.6	82.8	**88.5**	79.7	**84.8**	83.5	**89.5**	80.0	**85.2**	81.4	**87.3**	79.4	**84.5**	79.3	**84.4**	78.5	83.3	81.4	**87.4**	79.5	**84.6**
July IV	77.5	82.0	**86.3**	79.8	83.9	81.3	**85.5**	79.4	83.5	79.5	83.5	78.2	82.2	81.2	**85.0**	79.2	83.0	82.2	**86.3**	79.8	83.7	80.9	**85.0**	79.4	83.3	78.6	82.6	78.0	82.0	80.1	**84.3**	78.9	82.9
Aug I	72.7	79.6	83.4	78.0	81.8	78.7	82.2	77.3	80.9	77.6	81.1	76.4	80.0	79.0	82.6	77.4	81.0	79.8	83.5	78.0	81.9	78.3	81.9	77.3	81.0	76.3	79.9	76.1	79.8	78.2	81.9	77.3	81.0
Aug II	81.3	82.2	**87.0**	79.1	83.2	81.0	**85.4**	78.0	81.8	78.0	81.7	76.5	80.1	80.0	**84.5**	78.2	82.2	81.7	**87.3**	79.3	83.7	79.5	**85.0**	78.1	82.2	76.5	80.1	76.2	79.7	79.7	83.9	78.1	82.0
Aug III	**91.5**	**86.6**	**94.0**	82.6	**88.7**	**86.0**	**92.9**	81.6	**87.4**	**84.1**	**90.5**	80.5	**86.0**	**85.9**	**92.4**	81.7	**87.5**	**86.7**	**93.8**	82.6	**88.7**	83.8	**91.0**	81.5	**87.3**	80.4	**86.3**	79.8	**85.2**	83.6	**91.1**	81.6	**87.5**
Aug IV	79.9	**85.0**	**90.0**	82.3	**87.2**	83.7	**88.0**	81.3	**85.8**	81.9	**86.3**	79.7	**84.3**	**84.2**	**88.4**	81.3	**85.8**	**85.2**	**89.8**	82.3	**87.0**	82.9	**87.3**	81.3	**85.7**	79.7	**84.4**	79.3	83.9	82.9	**87.7**	81.2	**85.9**
Sept I	59.7	70.9	71.8	70.1	71.0	70.8	71.7	69.8	70.8	70.6	71.4	69.5	70.4	70.9	71.7	69.9	70.8	71.0	71.9	70.2	71.1	70.4	71.4	69.8	70.8	69.7	70.7	69.3	70.2	70.5	71.4	69.8	70.8
Sept II	65.2	71.8	73.0	70.1	70.9	71.8	73.0	69.8	70.5	70.6	71.4	69.0	69.6	70.5	71.4	69.4	70.1	71.6	73.1	70.2	71.2	71.1	73.0	69.9	70.8	69.4	70.5	68.7	69.4	70.3	71.1	69.4	70.0
Sept III	75.9	75.7	79.2	73.3	75.8	76.2	79.5	72.9	75.2	76.0	79.1	72.5	74.7	75.9	78.8	72.8	75.1	75.9	79.1	73.4	75.9	74.7	78.5	72.8	75.3	73.3	77.4	71.8	74.2	74.3	78.1	72.7	75.1
Sept IV	64.5	73.2	74.9	71.9	73.6	72.9	74.5	71.4	73.0	72.7	74.3	71.1	72.7	73.2	74.8	71.6	73.2	73.3	74.9	71.9	73.6	72.3	74.1	71.4	73.0	71.5	73.5	70.7	72.4	72.6	74.5	71.6	73.3

Table 4-6 Performance of base building in different orientations with and without external shading devices

IRC Model

Quarters	Outside Dry Bulb Temp Tdb (°F)	BASE Operative Temperature M_0 T_{op} (°F)		IRC Operative Temperature M_{IRC} T_{op} (°F)		Wind Direction (°)	Wind Speed (m/s)	Base M_0 Indoor air velocity (m/s)	IRC M_{IRC} Indoor air velocity (m/s)	Cooling due to air speed M_0 (K)	Cooling due to air speed M_{IRC} (K)	Base Model M_0 :T_{adj} (°F)		IRC Model M_{IRC} :T_{adj} (°F)	
		First Floor	Second Floor	First Floor	Second Floor							First Floor	Second Floor	First Floor	Second Floor
June I	69.3	75.3	77.7	74.1	76.4	122.5	3.0	0.40	0.60	1.14	2.1	73.2	75.6	70.2	72.6
June II	78.5	77.5	80.9	75.2	78.0	157.2	4.0	0.60	0.70	2.14	2.6	73.7	77.1	70.5	73.3
June III	85.9	82.0	87.5	78.8	83.5	157.6	6.0	0.80	1.10	3.02	4.4	76.5	82.1	70.9	75.6
June IV	76.4	79.8	82.8	77.8	80.8	129.4	4.0	0.60	0.70	2.14	2.6	76.0	79.0	73.2	76.1
July I	72.1	78.1	81.7	76.6	80.0	97.0	2.0	0.30	0.30	0.58	0.6	77.0	80.7	75.5	78.9
July II	78.5	78.9	82.9	76.5	79.9	122.7	3.0	0.40	0.60	1.14	2.1	76.8	80.8	72.7	76.1
July III	85.9	82.7	88.7	79.5	**84.4**	139.6	3.0	0.40	0.60	1.14	2.1	80.6	86.6	75.6	80.6
July IV	77.5	81.3	85.5	79.1	82.7	93.4	2.0	0.30	0.30	0.58	0.6	80.2	**84.5**	78.0	81.7
Aug I	72.7	78.7	82.2	77.0	80.3	126.3	2.0	0.30	0.30	0.58	0.6	77.7	81.2	75.9	79.3
Aug II	81.3	81.0	85.4	77.8	81.5	150.4	4.0	0.60	0.70	2.14	2.6	77.1	81.5	73.1	76.8
Aug III	91.5	86.0	92.9	81.5	87.2	165.1	5.0	0.70	0.90	2.60	3.8	81.3	88.2	74.7	80.4
Aug IV	79.9	83.7	88.0	80.9	**85.0**	144.4	3.0	0.40	0.60	1.14	2.1	81.7	85.9	77.1	81.1
Sept I	59.7	70.8	71.7	69.5	70.3	109.0	2.0	0.30	0.30	0.58	0.6	69.8	70.6	68.5	69.2
Sept II	65.2	71.8	73.0	69.6	70.2	136.1	4.0	0.60	0.70	2.14	2.6	68.0	69.2	64.9	65.5
Sept III	75.9	76.2	79.5	72.7	75.0	162.1	5.0	0.70	0.90	2.60	3.8	71.5	74.8	65.9	68.2
Sept IV	64.5	72.9	74.5	71.0	72.4	121.0	3.0	0.40	0.60	1.14	2.1	70.8	72.4	67.1	68.6

Table 4-7 Comparison of adjusted operative temperature between base model and IRC model

The existing apartment (M_0) was then compared to the IRC model (M_{IRC}). The increased operable window area, which was almost two times larger than that of the base model, was able to induce more cooling due to increased average indoor air speed. This increased the percentage of discomfort area induced by higher indoor air speed in small areas of the living room when compared to that of the base building. The number of discomfort sessions decreased to zero in the IRC model. The adjusted operative temperatures in the M_{IRC}

model were lower than thermal comfort by a minimum of 2ºF in all cases when compared to the maximum comfort temperature of adaptive comfort standard. These data are listed in Table 4-7. The comparisons of adjusted operative temperature of the base model (M_0) and the M_{IRC} model are shown in Figure 4-7 and Figure 4-8.

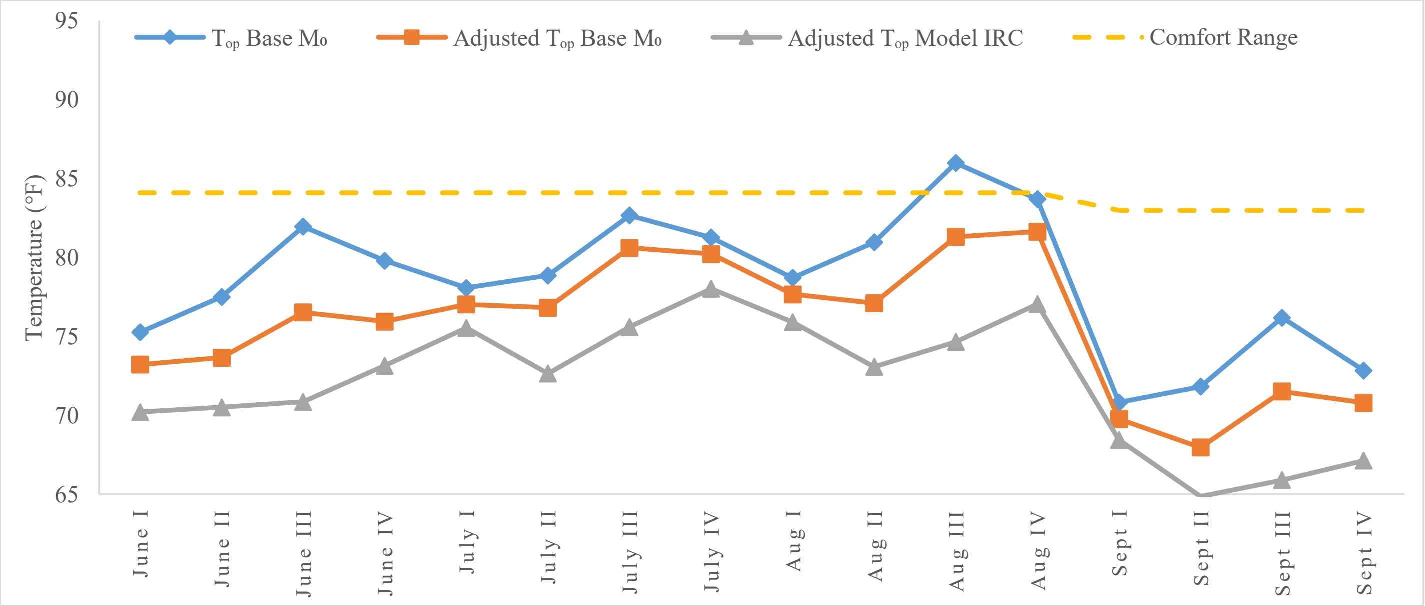


Figure 4-7 Comparison of adjusted operative temperatures of first floor between base and IRC models for different sessions of different months

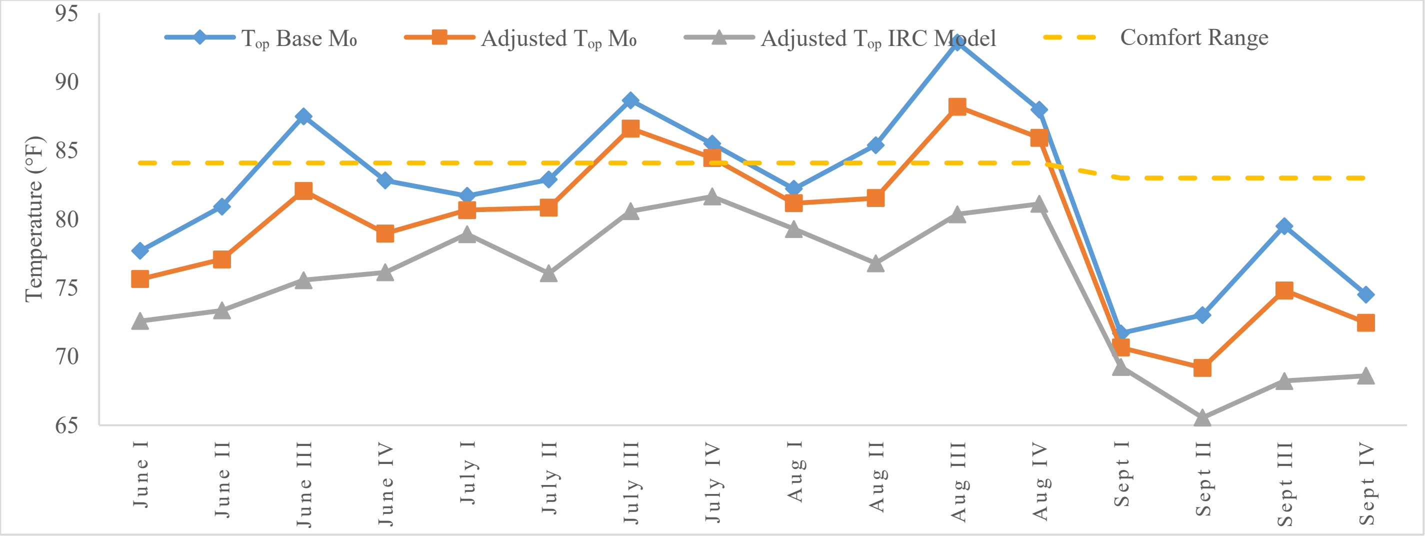


Figure 4-8 Comparison of adjusted operative temperatures of second floor between base and IRC models for different sessions of different months

Building Construction

The M_0 lightweight model was able to utilize natural ventilation and maintain thermal comfort in most, but not all, of the sessions. When the base model was modified to IRC recommended heavy mass construction (M_{0hvy}), keeping all other parameters constant, the adjusted operative temperature decreased to comfort temperature in all the sessions.

Quarters	Outside DB Temp	T_{adj} M_0 (°F)		T_{adj} M_{IRC} (°F)		T_{adj} M_{0hvy} (°F)		T_{adj} M_{IRChvy} (°F)	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
June I	69.28	73.23	75.64	71.43	73.84	70.2	72.6	71.6	73.3
June II	78.52	73.66	77.07	72.84	76.24	70.5	73.3	71.7	73.8
June III	**85.94**	76.53	82.06	74.05	79.57	70.9	75.6	69.8	72.3
June IV	76.42	75.96	78.96	75.13	78.13	73.2	76.1	72.4	74.2
July I	72.14	77.03	80.66	77.03	80.66	75.5	78.9	78.2	80.8
July II	78.52	76.82	80.84	75.02	79.04	72.7	76.1	75.6	78.3
July III	**85.86**	80.62	**86.61**	78.82	**84.81**	75.6	80.6	76.5	79.6
July IV	77.46	80.23	**84.45**	80.23	**84.45**	78.0	81.7	78.7	80.9
Aug I	72.74	77.68	81.16	77.68	81.16	75.9	79.3	78.1	80.5
Aug II	81.29	77.12	81.54	76.29	80.71	73.1	76.8	75.2	77.9
Aug III	**91.54**	81.31	**88.18**	79.19	**86.06**	74.7	80.4	74.5	77.6
Aug IV	79.92	81.65	**85.92**	79.85	**84.12**	77.1	81.1	76.9	79.3
Sept I	59.71	69.78	70.64	69.78	70.64	68.5	69.2	70.7	71.6
Sept II	65.18	67.98	69.16	67.15	68.34	64.9	65.5	67.1	68.1
Sept III	75.89	71.52	74.81	69.40	72.68	65.9	68.2	66.0	67.3
Sept IV	64.52	70.80	72.45	69.00	70.65	67.1	68.6	67.4	68.3

Table 4-8 Comparison of performance of base model (M0) and MIRC under two different construction systems

When the M_{IRC} was assigned the lightweight construction, the model showed a similar amount of comfortable sessions as the M_0 model using the lightweight construction system. The adjusted operative temperature (T_{adj}) for all the sessions, however, decreased significantly and were lower and closer to the comfort range. Similarly, the M_{IRChvy} model showed highly improved thermal comfort hours/sessions and lower temperature swing than M_{0hvy}. Each session of the months studied produced comfortable adjusted operative temperature in the M_{IRChvy} model. The data are available in Table 4-8.

Window-Wall-Ratio

The effect of Window-Wall-Ratio (WWR) on thermal comfort is significantly affected by increased glazing area, which admits higher heat gain. The model without any windows and no natural ventilation, demonstrated that windows are also significant for heat loss. Several sessions of the M_{w0} model had an operative temperature higher than 100°F.

The M_{w5} and M_{w10}, which had a WWR of 5% & 10% respectively, performed the best. All operative temperatures for each session were below the maximum adaptive thermal comfort level. The operative temperature increased consistently across all other models while WWR increased. Further study of M_{w5} and M_{w10} may be carried out as daylighting is also affected by WWR, one of the vital factors in determining comfort.

	Temperature in F															
Quarters	Outside T_{db}	Top M_0		T_{op} M_{w0}		T_{op} M_{w4}		T_{op} M_{w10}		T_{op} M_{w15}		T_{op} M_{w20}		T_{op} M_{w30}	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
June I	69.3	75.3	77.7	74.9	64.0	72.4	75.2	73.1	75.8	74.1	76.4	74.1	76.4	74.5	76.4
June II	78.5	77.5	80.9	74.1	**100.4**	72.6	75.3	73.6	76.4	75.2	78.0	75.4	78.2	76.5	79.2
June III	**85.9**	82.0	**87.5**	75.1	**108.8**	74.2	77.8	75.8	79.8	78.8	83.5	79.3	84.0	81.9	**86.8**
June IV	76.4	79.8	82.8	76.5	73.2	74.5	77.9	75.7	79.1	77.8	80.8	78.1	81.0	79.4	81.8
July I	72.1	78.1	81.7	76.9	65.3	74.6	78.3	75.4	79.0	76.6	80.0	76.7	80.0	77.3	80.2
July II	78.5	78.9	82.9	75.5	**101.7**	74.0	77.3	75.0	78.4	76.5	79.9	76.7	80.0	77.8	81.0
July III	**85.9**	82.7	**88.7**	76.3	**113.2**	75.3	79.3	76.7	81.1	79.5	**84.4**	79.9	**84.9**	82.3	**87.5**
July IV	77.5	81.3	**85.5**	77.7	72.5	75.7	79.7	77.0	80.8	79.1	82.7	79.4	83.0	80.8	**84.2**
Aug I	72.7	78.7	82.2	77.1	65.5	74.8	78.5	75.6	79.3	77.0	80.3	77.1	80.4	77.7	80.6
Aug II	81.3	81.0	**85.4**	76.1	**103.2**	74.7	78.2	75.9	79.5	77.8	81.5	78.1	81.8	79.6	83.2
Aug III	**91.5**	**86.0**	**92.9**	77.2	**115.9**	76.3	80.8	78.2	83.0	81.5	**87.2**	82.1	**87.9**	**85.1**	**91.2**
Aug IV	79.9	83.7	**88.0**	78.7	74.8	76.8	81.2	78.3	82.7	80.9	**85.0**	81.3	**85.3**	83.0	**86.5**
Sept I	59.7	70.8	71.7	71.0	52.4	68.9	70.0	69.1	70.2	69.5	70.3	69.5	70.2	69.4	69.8
Sept II	65.2	71.8	73.0	69.5	79.9	68.3	69.0	68.8	69.5	69.6	70.2	69.6	70.3	70.2	70.8
Sept III	75.9	76.2	79.5	70.4	**92.4**	69.7	71.1	70.8	72.4	72.7	75.0	73.0	75.4	74.8	77.4
Sept IV	64.5	72.9	74.5	71.7	58.6	69.4	70.8	70.0	71.5	71.0	72.4	71.2	72.7	71.8	73.1

Table 4-9 Operative temperature (T_{op}) for different window wall ratio (WWR)

July III and August III sessions have consistently offered challenges for indoor thermal comfort. Figure 4-9 and Figure 4-10 show the nature of change in operative temperature in those two sessions with relation to WWR.

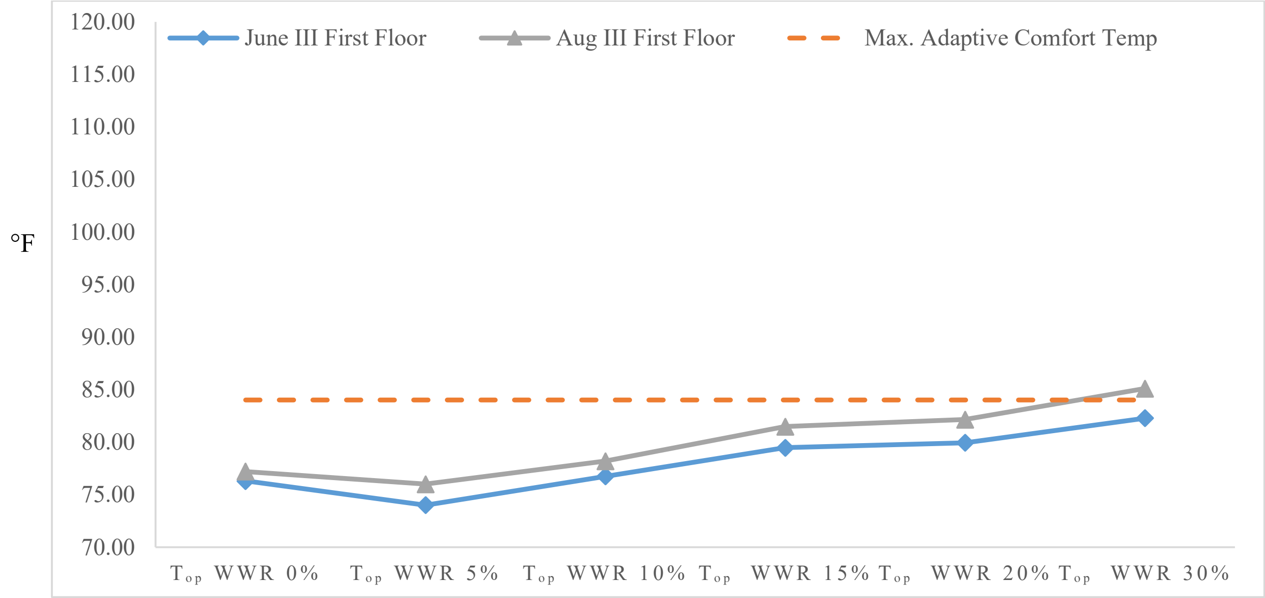


Figure 4-9 July III and August III sessions first floor operative temperature for different WWRs

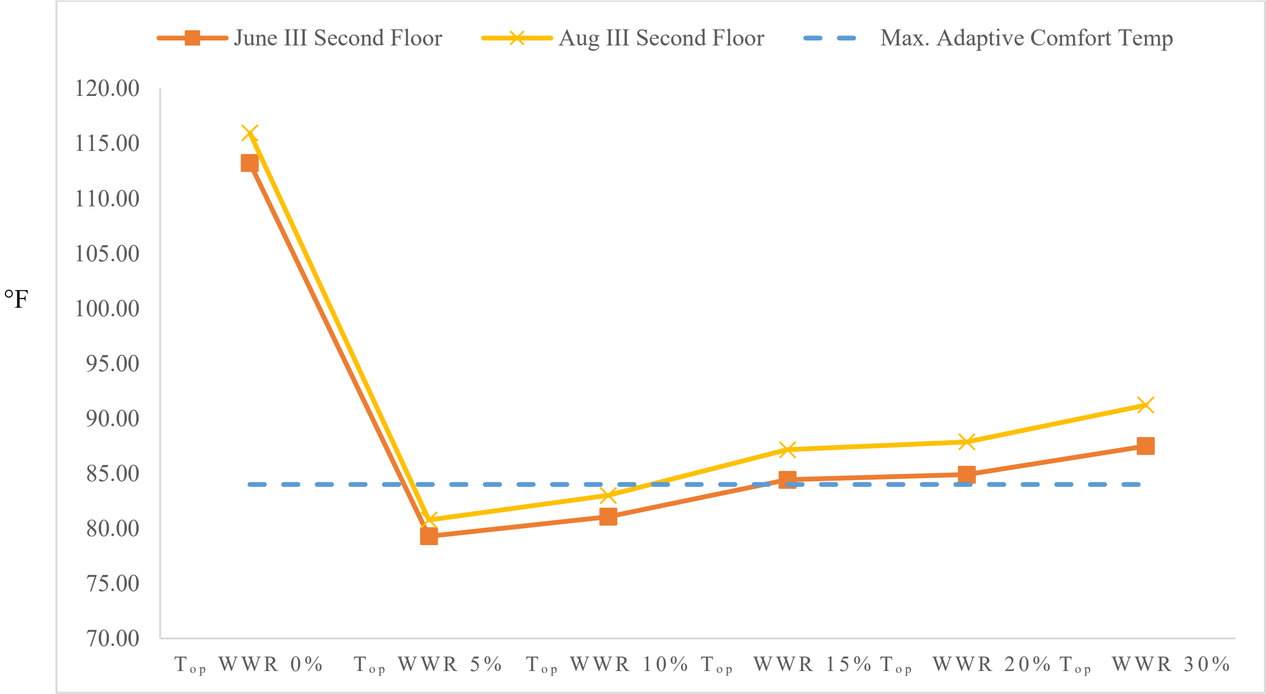


Figure 4-10 July III and August III sessions second floor operative temperature for different WWRs

It can be assumed that the heat gain through windows is primarily responsible for the constantly increasing T_{op} with respect to increasing WWR. Table 4-10 shows the solar gain through windows for different WWRs. The second floor showed more impact of heat gain, through the windows than the first floor. The ground contact occurring in the first floor might have assisted as a heat sink and maintained a cooler operative temperature compared to that of the second floor. Further investigation needs to be carried out in regards of cooling effect of earth contact for ground floor units versus upper story units that lack earth contact.

Floors	Heat Gain WWR 5% (kWh)	Heat Gain WWR 10% (kWh)	Heat Gain WWR 15% (kWh)	Heat Gain WWR 20% (kWh)	Heat Gain WWR 30% (kWh)
First Floor July III	0.786316	1.473327	2.956148	3.22363	4.677456
First Floor Aug III	1.005763	1.837941	3.618172	3.885484	5.591853
Second Floor July III	0.758337	1.429834	2.914918	3.039381	4.320727
Second Floor Aug III	0.973843	1.77229	3.552699	3.669712	5.137279

Table 4-10 Heat gain through window in different WWR models

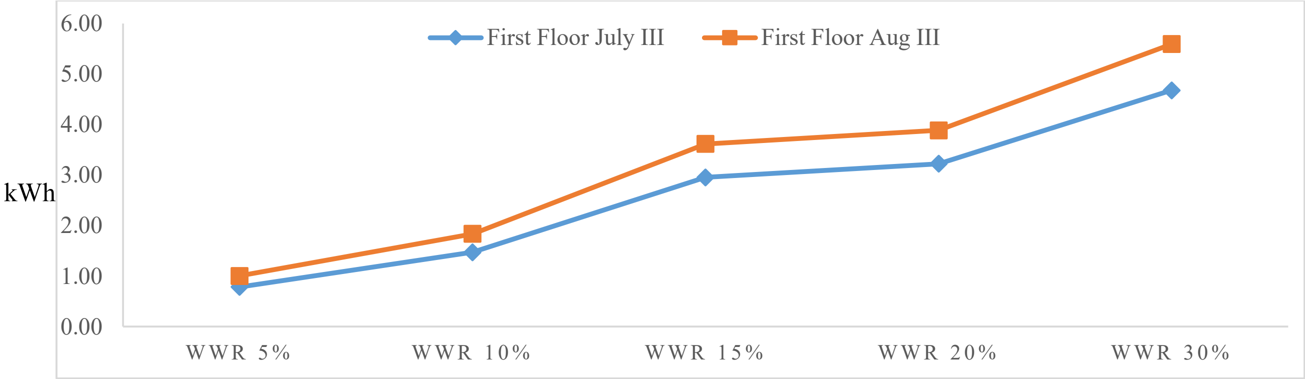


Figure 4-11 First floor heat gains through glazing/window in different WWR

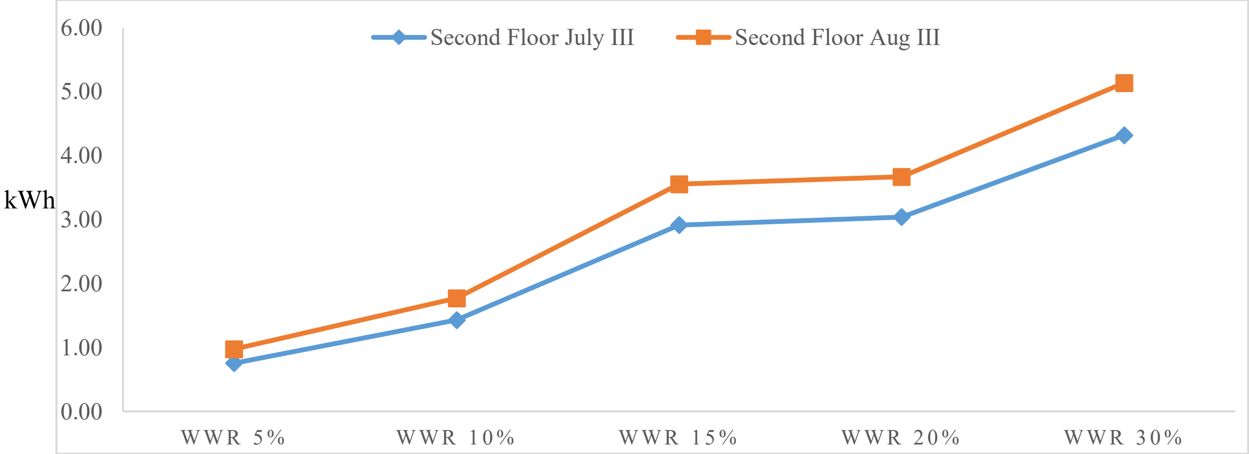


Figure 4-12 Second floor heat gains through glazing/window in different WWR

Comfort Hours

Finally, the effectiveness of natural ventilation was determined by comparing comfort hours in different models. The use of external shading devices in the existing model had positive effects on thermal comfort, increasing the comfort hour percentage to 100% for both floors during natural ventilation. Similarly, M_{0hvy}, M_{IRC}, M_{IRChvy}, M_{w5}, and M_{w10} were able to increase the thermal comfort hour percentage to 100% with shading.

Across all the simulations, except for the existing building where physiological cooling of natural ventilation is not considered, sessions I and II maintained 100% comfort hours. The existing apartment should be modified to increase the percentage of comfort hours in sessions III, and IV, which occur in the afternoon and evening. It should, however, be noted that this was achieved with the aid of external environmental conditions, namely adequate wind speed and air temperature. Natural ventilation can't solely maintain thermal comfort when the outdoor temperature is high and/or wind speed is low, as it cannot yield effective cooling. It is highly important that the occupants can operate available windows at suitable times and shut them when the external conditions are unfavorable.

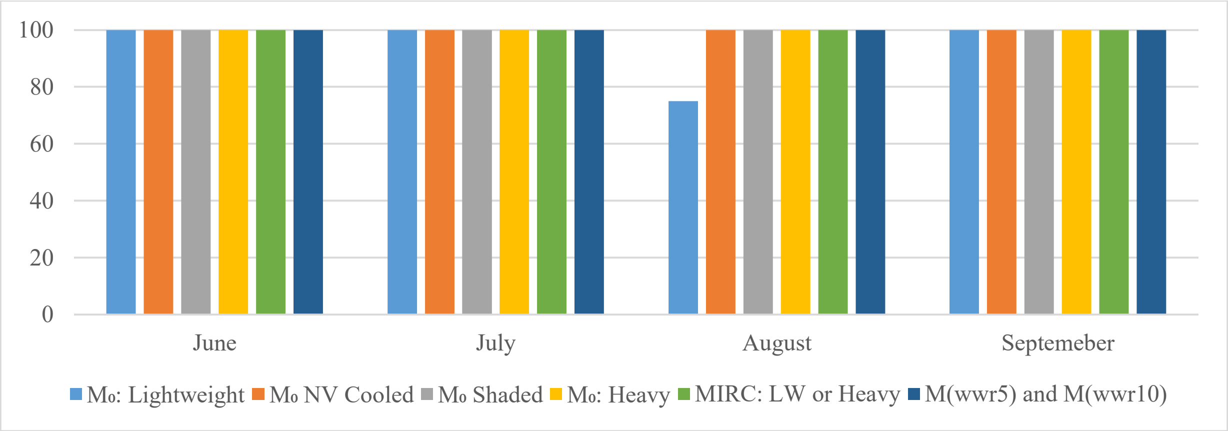


Figure 4-13 Monthly comfort hour percentage of the first floor in different model conditions

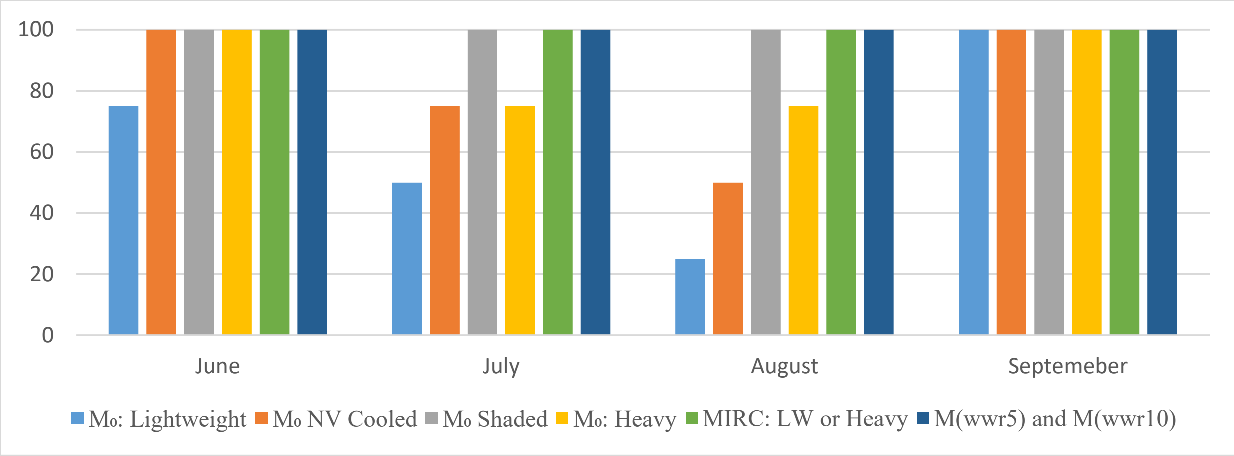


Figure 4-14 Monthly comfort hour percentage of the second floor in different model conditions

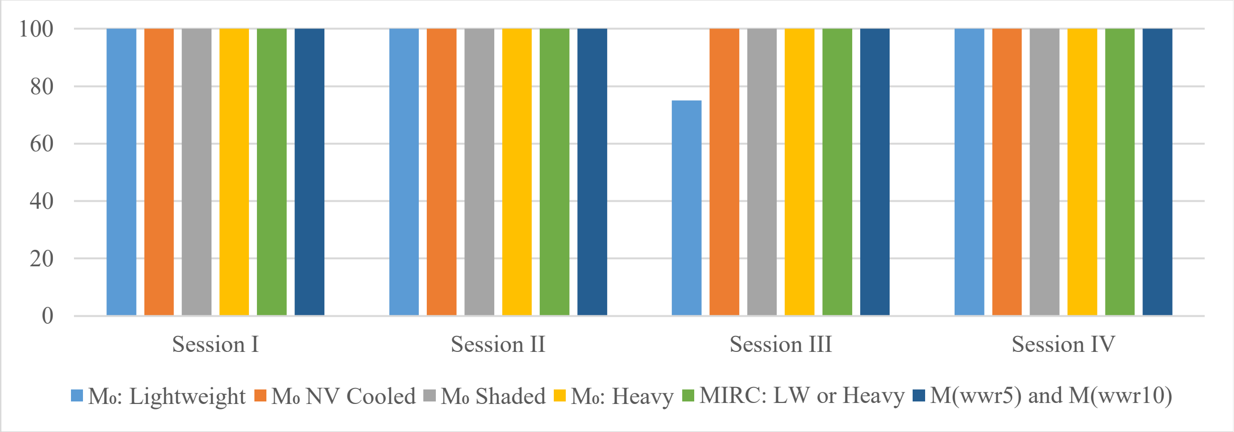


Figure 4-15 Session-wise comfort hour percentage of the first floor in different model conditions

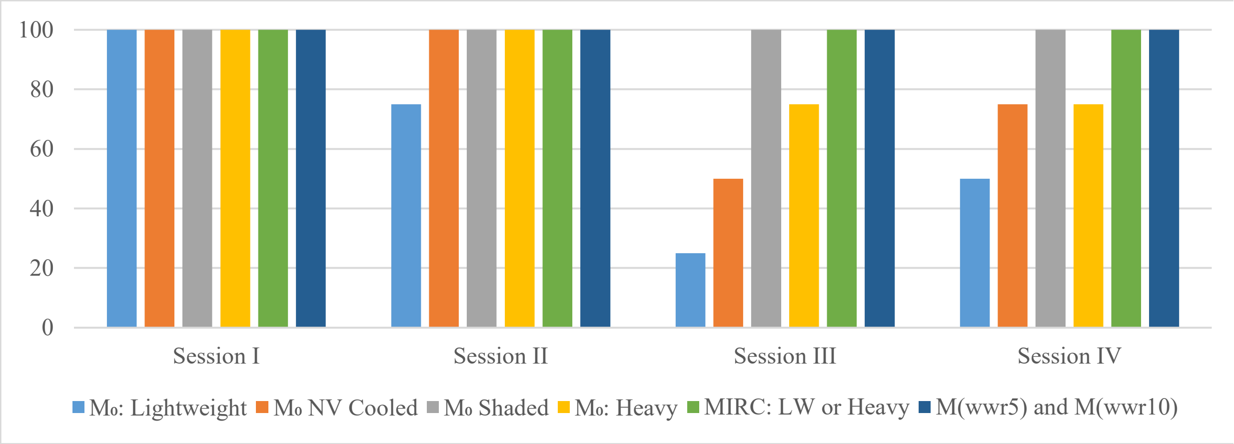


Figure 4-16 Session-wise comfort hour percentage of the second floor in different model conditions

It is clear from these graphs of comfort hours and sessions that natural ventilation was much less effective in the second floor unit, which was more sensitive to overheating. Increased skin heat gains from the roof, in both the cases of lightweight construction and a higher WWR, can be the reason for that difference although this hypothesis requires further study. The first floor unit being ground coupled wasn’t as sensitive to overheating.

Chapter 5 - Conclusion

The feasibility of using natural ventilation, specifically cross ventilation, for cooling multi-family apartment units during the summer months in Manhattan, KS, was the objective of this study. An initial hypothesis questioning the applicability of IRC's code for minimum operable window area in a high-wind area such as Kansas was tested. Moreover, orientation, external shading devices, construction system, and WWR were considered to understand how these features impact cooling loads that can be countered by cross ventilation. An apartment building from Kansas State University was selected for the study. Computational fluid dynamics was used to deduce the respective indoor air speed for varying magnitudes of outdoor wind. In another set of simulations, an operative temperature for existing apartment units was calculated. Accounting for physiological cooling due to elevate indoor air speed, adjusted operative temperature of the existing apartment was then compared with that from models modified by orientation, shading devices, operable window area, construction systems, and WWR. Across these variations, IRC minimums and standards for ventilation area, construction system, and insulation were incorporated.

The climatic data demonstrated exterior wind speeds could produce sufficient indoor air speed to yield effective physiological cooling. Physiological cooling, in turn, enhanced thermal comfort in different periods during the cooling season. External shading devices, in particular, were most effective in reducing loads to make thermal comfort attainable. Similarly, the IRC-recommended operable window area with both heavy mass construction and light construction, as well as conservative WWRs (5% and 10%) moderated loads so that 100% thermal comfort was attainable. It was also evident from the study that ground coupled first floor units are much less sensitive to overheating than second floor units, which could not provide thermal comfort during natural ventilation. The difference between first and second level units is likely a combination of the cooling impact of ground coupling and the increased skin heat gain from the roof, though a detailed understanding of how these mechanisms work together in multiple-floor units requires further investigations.

The orientation of the existing apartment building, which is L-shaped and oriented at 45 degrees from south, was justified by this study. Orientating the building in a cardinal direction improves the cooling performance of one wing but decreases performance for the other wing at the same time. The NE orientation, coincidentally, can provide moderate indoor temperatures in both the wings simultaneously.

The IRC-recommended minimum operable window area, which is 4% of the total area being ventilated, demonstrated some areas of uncomfortable indoor air speed for the studied apartment given the average wind speeds for the climate of Manhattan, but uncomfortable regions were limited to a small area in the apartment units. It may be noted that disturbing instances of high air speed (over 14 m/s) are rare and in reality, occupants can control the openings of windows at such occasions.

These data and results demonstrated that natural ventilation can be effectively used for cooling during the summer season in the central region of the U.S., a climate with warm summers but ample wind. The use of proper external shading devices, optimal building orientation, and heavier building construction are critical to maximizing thermal comfort with the use of natural ventilation in multi-family apartments. Light-weight construction, on the other hand, makes effective cooling by natural ventilation difficult especially for units that are above ground and subjected to heat gains from roofs. Moreover, the research underscores the importance of preserving access to wind, which drives cross ventilation. Decreased wind speed due to obstructions such as landscaping, adjacent buildings, and unfavorable topography can also reduce the effectiveness of natural ventilation.

Obtaining thermal comfort is possible through multiple combinations of operable window area, orientation, shading, WWR, and construction systems although individual variables were demonstrated to have significant impacts on thermal comfort on their own. In this study the use of energy simulation was critical in evaluating the performance impacts of these variables and underscores the importance of this tool for optimizing buildings in mixed climates.

L-shaped buildings should strictly comply with IRC recommended minimum operable window area, or even higher operable window areas to ensure effectiveness. This approach is justified because the resultant indoor air velocity, which provides physiological cooling, does not rise above 1.1 m/s in the climate of the Central U.S. while up to 2 m/s is acceptable. The best orientation of such buildings is 45° off of cardinal directions. In addition to proper orientation, shading devices and heavy mass construction are important in achieving thermal comfort for the uppermost units in multi-floor dwellings.

Single-wing, linear or elongated buildings of lightweight construction should be oriented to the south and can have an operable window area of low as 50% of the IRC requirements and still yield indoor thermal comfort at both levels with shading devices. Such a building would require relatively conservative WWR, no more than 15% in such case.

In conclusion, multi-family housing designed to reduce heat gains can utilize natural ventilation to offset a large amount, if not all, of cooling load and maintain indoor thermal comfort during all of the summer months. The perspective of this study opposes the notion of extensive use of HVAC in multi-family buildings to maintain thermal comfort during high outdoor temperatures. The availability of significant average wind speed, as low as 2 m/s, can maintain thermal comfort in most of the overheating periods in the Central U.S. Therefore, multi-family housings in hotter climatic regions with ample wind can utilize cross-ventilation for cooling indoors in summer months, conserving substantial energy.

Chapter 6 - Future Studies

Several opportunities for future work were identified in the process of this study. This chapter intends to elaborate on these possible future research paths.

It was observed in the research that most of the first and the second sessions can maintain thermal comfort but the third and the fourth sessions (the afternoon and evening periods) are more challenging. This pattern suggests that overheating in the climate of the central states is delayed during the day, creating peak cooling loads later in the afternoon and evening. The relationship of ventilation strategies and other variable to delayed overheating could be studied further, and optimized solutions to this problem could be proposed.

Similarly, multi-floor building present a special case. First floor units are coupled with the ground, which assists cooling, and are further protected by heat gains from units on the upper floor. Meanwhile, upper floor units subjected to heat gains from the roof have more difficulty maintaining thermal comfort. The role of ground coupling and possible buffers to heat gain, such as ventilated attic spaces should be investigated to better understand the cooling loads that natural ventilation must counter in the central U.S. to maintain thermal comfort.

Heavy construction systems proved effective compared to lightweight construction in offering thermal comfort in conjunction with natural ventilation. However, heavy construction’s advantage was only the result of the poor performance of upper floor units and their sensitivity to roof heat gain with lightweight construction. Therefore, it may be proposed to increase the performance of upper floors by using either heavy construction or additional insulation strategically, while the lower units may be built conventionally. Such approaches may be termed hybrid construction systems, and can be evaluated in a separate study experimenting with the location of mass, buffer spaces, and additional insulation and the impact of overall construction on natural ventilation.

The results of the study also showed that low WWRs of 5% and 10% were able to maintain thermal comfort with lightweight construction, but the study did not take into account the impact of lower glazing areas on daylighting. Daylighting plays a vital role in visual comfort and well-being of occupants, while also reducing daytime internal gains from electric lighting. An optimum WWR would offer quality daylight and be suitable for natural ventilation and thermal comfort, and should be investigated in future studies.

There were many sessions where operative and adjusted operative temperatures were very close to attaining thermal comfort temperature. The potential and feasibility of hybrid cooling systems, which incorporate mechanical systems with passive strategies, can boost thermal comfort with low-energy methods like fans in sessions where temperatures approached the comfort range. The impact of different types of hybrid systems in the central U.S. climate may be further investigated.

Bibliography

ASHRAE, ASHRAE Standard. 2013. "Standard 55-2013." *Thermal Environmental Conditions for Human Occupancy*.

ASHRAE, HVAC APP SI HDBK. 2015. "HVAC Applications Handbook." *IP Edition*.

Bainbridge, David and Ken Haggard. 2011. *Passive Solar Architecture: Heating, Cooling, Ventilation, Daylighting and More using Natural Flows* Chelsea Green Publishing.

Berglund, Larry G. 1998. "Comfort and Humidity." *ASHRAE Journal* 40 (8): 35.

Brager, Gail S. and Richard J. de Dear. 1998. "Thermal Adaptation in the Built Environment: A Literature Review." *Energy and Buildings* 27 (1): 83-96.

Chu, Chia Ren, Y-H Chiu, and Yu-Wen Wang. 2010. "An Experimental Study of Wind-Driven Cross Ventilation in Partitioned Buildings." *Energy and Buildings* 42 (5): 667-673.

Clements-Croome, Derek. 2002. *Naturally Ventilated Buildings: Building for the Senses, the Economy and Society* Routledge.

de Dear, Richard J. and Gail S. Brager. 2002. "Thermal Comfort in Naturally Ventilated Buildings: Revisions to ASHRAE Standard 55." *Energy and Buildings* 34 (6): 549-561. doi:http://dx.doi.org.er.lib.k-state.edu/10.1016/S0378-7788(02)00005-1.

de Saulles, Tom. 2009. *Thermal Mass Explained*: The Concrete Centre.

DeKay, Mark and GZ Brown. 2013. *Sun, Wind, and Light: Architectural Design Strategies* John Wiley & Sons.

———. 2001. "Sun, Wind, and Light: Architectural Design Strategies." .

Deru, Michael P. and Paul A. Torcellini. 2005. *Standard Definitions of Building Geometry for Energy Evaluation* National Renewable Energy Laboratory.

EIA. "Electricity in the United States.".

———. . 2016b. *Monthly Energy Review*: U.S. Energy Environment Administration.

Etheridge, David. 2011. *Natural Ventilation of Buildings Theory, Measurement and Design*. 2nd ed.. ed. Chicester: Chicester : Wiley.

Fathy, Hassan. 1986. "Natural Energy and Vernacular Architecture." *Principales and Examples with Referances to Hot and Climates.the Univercity of Chicago Press.Ed Chicago*.

Gensler. "High-Performance Building Envelopes." Gensler, accessed 11/16, 2016, http://www.gensler.com/research-insight/research/high-performance-building-envelopes.

Givoni, Baruch. 1994. *Passive and Low Energy Cooling of Buildings*. New York: New York : Van Nostrand Reinhold.

Heiselberg, Per. 2002. *Principles of Hybrid Ventilation*, edited by Per Heiselberg. First ed. Aalborg, Denmark: Aalborg University.

IBC, ICC. 2012. "International Code Council." *International Building Code.International Code Council: Washington DC, United States*.

Institute, Construction Specifications. 2013. *The CSI Sustainable Design and Construction Practice Guide*. Hoboken: Hoboken : Wiley.

Intergovernmental Panel on Climate Change. 2015. *Climate Change 2014: Mitigation of Climate Change*. Vol. 3 Cambridge University Press.

James, Paul. 2014. *Urban Sustainability in Theory and Practice: Circles of Sustainability* Routledge.

Kansas State University. "My Community, My Jardine, Kansas State University.", accessed 10/10, 2016, http://housing.k-state.edu/pdfs/housing/082914%20Jardine%20Handbook%20AR.pdf.

Khan, Naghman, Yuehong Su, and Saffa B. Riffat. 2008. "A Review on Wind Driven Ventilation Techniques." *Energy and Buildings* 40 (8): 1586-1604.

Li, Yuguo and Per Heiselberg. 2003. "Analysis Methods for Natural and Hybrid Ventilation–a Critical Literature Review and Recent Developments." *International Journal of Ventilation* 1 (4): 3-20.

Martin, Laura and Jeffery Jones. 2016. *Annual Energy Outlook 2016*. US: EIA.

Mehta, Madan, Walter Scarborough, and Diane Armpriest. 2010. *Building Construction: Principles, Materials, and Systems* Pearson Prentice Hall Ohio.

Melaragno, Michele. 1982. "Wind in Architectural and Environmental Design." .

Milne, Murray, Robin Liggett, and Rashed Al-Shaali. 2007. "Climate Consultant 3.0: A Tool for Visualizing Building Energy Implications of Climates."AMERICAN SOLAR ENERGY SOCIETY; AMERICAN INSTITUTE OF ARCHITECTS, .

Parker, Danny, Philip Fairey, and Robert Hendron. 2010. "Updated Miscellaneous Electricity Loads and Appliance Energy Usage Profiles for use in Home Energy Ratings, the Building America Benchmark Procedures and Related Calculations." *Florida Solar Energy Center, FSECCR-1837-10*.

Prajongsan, Pimolsiri and Steve Sharples. 2012. "Enhancing Natural Ventilation, Thermal Comfort and Energy Savings in High-Rise Residential Buildings in Bangkok through the use of Ventilation Shafts." *Building and Environment* 50: 104-113.

Robinson, Sid, ES Turrell, HS Belding, and SM Horvath. 1943. "Rapid Acclimatization to Work in Hot Climates." *American Journal of Physiology--Legacy Content* 140 (2): 168-176.

Rosenbaum, Marc. 1999. "Passive and Low Energy Cooling Survey." *Environmental Building News, Pp1-14*.

Santamouris, Mat and Peter Wouters. 2006. *Building Ventilation: The State of the Art* Routledge.

Santamouris, Matheos and Francis Allard. 1998. *Natural Ventilation in Buildings: A Design Handbook* Earthscan.

Santamouris, M. and D. Asimakopoulos. 1996. *Passive Cooling of Buildings*. London: London : James & James.

Su, Xing and Xu Zhang. 2010. "Environmental Performance Optimization of Window–wall Ratio for Different Window Type in Hot Summer and Cold Winter Zone in China Based on Life Cycle Assessment." *Energy and Buildings* 42 (2): 198-202.

Sullivan, R., ES Lee, and S. Selkowitz. 1992. "A Method of Optimizing Solar Control and Daylighting Performance in Commercial Office Buildings." *LBL-32931, Lawrence Berkeley Laboratory, Berkeley, CA*.

Szokolay, Steven V. 2008. "Introduction to ARCHITECTURAL SCIENCE-the Basis of Sustainable Design 2nd Edition." .

Tronchin, Lamberto and Kristian Fabbri. 2008. "Energy Performance Building Evaluation in Mediterranean Countries: Comparison between Software Simulations and Operating Rating Simulation." *Energy and Buildings* 40 (7): 1176-1187.

U.S. EPA. "Learn about Sustainability." US Environmental Protection Agency, accessed 11/14, 2016, https://www.epa.gov/sustainability/learn-about-sustainability#what.

Wikipedia.org. www.wikipedia.org, accessed 11/11, 2016, https://en.wikipedia.org/wiki/Typical_meteorological_year.

Appendix A - Apartment Details

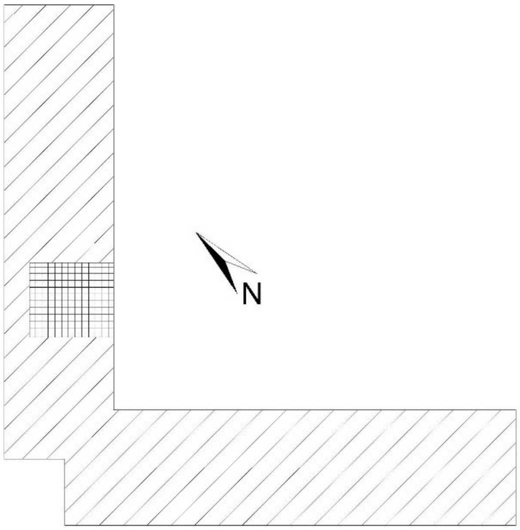


Figure: A-1 The L-Shaped apartment building

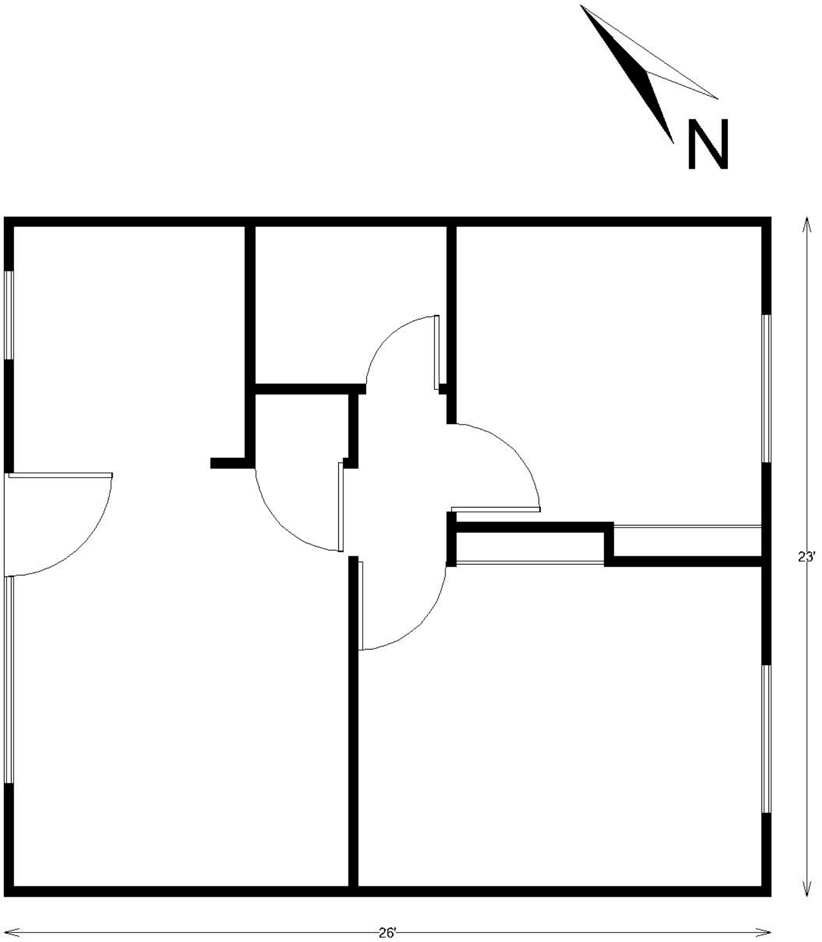


Figure: A-2 Plan of the studied apartment

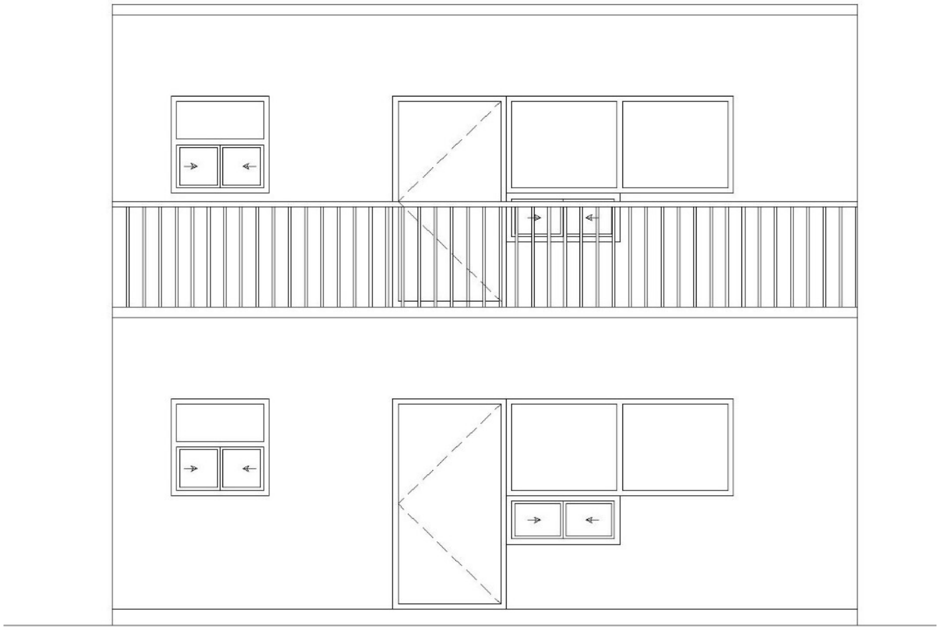


Figure: A-3 Front elevation of the apartment

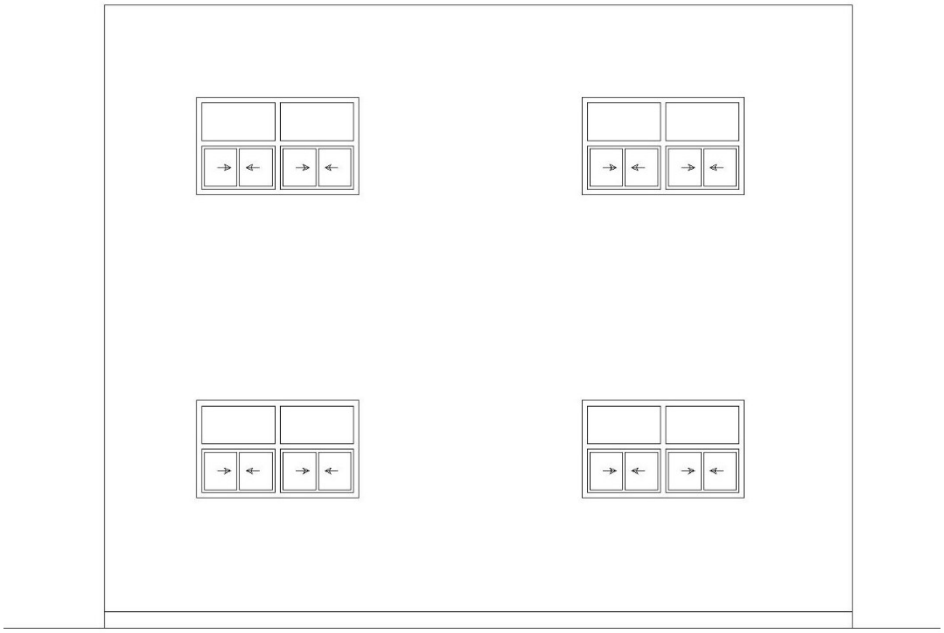


Figure: A-4 Rear elevation of the apartment

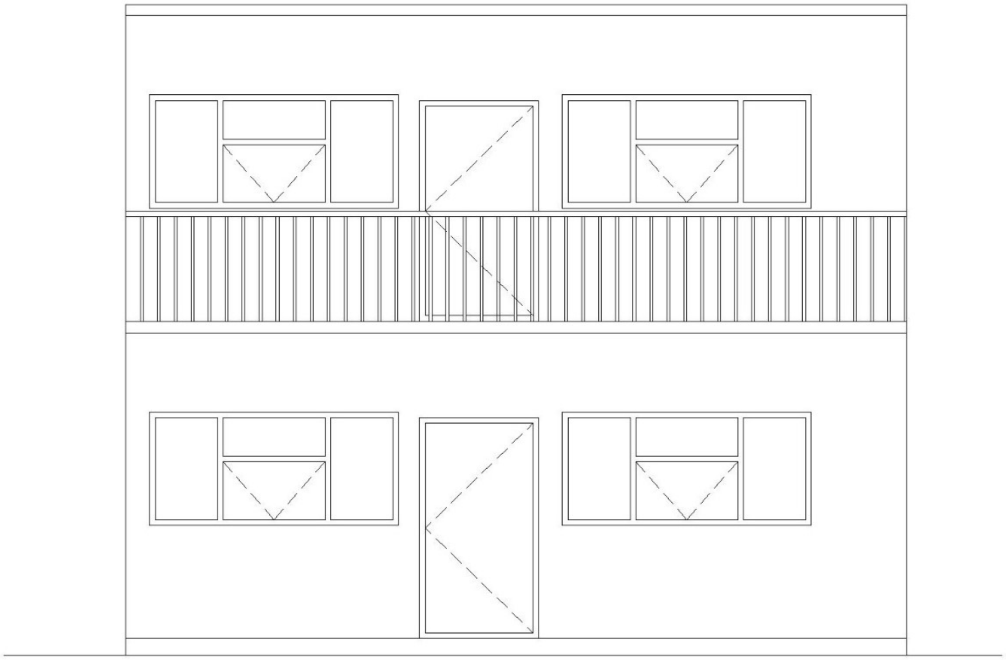


Figure: A-5 Front elevation of modified model, M_{w20}, with a WWR of 20%

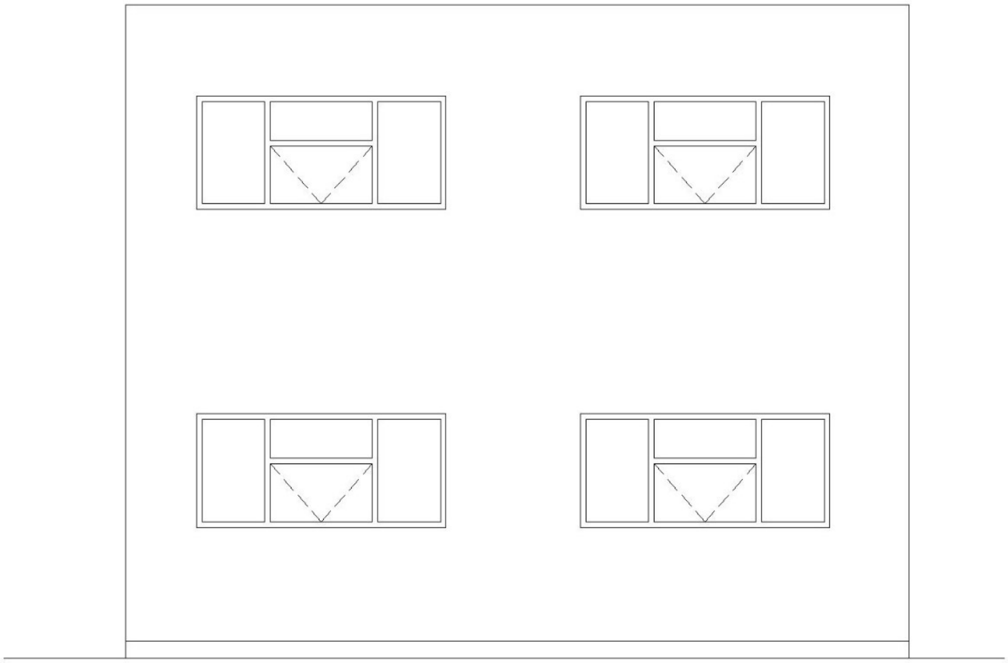
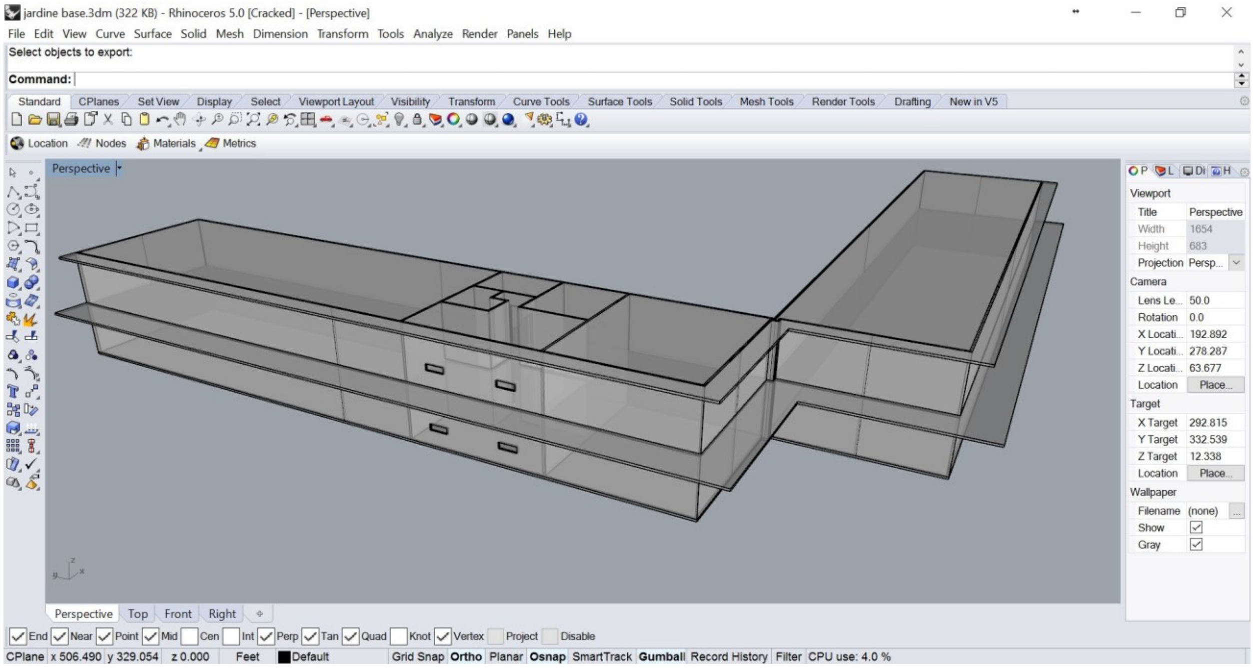


Figure: A-6 Rear elevation of modified model, M_{w20}, with a WWR of 20%



jardine base.3dm (322 KB) - Rhinoceros 5.0 [Cracked] - [Perspective]

Select objects to export:

Command:

Viewport
Title Perspective
Width 1654
Height 683
Projection Persp...

Camera
Lens Le... 50.0
Rotation 0.0
X Locati... 192.892
Y Locati... 278.287
Z Locati... 63.677

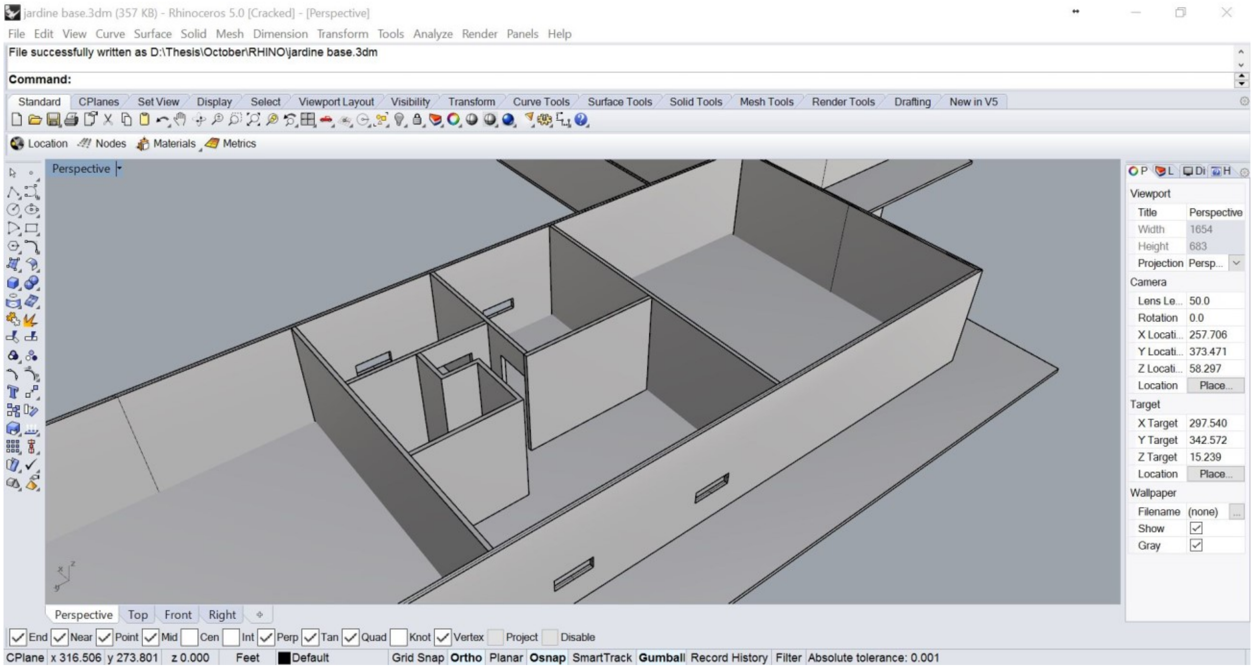
Target
X Target 292.815
Y Target 332.539
Z Target 12.338

Wallpaper
Filename (none)
Show ☑
Gray ☑

☑ End ☑ Near ☑ Point ☑ Mid ☐ Cen ☐ Int ☑ Perp ☑ Tan ☑ Quad ☐ Knot ☑ Vertex ☐ Project ☐ Disable

CPlane x 506.490 y 329.054 z 0.000 Feet Default Grid Snap Ortho Planar Osnap SmartTrack Gumball Record History Filter CPU use: 4.0 %

Figure: A-7 3D x-ray view of the whole building and the apartment blocks that was studied



jardine base.3dm (357 KB) - Rhinoceros 5.0 [Cracked] - [Perspective]

File successfully written as D:\Thesis\October\RHINO\jardine base.3dm

Command:

Viewport
Title Perspective
Width 1654
Height 683
Projection Persp...

Camera
Lens Le... 50.0
Rotation 0.0
X Locati... 257.706
Y Locati... 373.471
Z Locati... 58.297

Target
X Target 297.540
Y Target 342.572
Z Target 15.239

Wallpaper
Filename (none)
Show ☑
Gray ☑

☑ End ☑ Near ☑ Point ☑ Mid ☐ Cen ☐ Int ☑ Perp ☑ Tan ☑ Quad ☐ Knot ☑ Vertex ☐ Project ☐ Disable

CPlane x 316.506 y 273.801 z 0.000 Feet Default Grid Snap Ortho Planar Osnap SmartTrack Gumball Record History Filter Absolute tolerance: 0.001

Figure: A-8 View of a typical two-bedroom apartment that was investigated

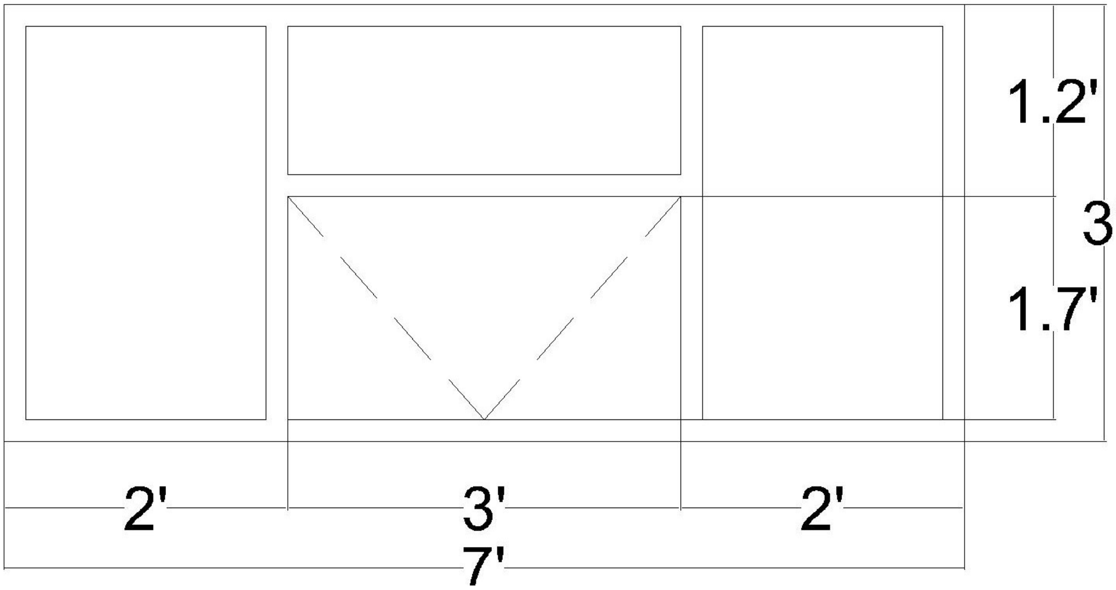


Figure: A-9 Window detail of M_{w20} model, showing operable window area

Appendix B - CFD Results

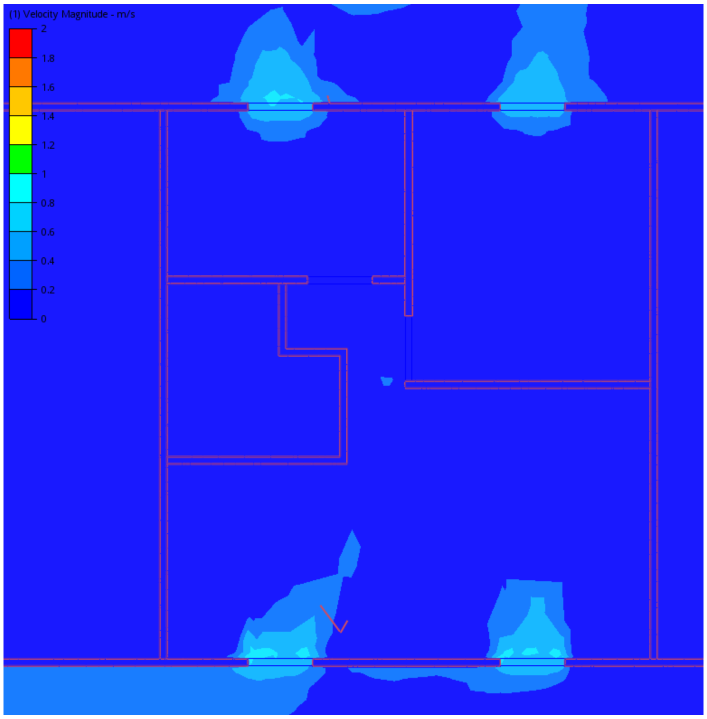


Figure: B-1 CFD simulated indoor air speed for 1 m/s external air, first floor, base model M_0

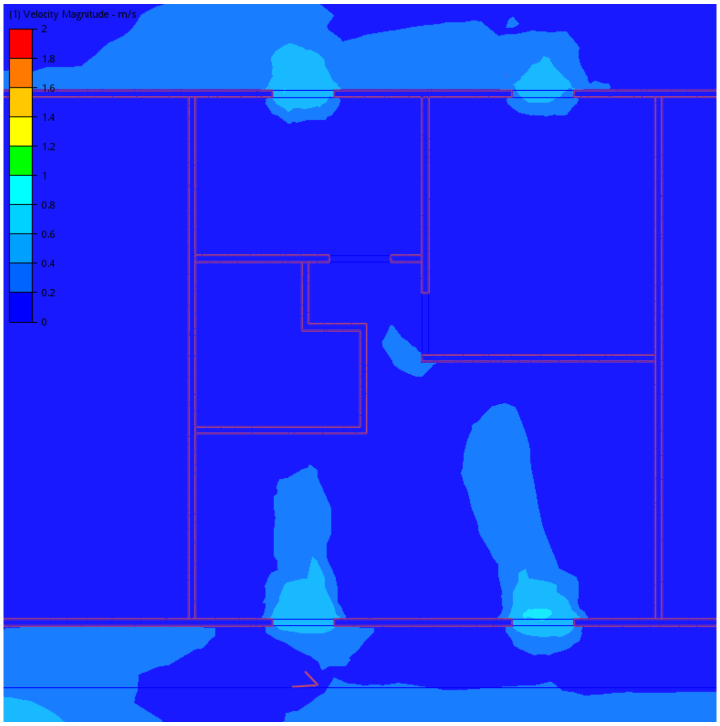


Figure: B-2 CFD simulated indoor air speed for 1 m/s external air, second floor, base model M_0

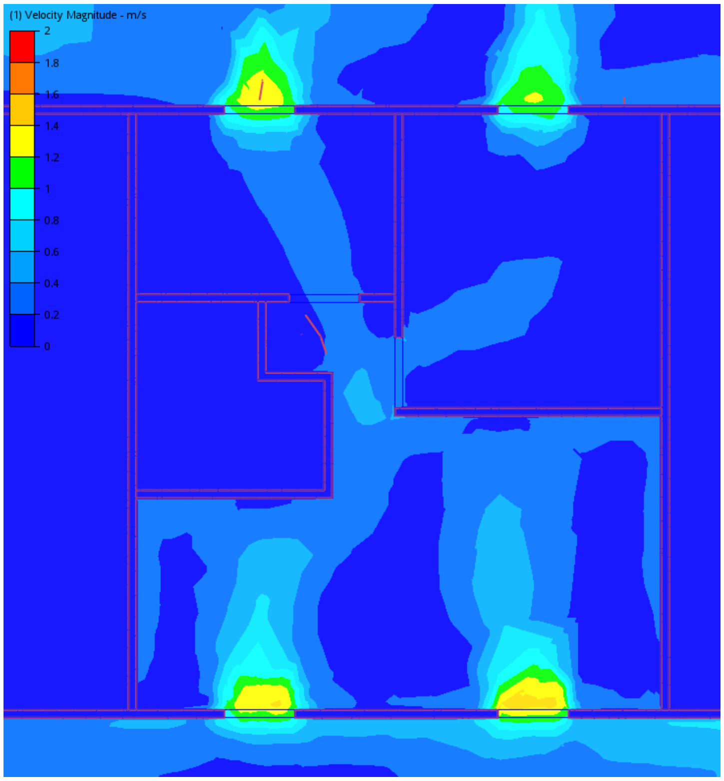


Figure: B-3 CFD simulated indoor air speed for 2 m/s external air, first floor, base model M_0

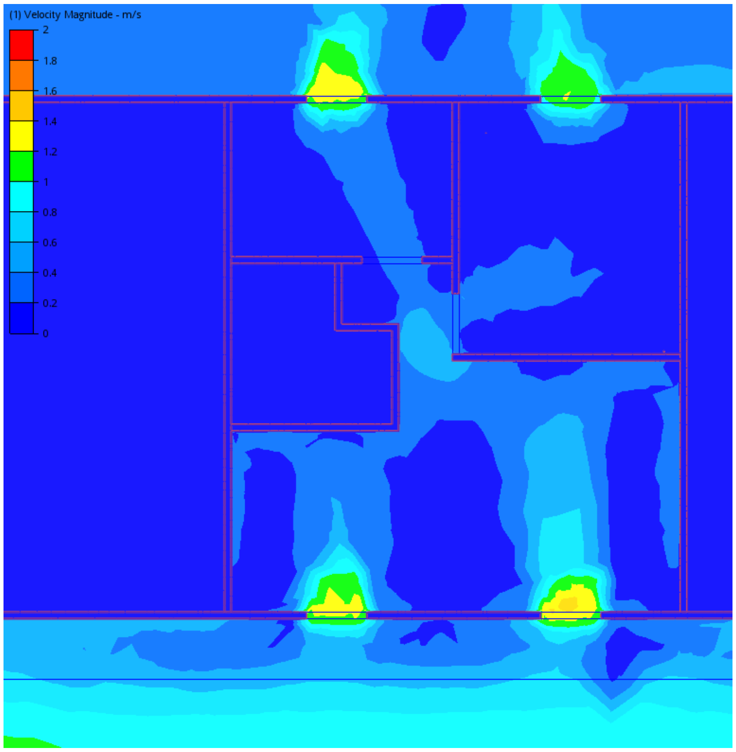


Figure: B-4 CFD simulated indoor air speed for 2 m/s external air, second floor, base model M_0

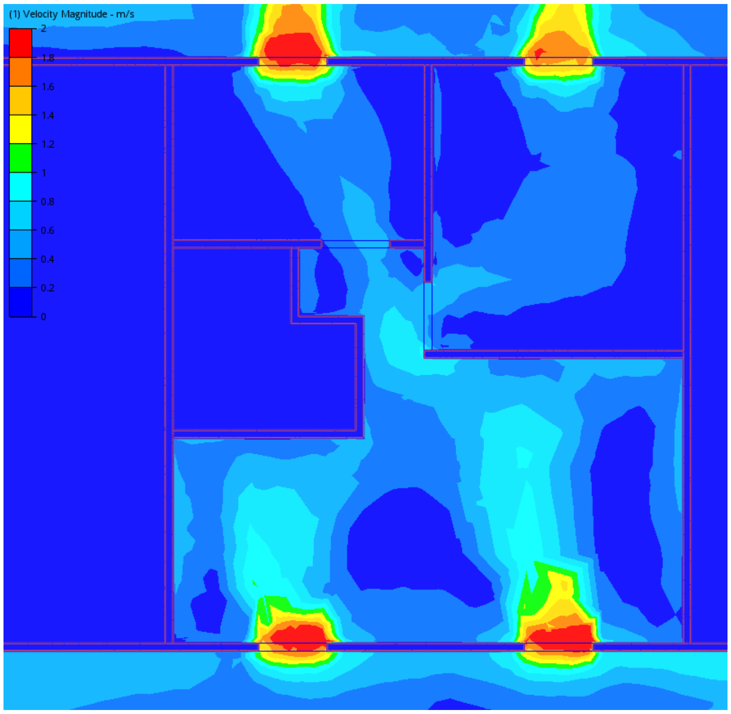


Figure: B-5 CFD simulated indoor air speed for 3 m/s external air, first floor, base model M_0

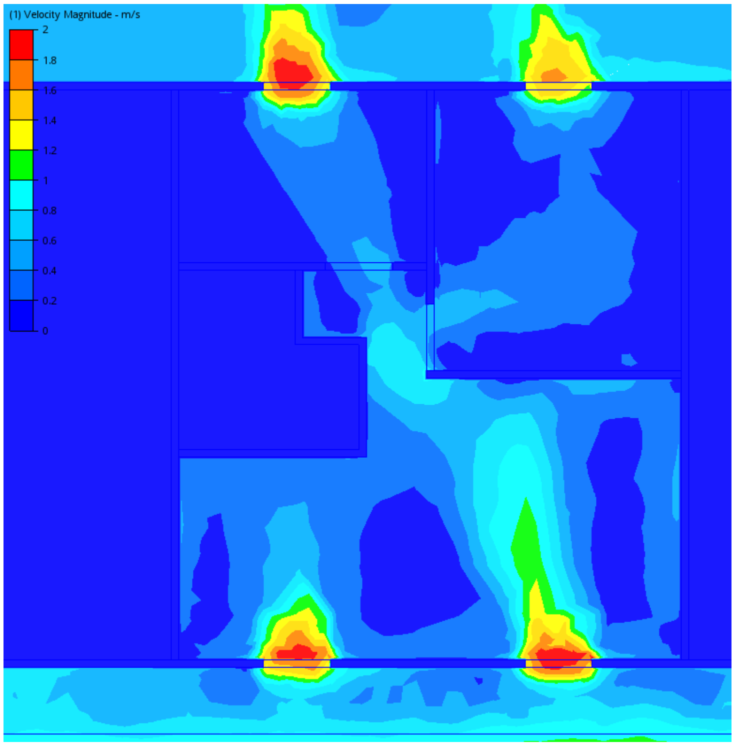


Figure: B-6 CFD simulated indoor air speed for 3 m/s external air, second floor, base model M_0

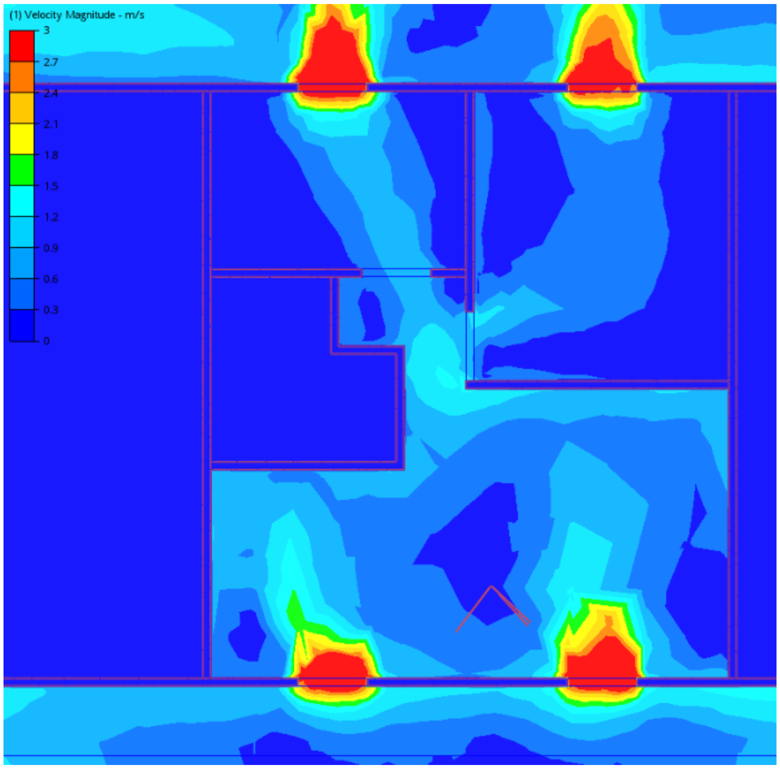


Figure: B-7 CFD simulated indoor air speed for 4 m/s external air, first floor, base model M_0

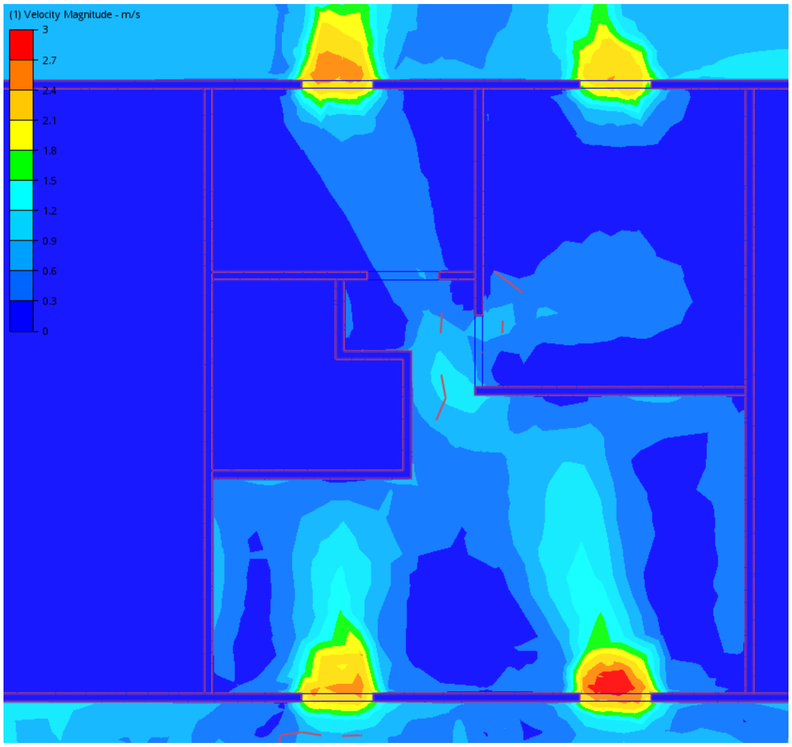


Figure: B-8 CFD simulated indoor air speed for 4 m/s external air, second floor, base model M_0

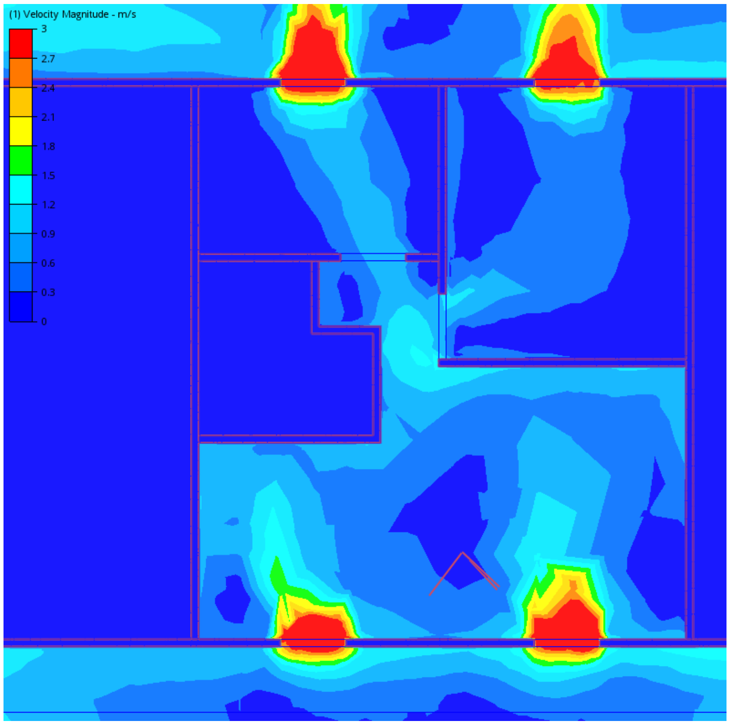


Figure: B-9 CFD simulated indoor air speed for 5 m/s external air, first floor, base model M0

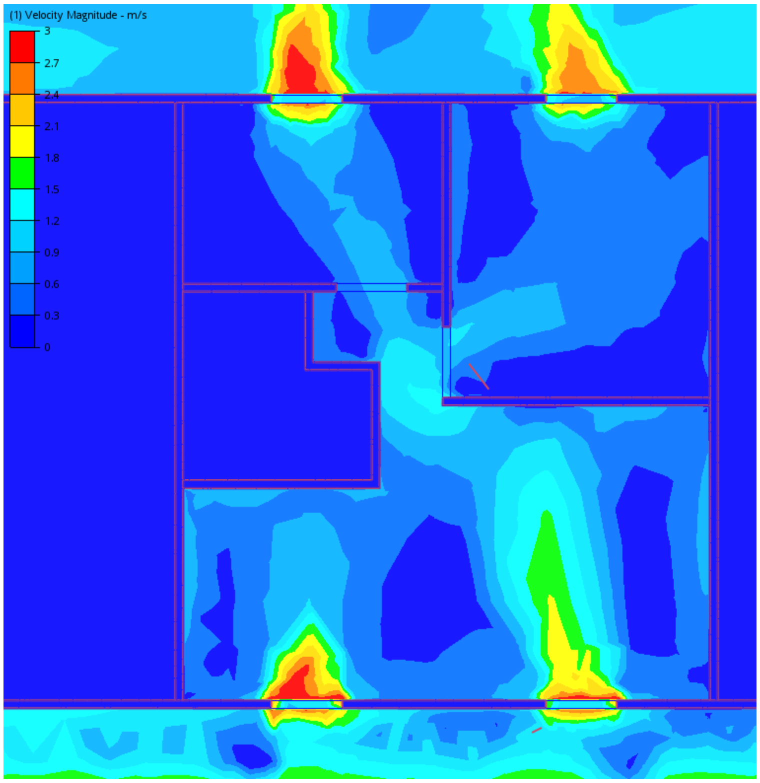


Figure: B-10 CFD simulated indoor air speed for 5 m/s external air, second floor, base model M0

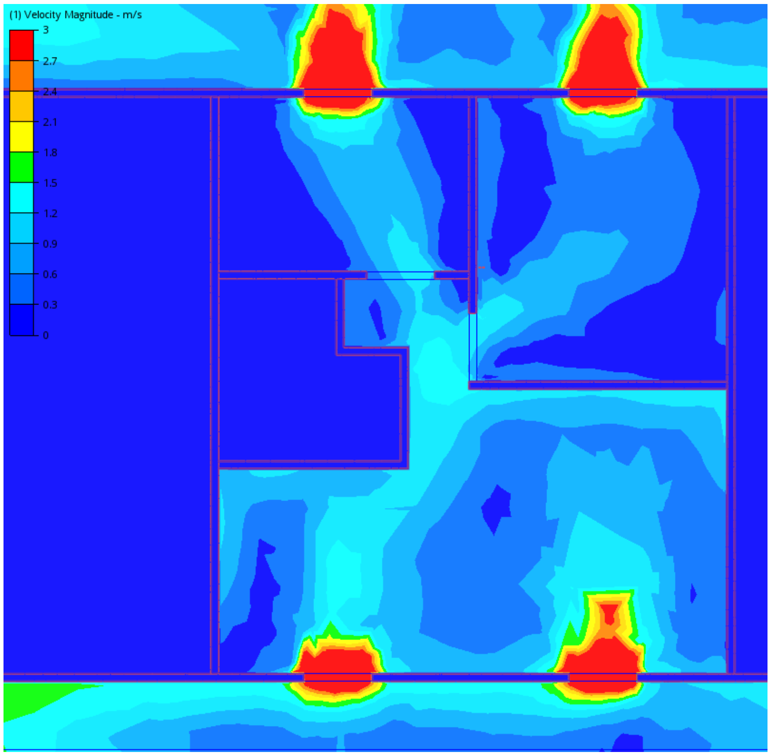


Figure: B-11 CFD simulated indoor air speed for 6 m/s external air, first floor, base model M0

Figure: B-12 CFD simulated indoor air speed for 6 m/s external air, second floor, base model M0

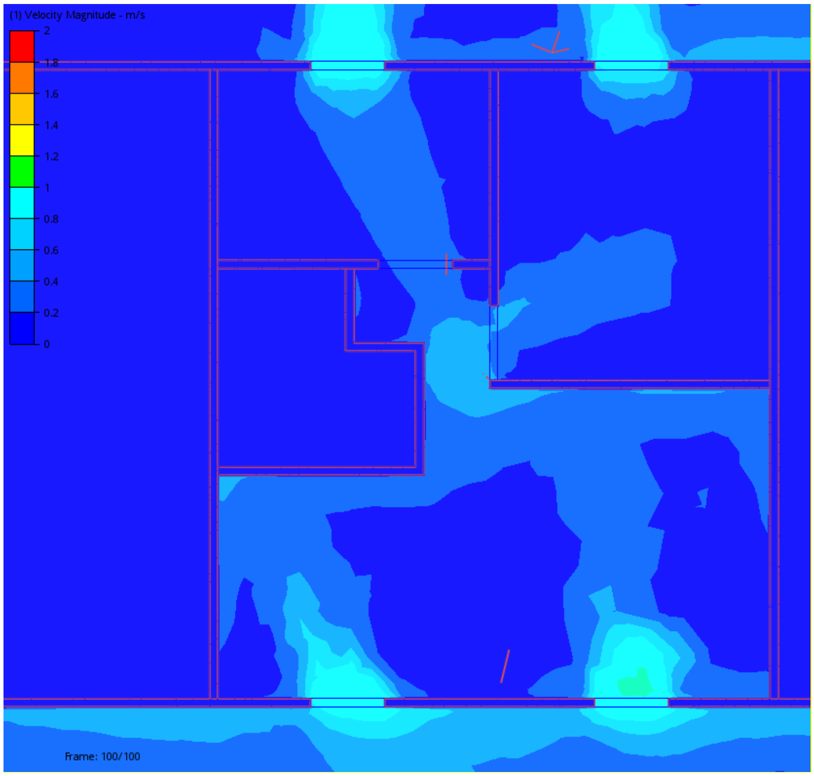


Figure: B-13 CFD simulated indoor air speed for 1 m/s external air, first floor, IRC model M_{IRC}

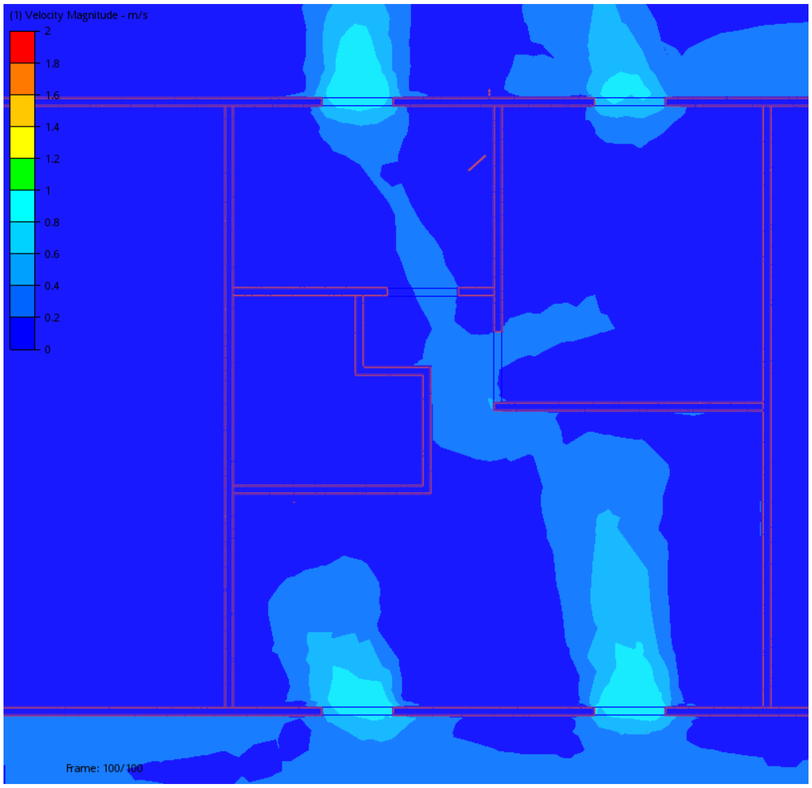


Figure: B-14 CFD simulated indoor air speed for 1 m/s external air, second floor, IRC model M_{IRC}

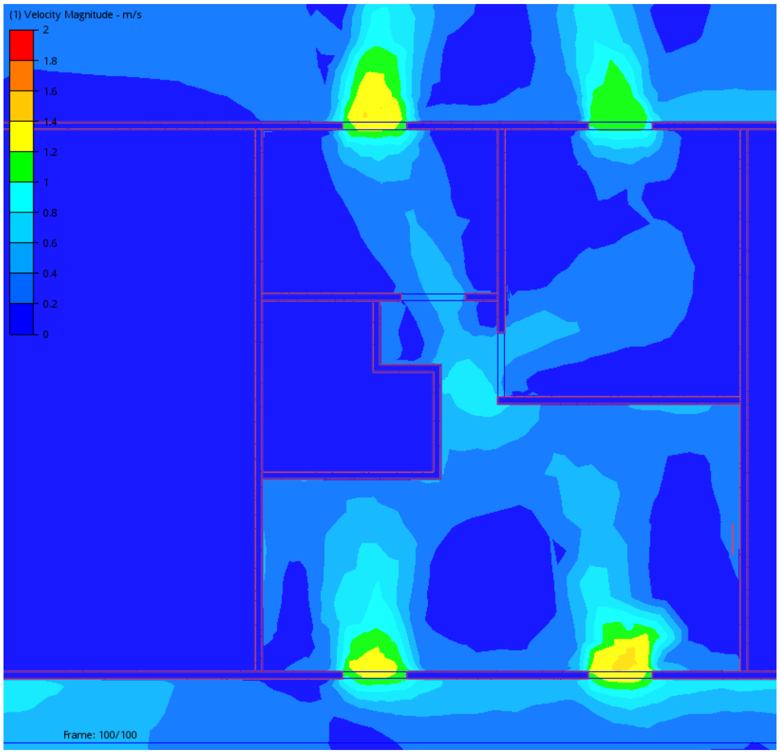


Figure: B-15 CFD simulated indoor air speed for 2 m/s external air, first floor, IRC model M_{IRC}

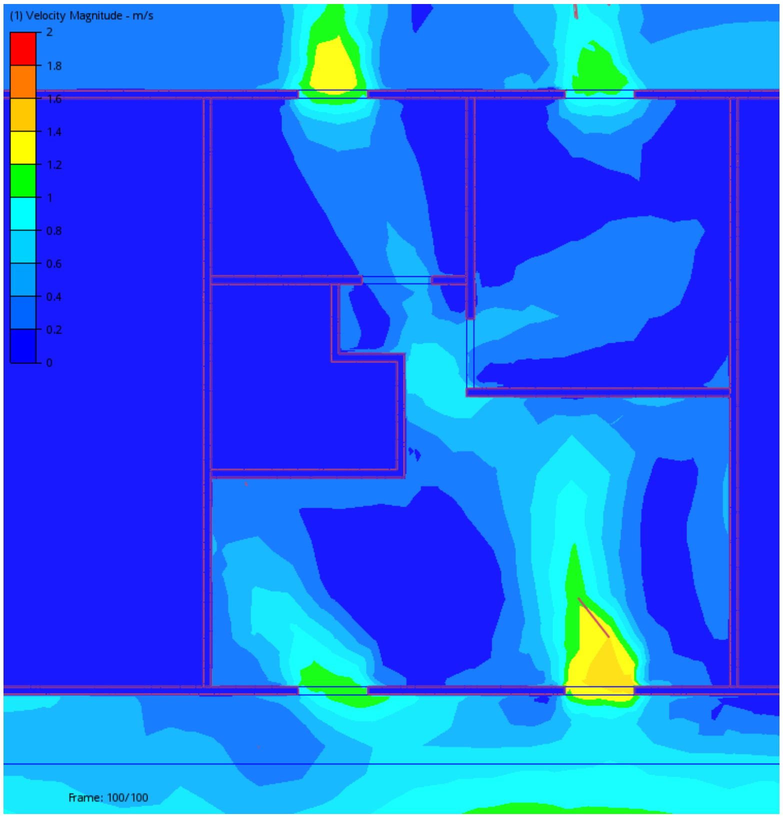


Figure: B-16 CFD simulated indoor air speed for 2 m/s external air, second floor, IRC model M_{IRC}

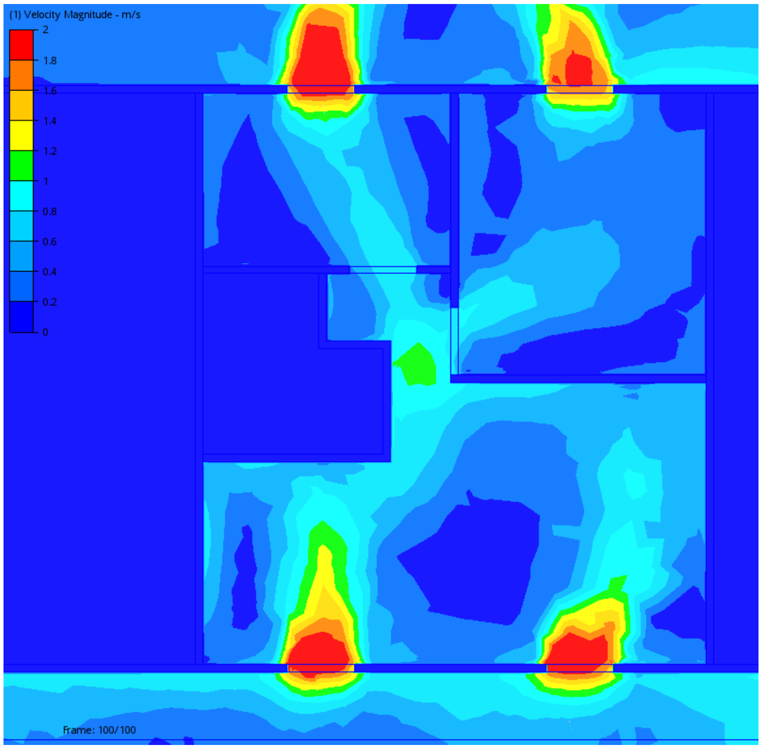


Figure: B-17 CFD simulated indoor air speed for 3 m/s external air, first floor, IRC model M_{IRC}

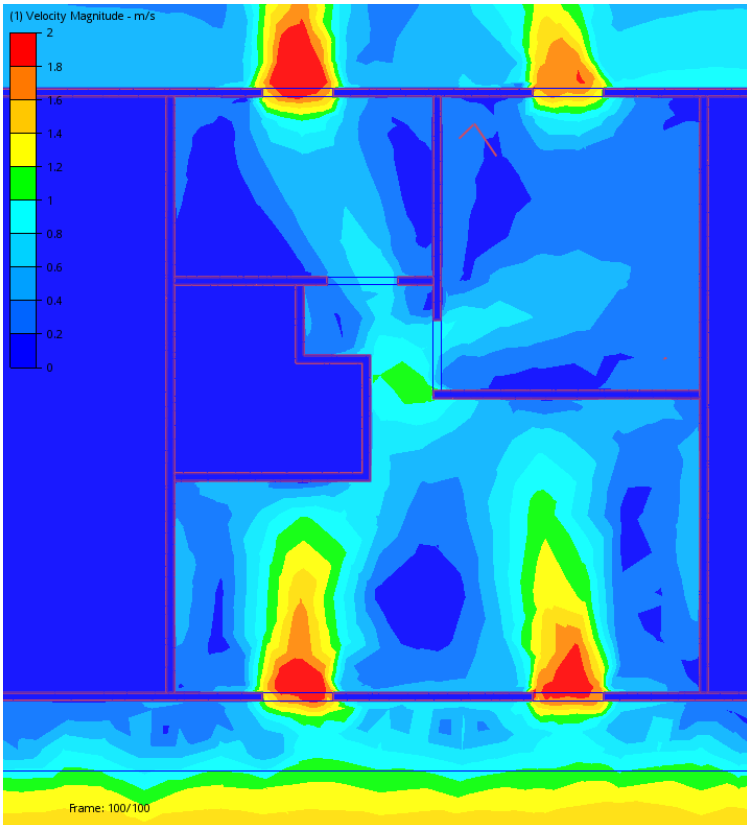


Figure: B-18 CFD simulated indoor air speed for 3 m/s external air, second floor, IRC model M_{IRC}

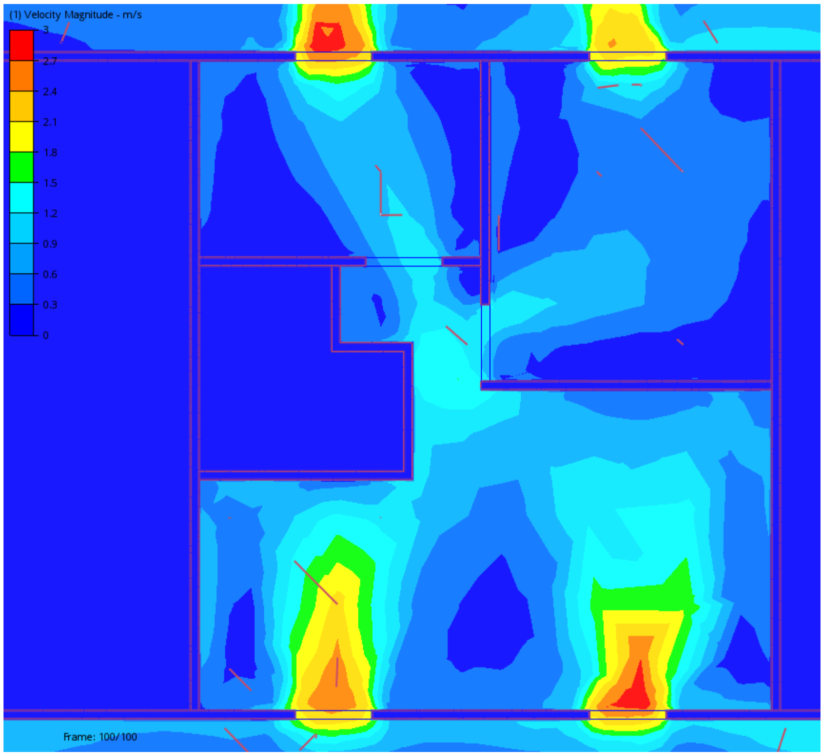


Figure: B-19 CFD simulated indoor air speed for 4 m/s external air, first floor, IRC model M_{IRC}

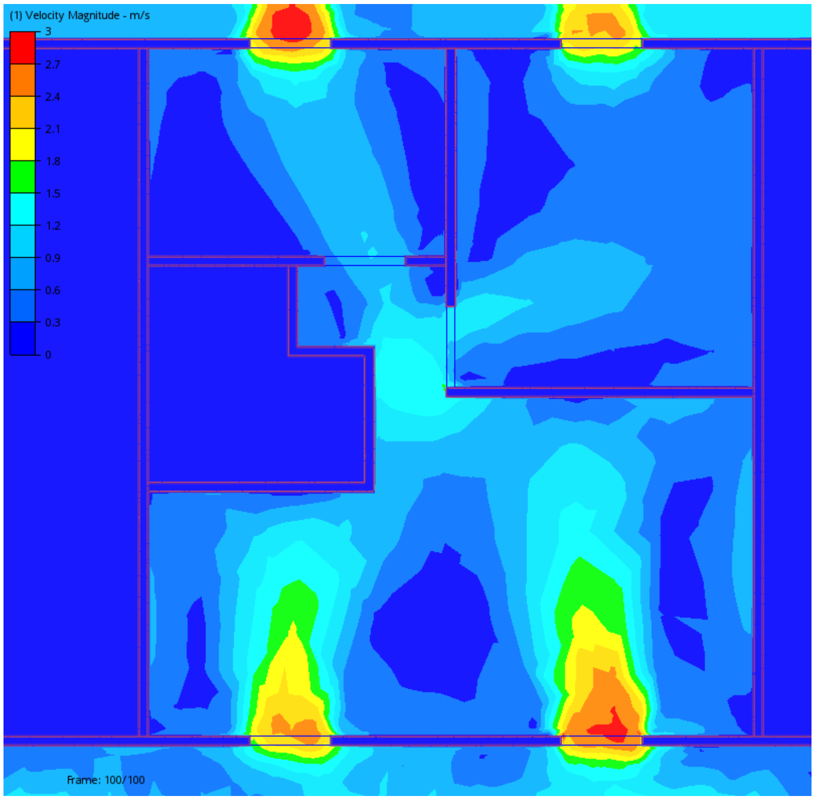


Figure: B-20 CFD simulated indoor air speed for 4 m/s external air, second floor, IRC model M_{IRC}

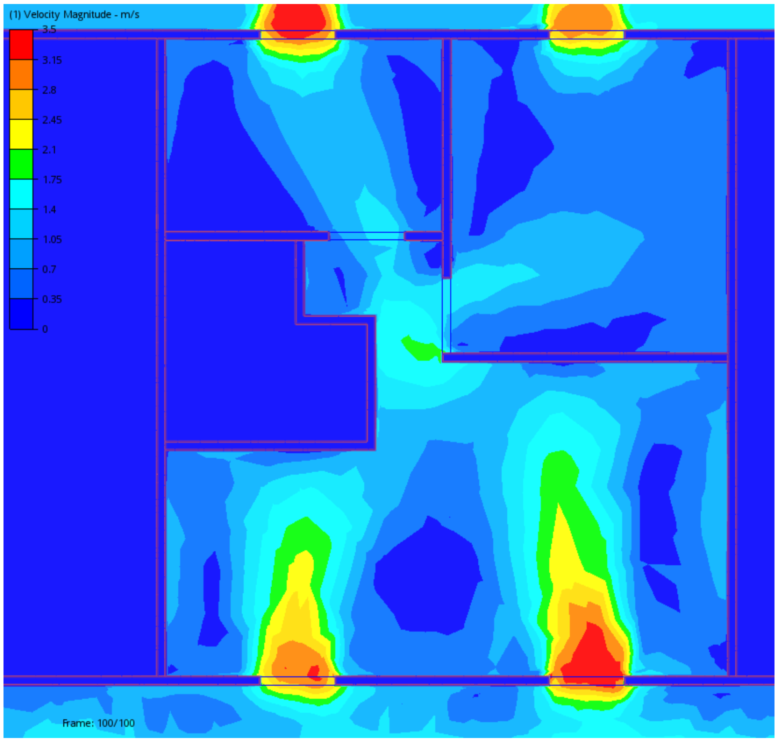


Figure: B-21 CFD simulated indoor air speed for 5 m/s external air, first floor, IRC model M_{IRC}

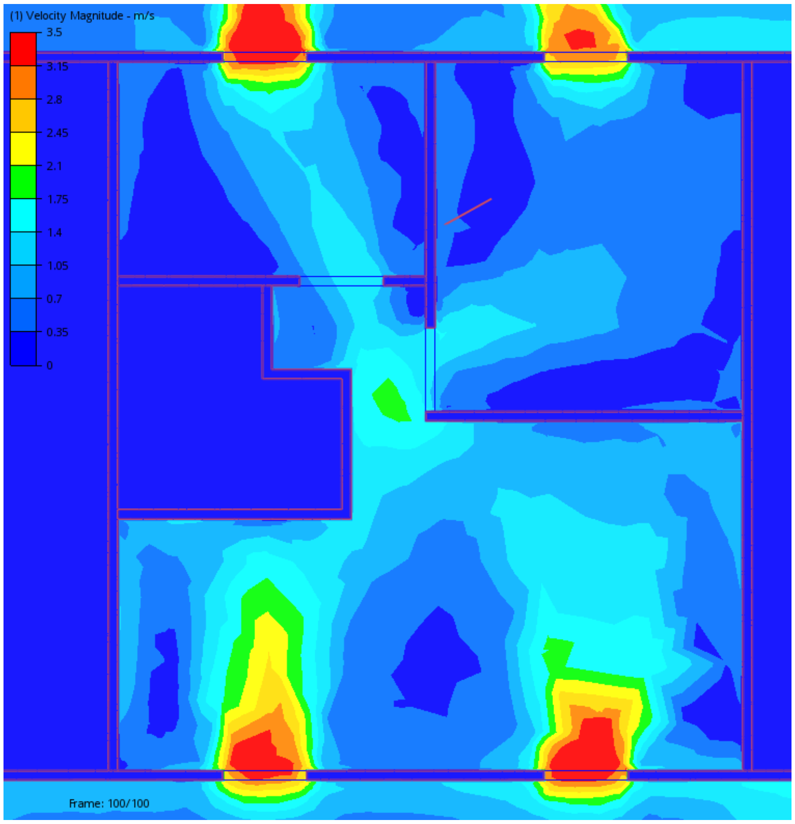


Figure: B-22 CFD simulated indoor air speed for 5 m/s external air, second floor, IRC model M_{IRC}

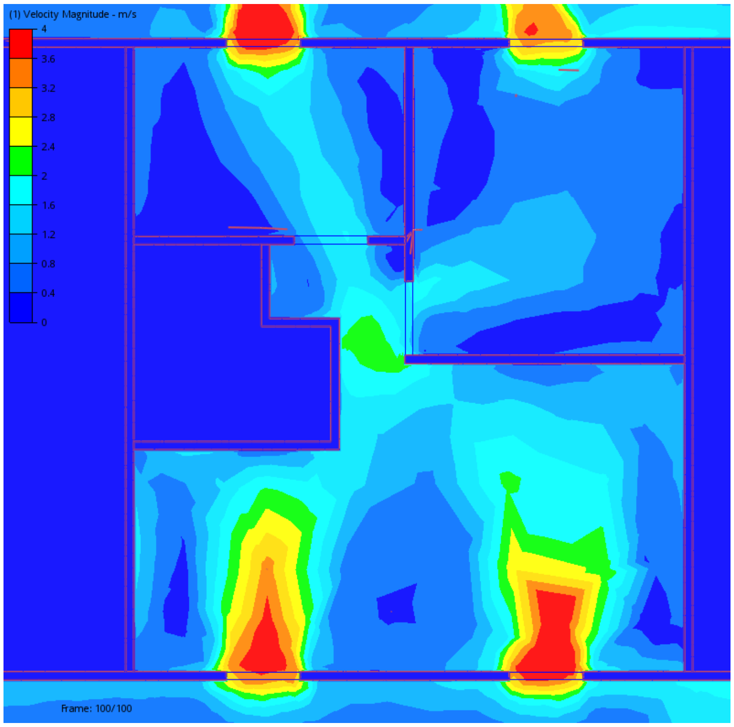


Figure: B-23 CFD simulated indoor air speed for 6 m/s external air, first floor, IRC model M_{IRC}

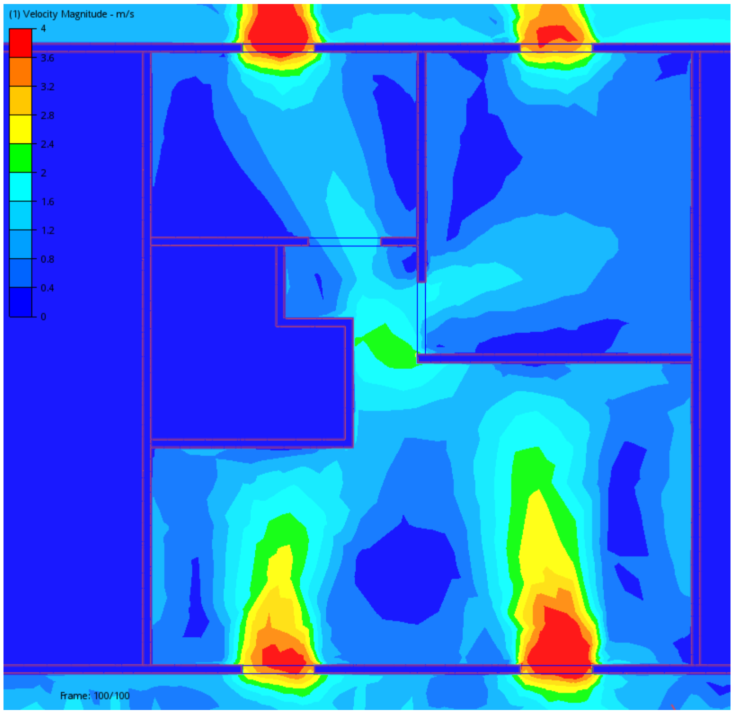


Figure: B-24 CFD simulated indoor air speed for 6 m/s external air, second floor, IRC model M_{IRC}

Floor Level		1 m/s	2 m/s	3 m/s	4 m/s	5 m/s	6 m/s
Base Building (M_0)	First Floor	0.2 m/s	0.3 m/s	0.4 m/s	0.6 m/s	0.7 m/s	0.8 m/s
	Second	0.2 m/s	0.3 m/s	0.4 m/s	0.7 m/s	0.7 m/s	0.8 m/s
IRC model (M_{IRC})	First	0.2 m/s	0.3 m/s	0.6 m/s	0.7 m/s	0.9 m/s	1.1 m/s
	Second	0.2 m/s	0.3 m/s	0.5 m/s	0.7 m/s	0.8 m/s	1.0 m/s

Table: B-1 Average indoor air speed due to varying outdoor wind

Discomfort Area %	2 mps	6 mps	10 mps	14 mps
Living Room, Base, M_0	0%	5.45%	14%	26.26%
Living Room, IRC model, M_{IRC}	0%	8.51%	30.98%	42.28%
Overall, Base, M_0	0%	3.54%	8.95%	20.99%
Overall, IRC model, M_{IRC}	0%	5.11%	20.3%	29.88%

Table: B-2 Comparison of percentage of discomfort area in living room and overall apartment in M_0 and M_{IRC}

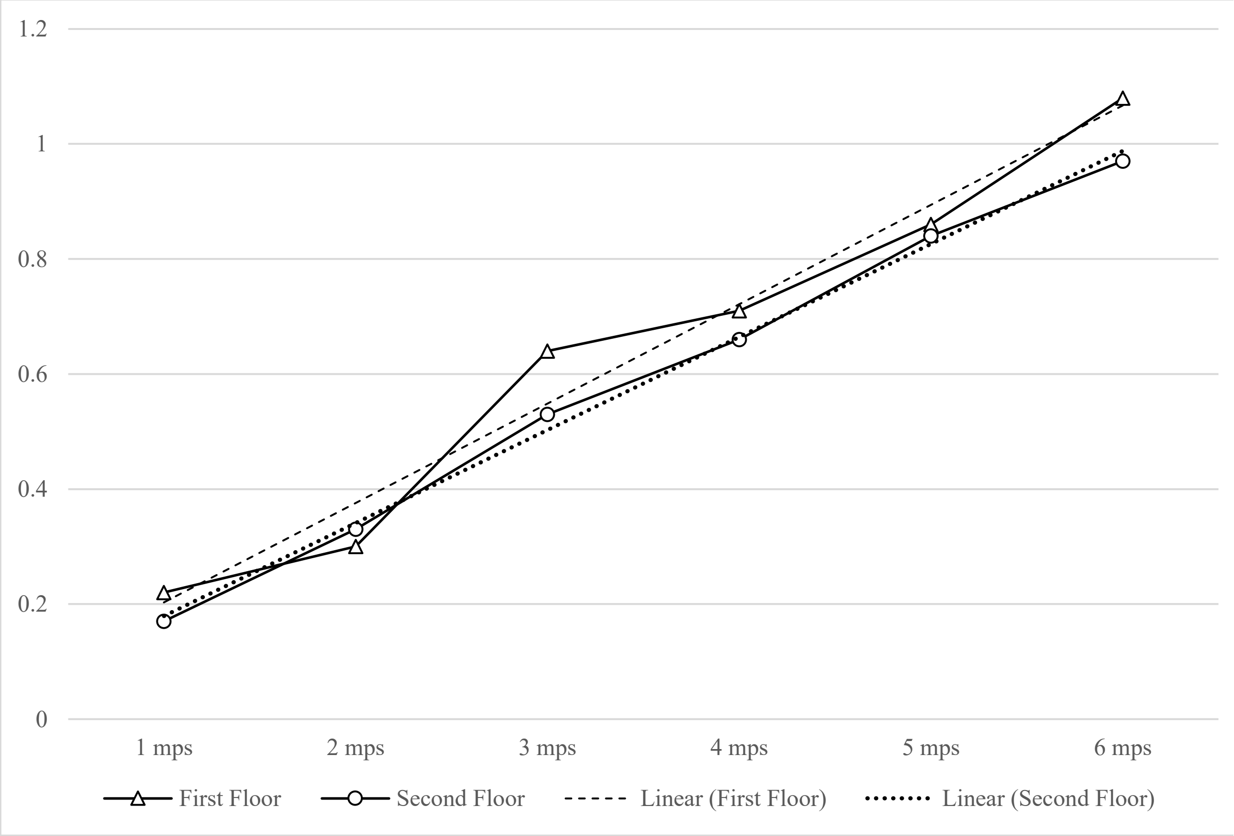


Figure: B-25 Equivalent average indoor air speed for varying outdoor air speed in base building (M_0)

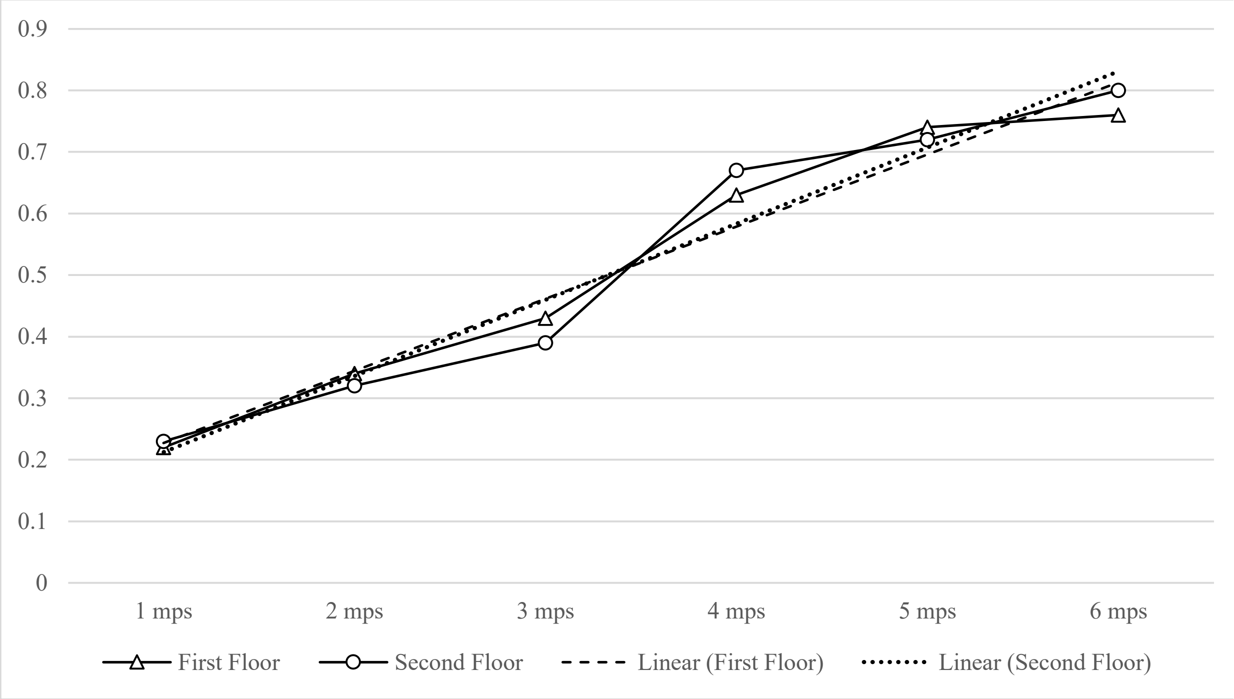


Figure: B-26 Equivalent average indoor air speed for varying outdoor air speed in IRC Model (M_{IRC})

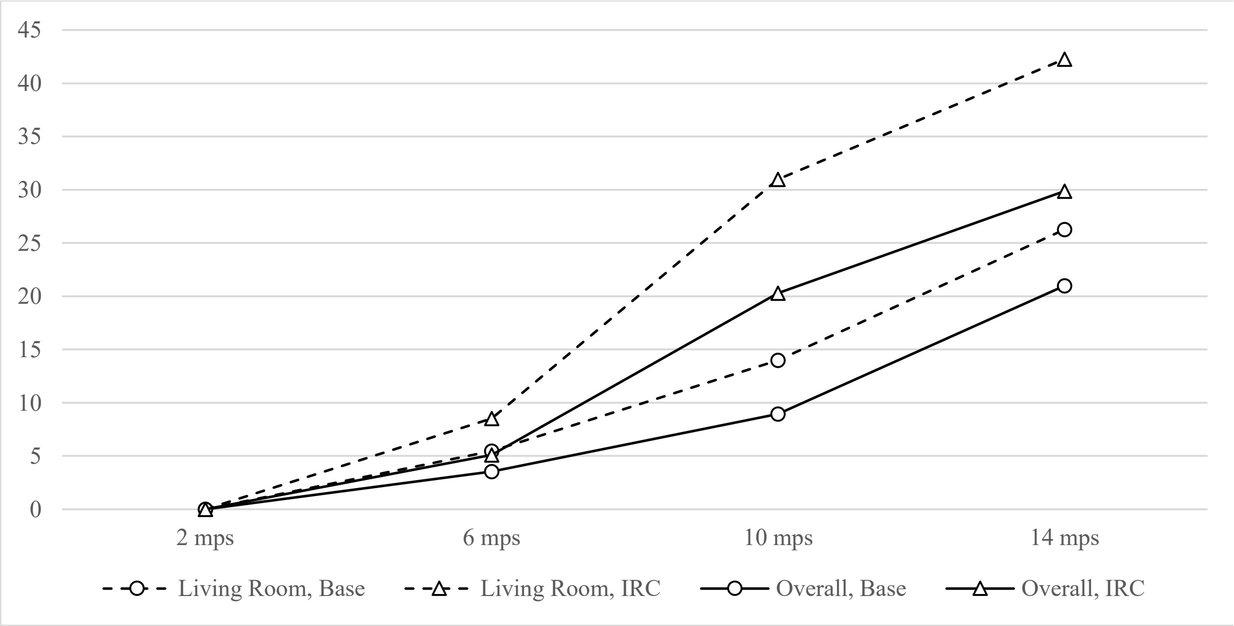
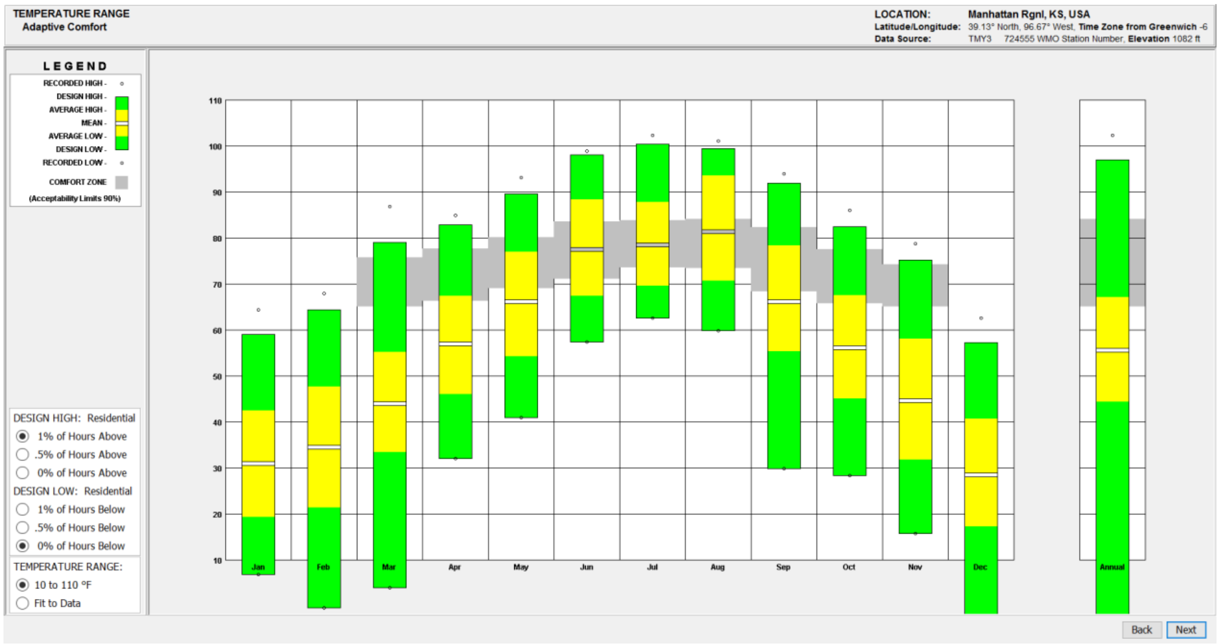


Figure: B-27 Percentage area discomfort with varying speed of air in Base model (M_0) and IRC model (M_{IRC})

Appendix C - Climatic Data

These climatic data were obtained from Climate Consultant 6.0. They are characteristic climatic data for Manhattan, KS.



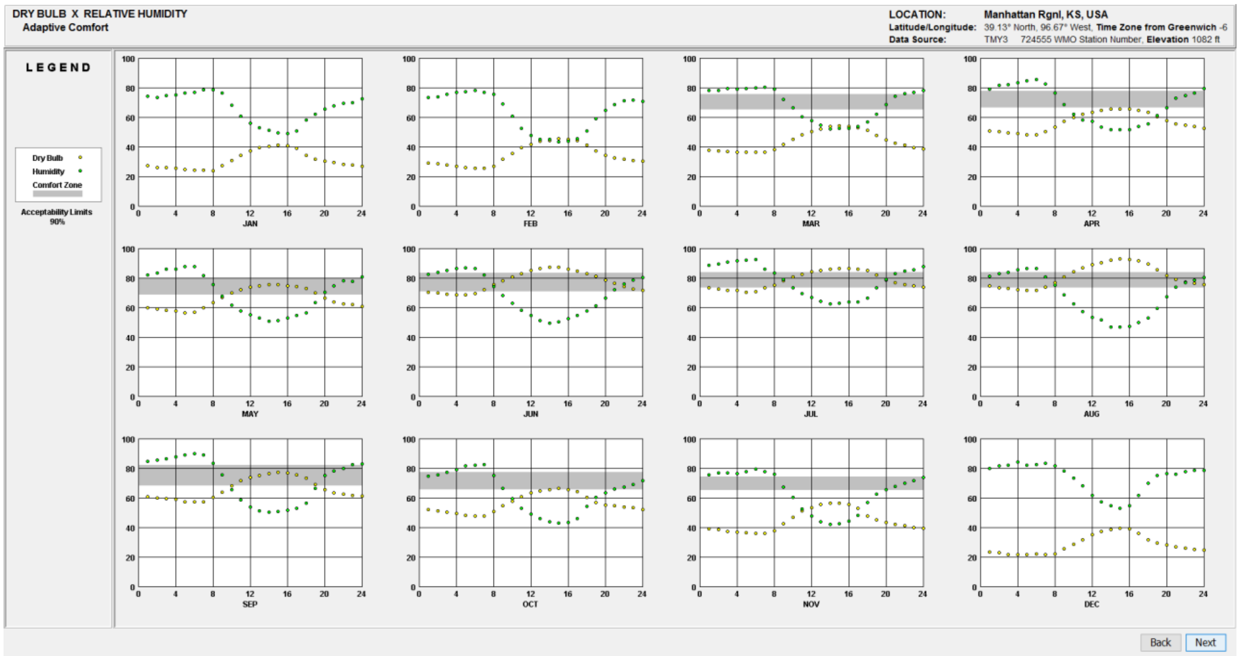
TEMPERATURE RANGE
Adaptive Comfort

LOCATION: **Manhattan Rgnl, KS, USA**
Latitude/Longitude: 39.13° North, 96.67° West, **Time Zone from Greenwich** -6
Data Source: TMY3 724555 WMO Station Number, **Elevation** 1082 ft

DESIGN HIGH: Residential
● 1% of Hours Above
○ .5% of Hours Above
○ 0% of Hours Above
DESIGN LOW: Residential
○ 1% of Hours Below
○ .5% of Hours Below
● 0% of Hours Below

TEMPERATURE RANGE:
● 10 to 110 °F
○ Fit to Data

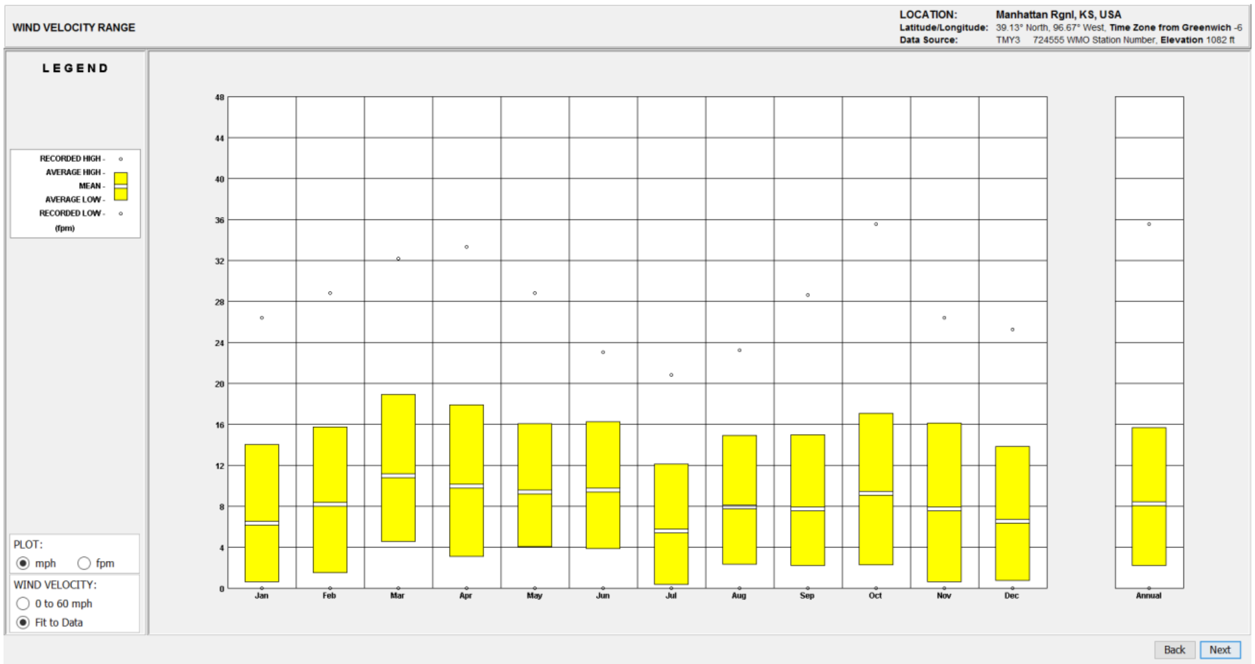
Figure: C-1 Mean, average high, design high, record high, maximum adaptive comfortable temperature chart for all the months (Source: Climate Consultant 6)



DRY BULB X RELATIVE HUMIDITY
Adaptive Comfort

LOCATION: **Manhattan Rgnl, KS, USA**
Latitude/Longitude: 39.13° North, 96.67° West, **Time Zone from Greenwich** -6
Data Source: TMY3 724555 WMO Station Number, **Elevation** 1082 ft

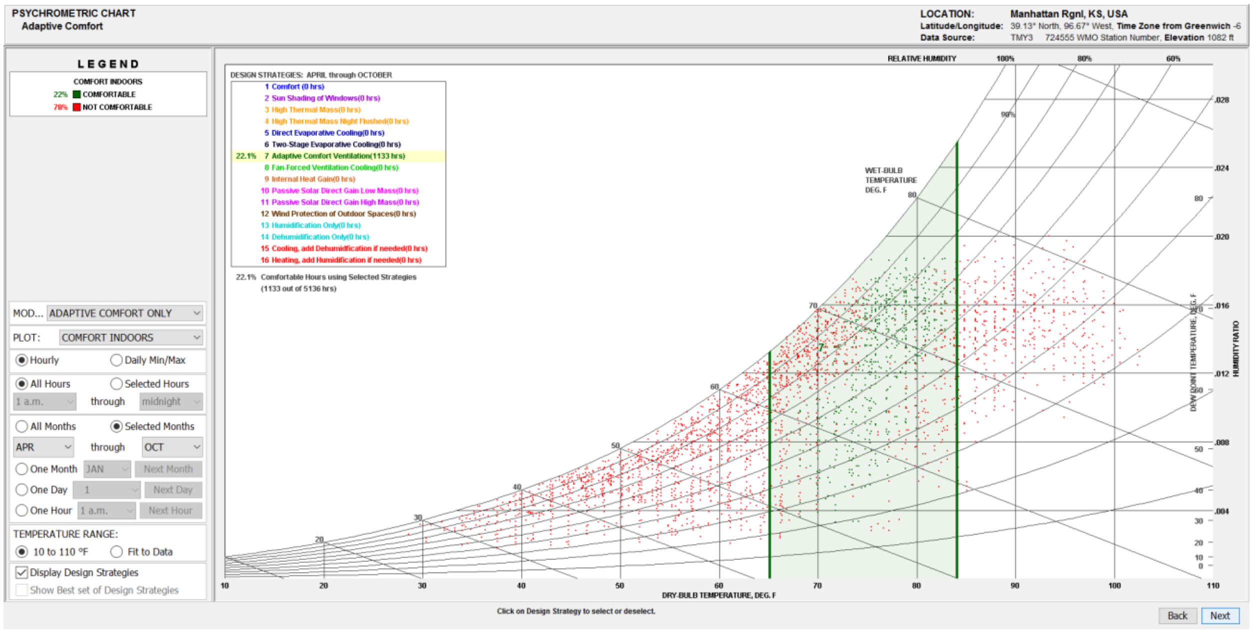
Figure: C-2 Average humidity and average dry bulb temperature for different hours of all the months (Source: Climate Consultant 6)


WIND VELOCITY RANGE

LOCATION: Manhattan Rgnl, KS, USA
Latitude/Longitude: 39.13° North, 96.67° West, Time Zone from Greenwich -6
Data Source: TMY3 724555 WMO Station Number, Elevation 1082 ft

PLOT: ● mph ○ fpm
WIND VELOCITY: ○ 0 to 60 mph ● Fit to Data

Figure: C-3 Mean, average high, record high wind velocity range for all the months (Source: Climate Consultant 6)


PSYCHROMETRIC CHART
Adaptive Comfort

LOCATION: Manhattan Rgnl, KS, USA
Latitude/Longitude: 39.13° North, 96.67° West, Time Zone from Greenwich -6
Data Source: TMY3 724555 WMO Station Number, Elevation 1082 ft

LEGEND
COMFORT INDOORS
22% 🟩 COMFORTABLE
78% 🟥 NOT COMFORTABLE

MOD... ADAPTIVE COMFORT ONLY
PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Selected Hours
1 a.m. through midnight
○ All Months ● Selected Months
APR through OCT
○ One Month JAN Next Month
○ One Day 1 Next Day
○ One Hour 1 a.m. Next Hour
TEMPERATURE RANGE:
● 10 to 110 °F ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

DESIGN STRATEGIES: APRIL through OCTOBER
1 Comfort (0 hrs)
2 Sun Shading of Windows(0 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
6 Two-Stage Evaporative Cooling(0 hrs)
22.1% 7 Adaptive Comfort Ventilation(1133 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
9 Internal Heat Gain(0 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
14 Dehumidification Only(0 hrs)
15 Cooling, add Dehumidification if needed(0 hrs)
16 Heating, add Humidification if needed(0 hrs)

22.1% Comfortable Hours using Selected Strategies
(1133 out of 5136 hrs)

Click on Design Strategy to select or deselect.

Figure: C-4 Psychrometric chart for the months of June-September

Appendix D - Design Builder

General

Dwell_DomLounge_Occ_R_ON

Source	UK NCM
Category	Residential
Region	General
Schedule type	2-Compact

Profiles

Schedule:Compact,
Dwell_DomLounge_Occ,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 16:00, 0.5,
Until: 18:00, 0.66667,
Until: 22:00, 1,
Until: 23:00, 0.66667,
Until: 24:00, 0,

Figure: D-1 Occupancy schedule for Living Room

General

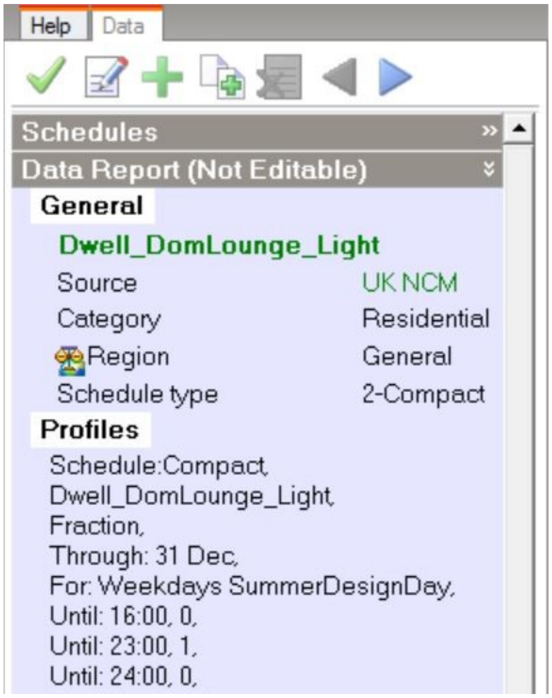
Dwell_DomBed_Occ

Source	UK NCM
Category	Residential
Region	General
Schedule type	2-Compact

Profiles

Schedule:Compact,
Dwell_DomBed_Occ,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 1,
Until: 08:00, 0.5,
Until: 09:00, 0.25,
Until: 22:00, 0,
Until: 23:00, 0.25,
Until: 24:00, 0.75,

Figure: D-2 Occupancy schedule for Bed Room



General

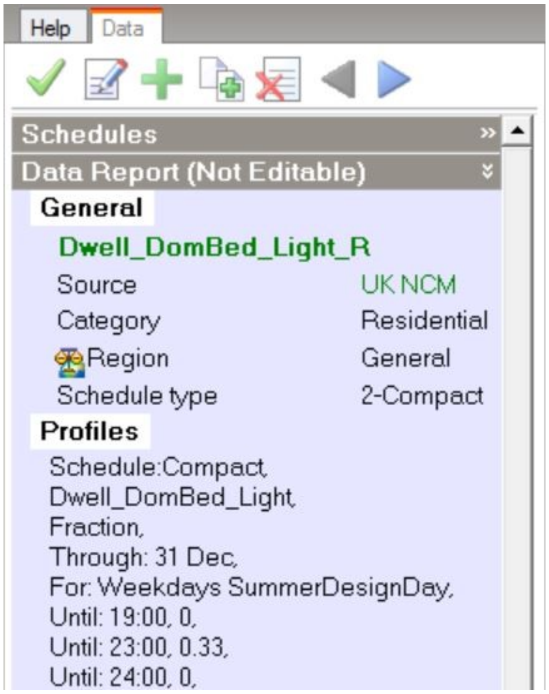
Dwell_DomLounge_Light

Source	UK NCM
Category	Residential
Region	General
Schedule type	2-Compact

Profiles

Schedule:Compact,
Dwell_DomLounge_Light,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 16:00, 0,
Until: 23:00, 1,
Until: 24:00, 0,

Figure: D-3 Lighting schedule for Living Room



General

Dwell_DomBed_Light_R

Source	UK NCM
Category	Residential
Region	General
Schedule type	2-Compact

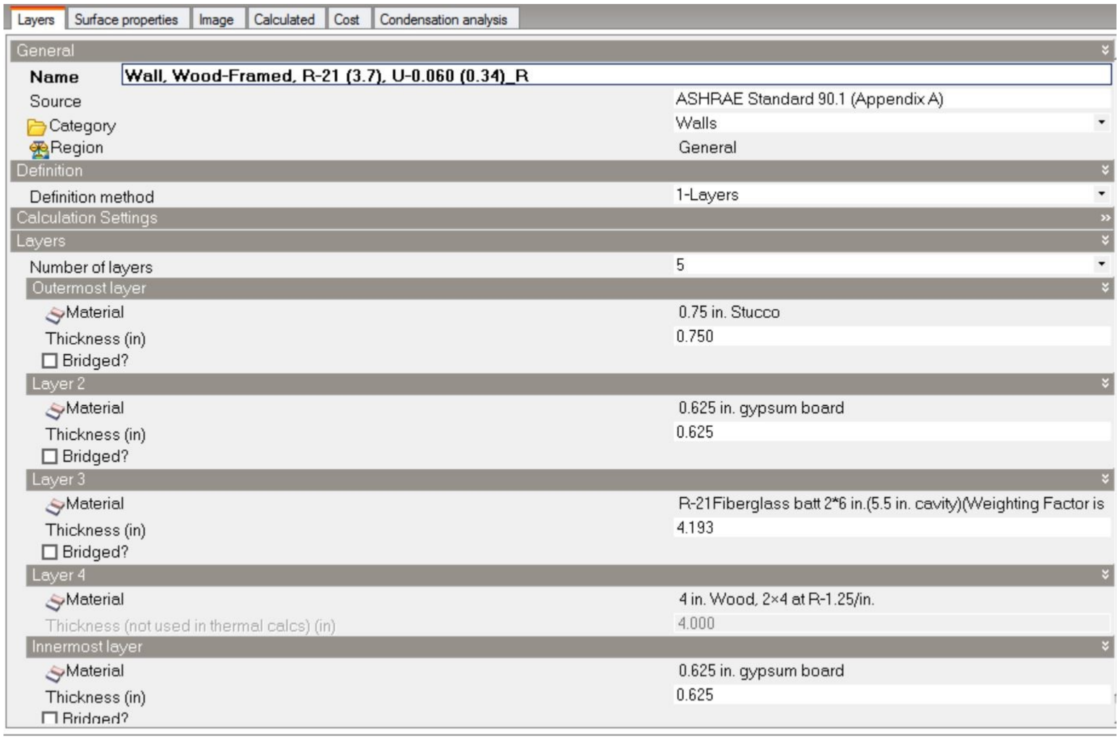
Profiles

Schedule:Compact,
Dwell_DomBed_Light,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 19:00, 0,
Until: 23:00, 0.33,
Until: 24:00, 0,

Figure: D-4 Lighting schedule for Bed Room

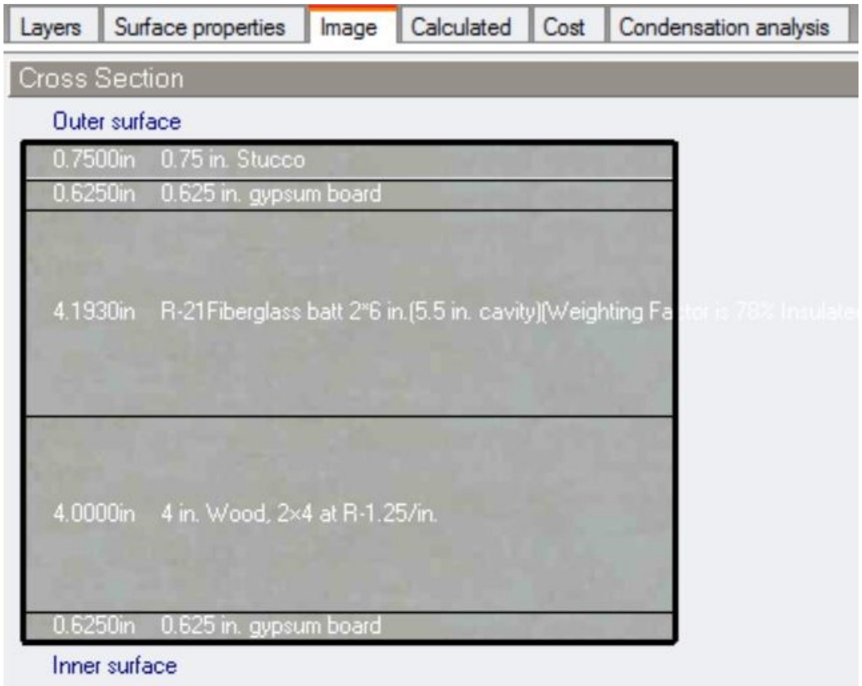
Lighting Template	
Template	IECC-2000
General Lighting	
☑ On	
Normalised power density (W/ft2-fc)	0.0340000
Schedule	Dwell_DomBed_Light
Luminaire type	1-Suspended
Radiant fraction	0.420
Visible fraction	0.180
Convective fraction	0.400
Lighting Control	
☑ On	
Working plane height (ft)	2.63
Control type	1-Linear
Min output fraction	0.100
Min input power fraction	0.100
Glare	
Lighting Area 1	
Lighting Area 2	
Task and Display Lighting	
☐ On	
Cost	

Figure: D-5 Lighting schedule and setting for all models



General	
Name	Wall, Wood-Framed, R-21 (3.7), U-0.060 (0.34)_R
Source	ASHRAE Standard 90.1 (Appendix A)
Category	Walls
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	5
Outermost layer	
Material	0.75 in. Stucco
Thickness (in)	0.750
☐ Bridged?	
Layer 2	
Material	0.625 in. gypsum board
Thickness (in)	0.625
☐ Bridged?	
Layer 3	
Material	R-21Fiberglass batt 2*6 in.(5.5 in. cavity)(Weighting Factor is
Thickness (in)	4.193
☐ Bridged?	
Layer 4	
Material	4 in. Wood, 2×4 at R-1.25/in.
Thickness (not used in thermal calcs) (in)	4.000
Innermost layer	
Material	0.625 in. gypsum board
Thickness (in)	0.625
☐ Bridged?	

Figure: D-6 IRC recommended lightweight construction external wall, general information



Cross Section

Outer surface

0.7500in 0.75 in. Stucco

0.6250in 0.625 in. gypsum board

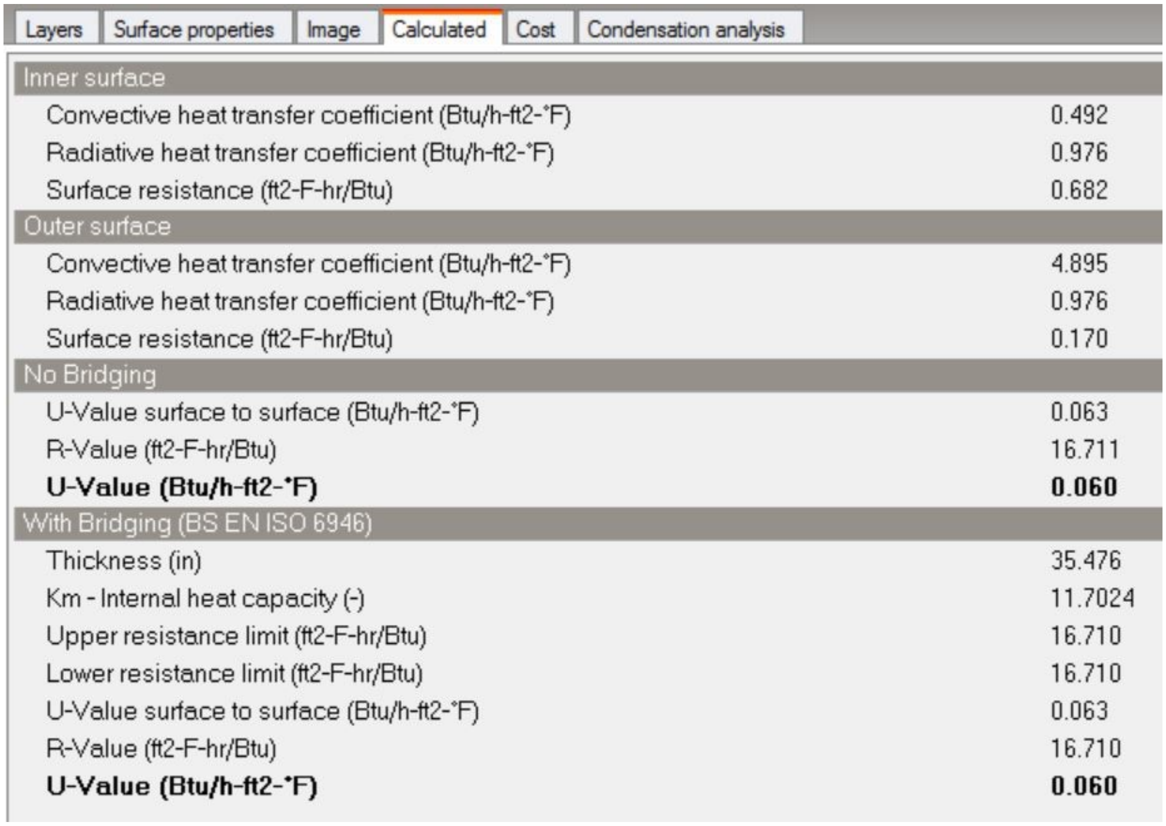
4.1930in R-21Fiberglass batt 2*6 in.(5.5 in. cavity)[Weighting Factor is 78% Insulate

4.0000in 4 in. Wood, 2x4 at R-1.25/in.

0.6250in 0.625 in. gypsum board

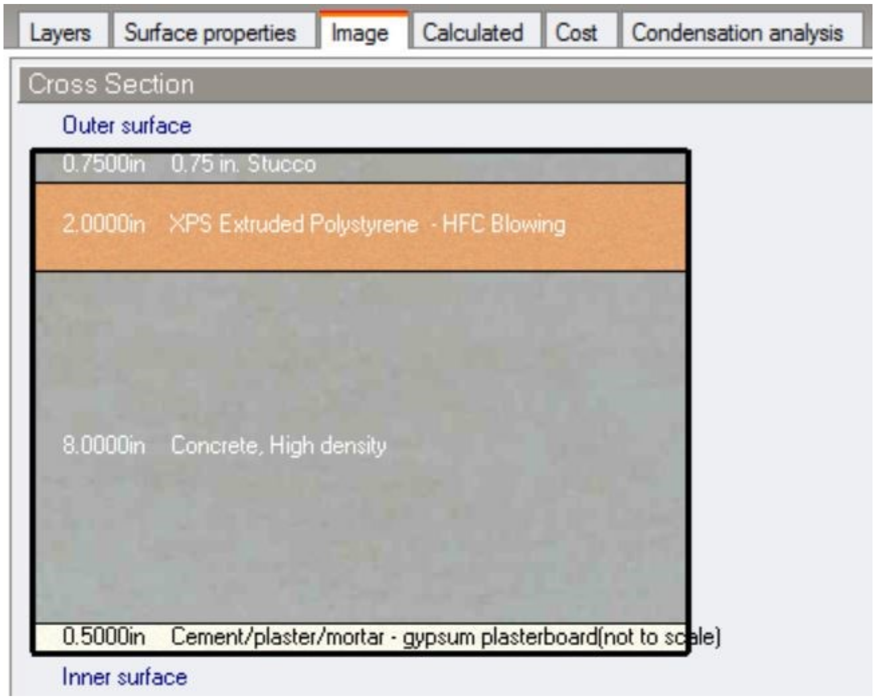
Inner surface

Figure: D-7 IRC recommended lightweight construction external wall, cross section



Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.492
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.682
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	4.895
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.170
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.063
R-Value (ft2-F-hr/Btu)	16.711
U-Value (Btu/h-ft2-°F)	**0.060**
With Bridging (BS EN ISO 6946)	
Thickness (in)	35.476
Km - Internal heat capacity (-)	11.7024
Upper resistance limit (ft2-F-hr/Btu)	16.710
Lower resistance limit (ft2-F-hr/Btu)	16.710
U-Value surface to surface (Btu/h-ft2-°F)	0.063
R-Value (ft2-F-hr/Btu)	16.710
U-Value (Btu/h-ft2-°F)	**0.060**

Figure: D-8 IRC recommended lightweight construction external wall, R-value calculation



Cross Section

Outer surface

0.7500in 0.75 in. Stucco

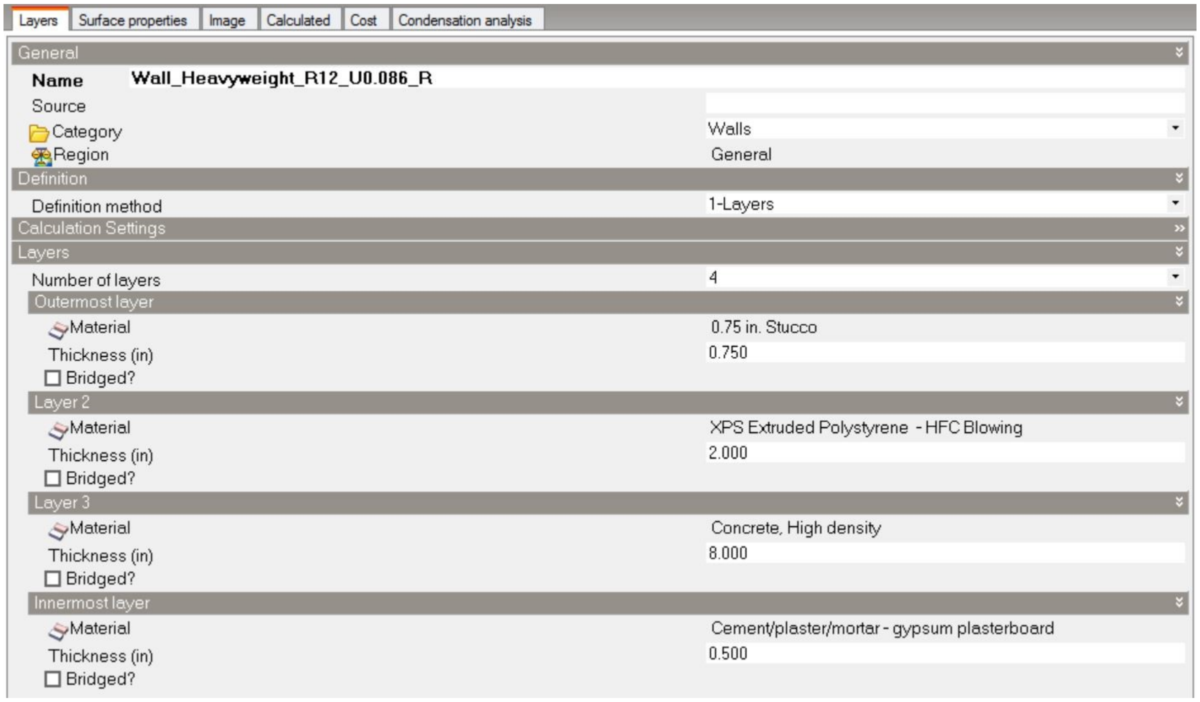
2.0000in XPS Extruded Polystyrene - HFC Blowing

8.0000in Concrete, High density

0.5000in Cement/plaster/mortar - gypsum plasterboard(not to scale)

Inner surface

Figure: D-9 IRC recommended heavy mass construction external wall, cross section



General

Name **Wall_Heavyweight_R12_U0.086_R**

Source

Category: Walls

Region: General

Definition

Definition method: 1-Layers

Calculation Settings

Layers

Number of layers: 4

Outermost layer

Material: 0.75 in. Stucco

Thickness (in): 0.750

☐ Bridged?

Layer 2

Material: XPS Extruded Polystyrene - HFC Blowing

Thickness (in): 2.000

☐ Bridged?

Layer 3

Material: Concrete, High density

Thickness (in): 8.000

☐ Bridged?

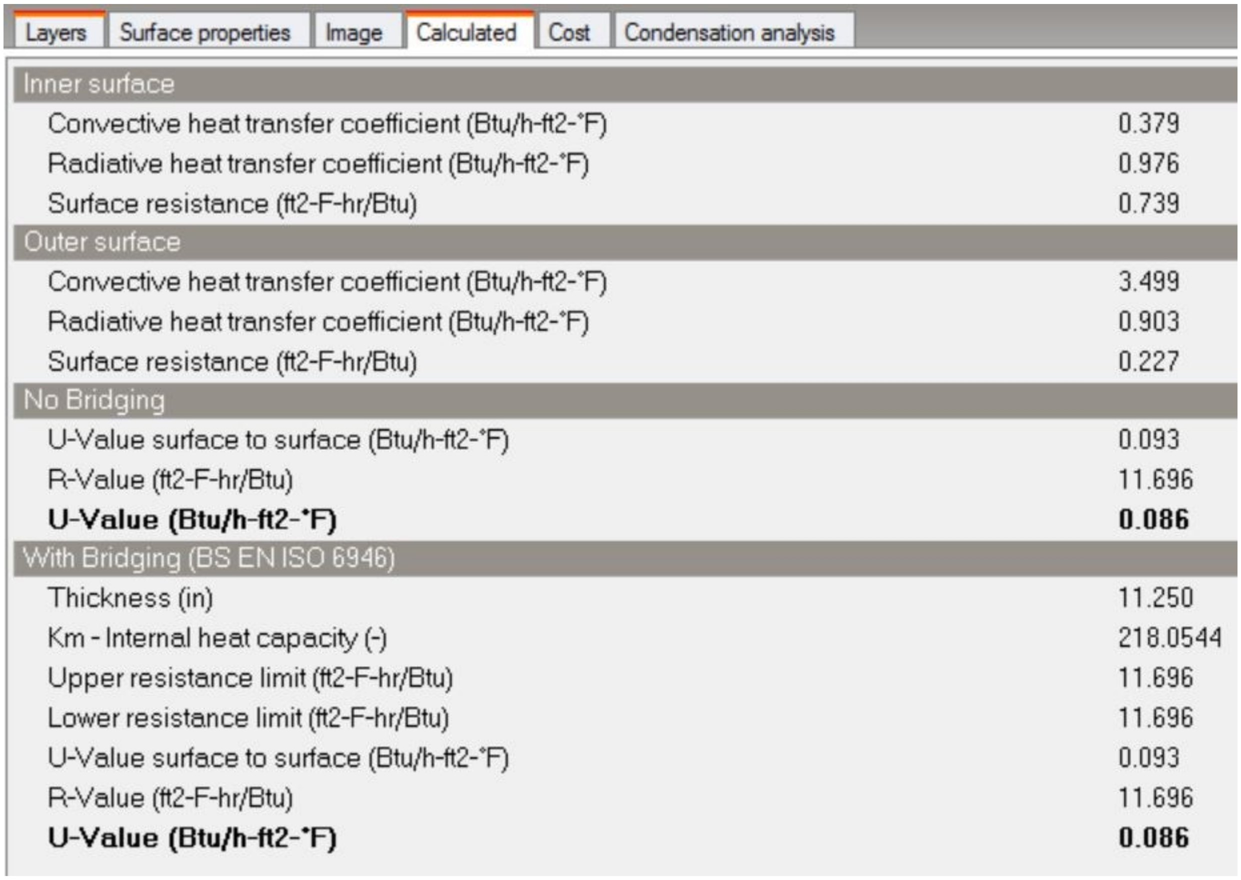
Innermost layer

Material: Cement/plaster/mortar - gypsum plasterboard

Thickness (in): 0.500

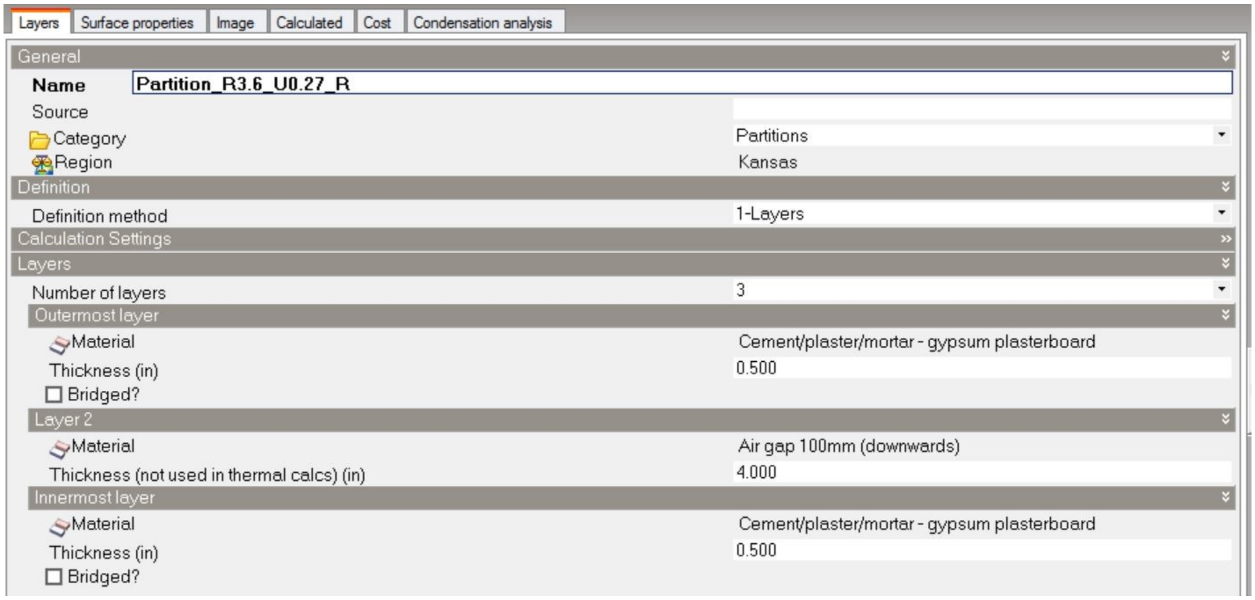
☐ Bridged?

Figure: D-10 IRC recommended heavy mass construction external wall, general information



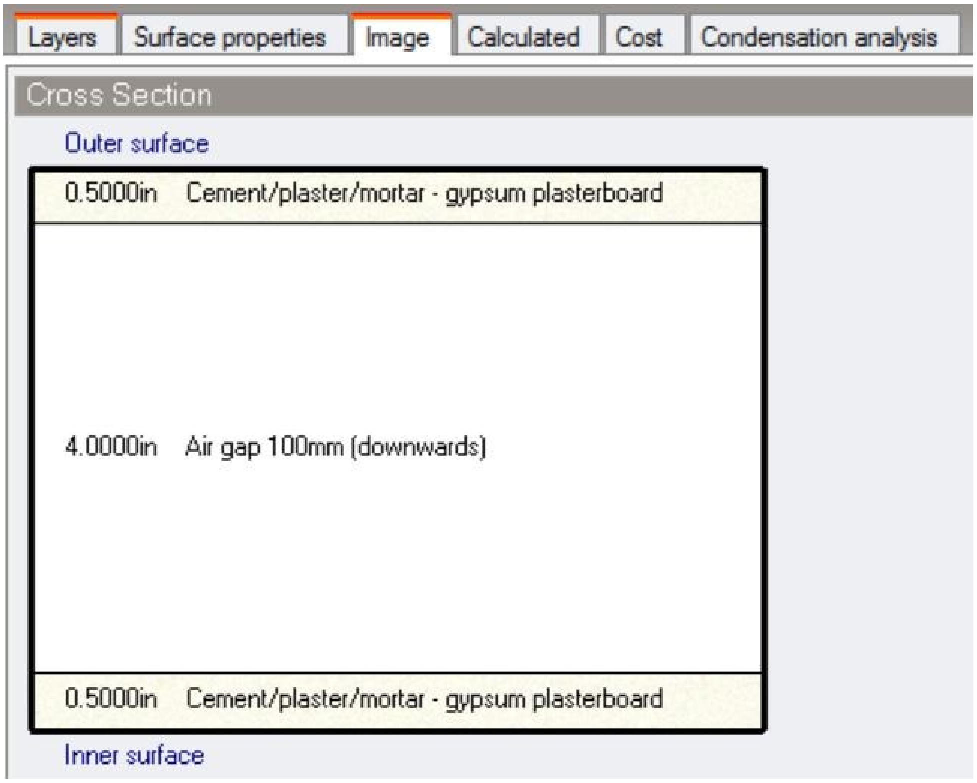
Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.379
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.739
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	3.499
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.903
Surface resistance (ft2-F-hr/Btu)	0.227
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.093
R-Value (ft2-F-hr/Btu)	11.696
U-Value (Btu/h-ft2-°F)	**0.086**
With Bridging (BS EN ISO 6946)	
Thickness (in)	11.250
Km - Internal heat capacity (-)	218.0544
Upper resistance limit (ft2-F-hr/Btu)	11.696
Lower resistance limit (ft2-F-hr/Btu)	11.696
U-Value surface to surface (Btu/h-ft2-°F)	0.093
R-Value (ft2-F-hr/Btu)	11.696
U-Value (Btu/h-ft2-°F)	**0.086**

Figure: D-11 IRC recommended heavy mass construction external wall, R-value calculation



General	
Name	Partition_R3.6_U0.27_R
Source	
Category	Partitions
Region	Kansas
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	3
Outermost layer	
Material	Cement/plaster/mortar - gypsum plasterboard
Thickness (in)	0.500
☐ Bridged?	
Layer 2	
Material	Air gap 100mm (downwards)
Thickness (not used in thermal calcs) (in)	4.000
Innermost layer	
Material	Cement/plaster/mortar - gypsum plasterboard
Thickness (in)	0.500
☐ Bridged?	

Figure: D-12 Party wall for all models, general information



Outer surface

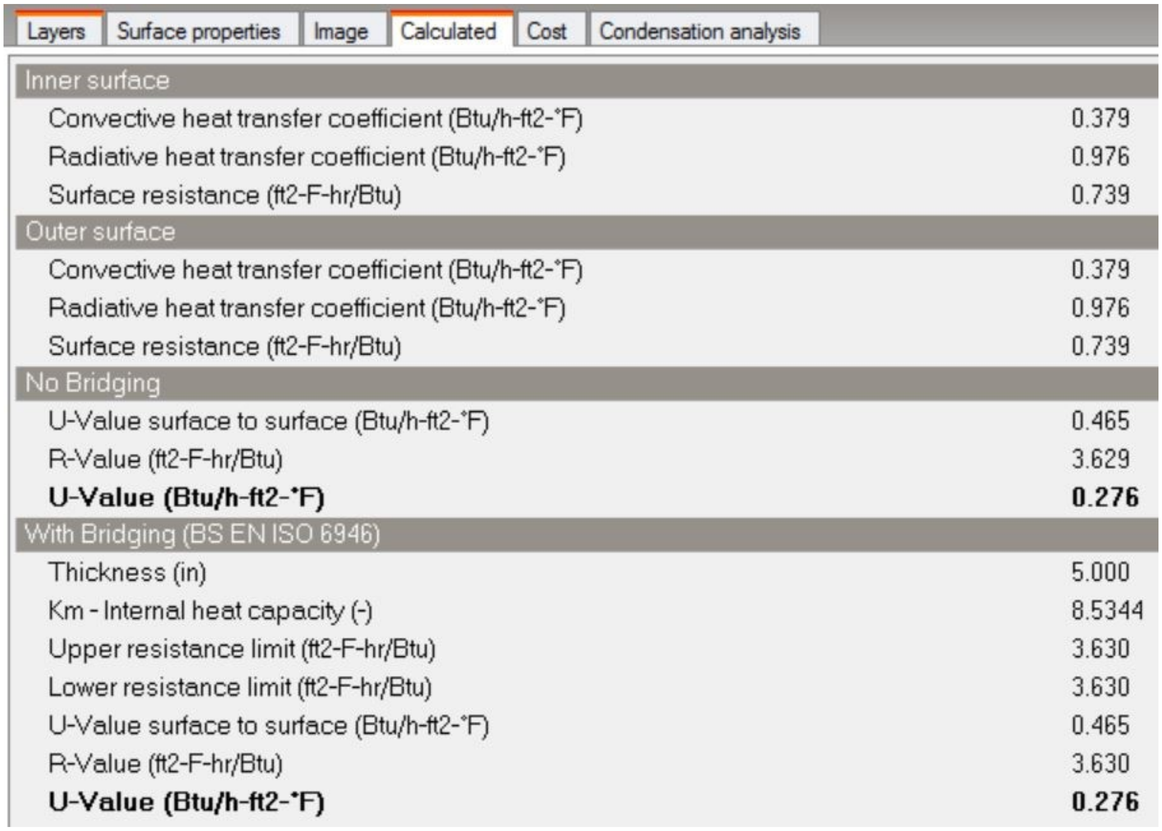
0.5000in Cement/plaster/mortar - gypsum plasterboard

4.0000in Air gap 100mm (downwards)

0.5000in Cement/plaster/mortar - gypsum plasterboard

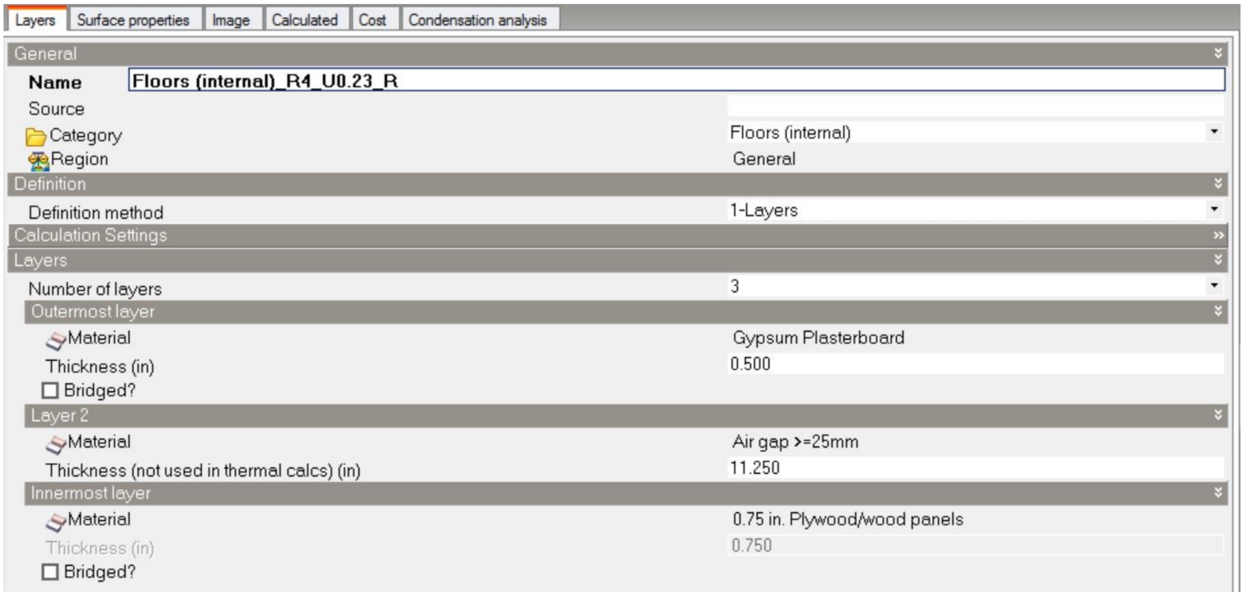
Inner surface

Figure: D-13 Party wall for all models, cross-section



Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.379
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.739
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.379
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.739
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.465
R-Value (ft2-F-hr/Btu)	3.629
U-Value (Btu/h-ft2-°F)	**0.276**
With Bridging (BS EN ISO 6946)	
Thickness (in)	5.000
Km - Internal heat capacity (-)	8.5344
Upper resistance limit (ft2-F-hr/Btu)	3.630
Lower resistance limit (ft2-F-hr/Btu)	3.630
U-Value surface to surface (Btu/h-ft2-°F)	0.465
R-Value (ft2-F-hr/Btu)	3.630
U-Value (Btu/h-ft2-°F)	**0.276**

Figure: D-14 Party wall for all models, R-value calculation



General	
Name	Floors (internal)_R4_U0.23_R
Source	
Category	Floors (internal)
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	3
Outermost layer	
Material	Gypsum Plasterboard
Thickness (in)	0.500
☐ Bridged?	
Layer 2	
Material	Air gap >=25mm
Thickness (not used in thermal calcs) (in)	11.250
Innermost layer	
Material	0.75 in. Plywood/wood panels
Thickness (in)	0.750
☐ Bridged?	

Figure: D-15 Lightweight internal floor, general information

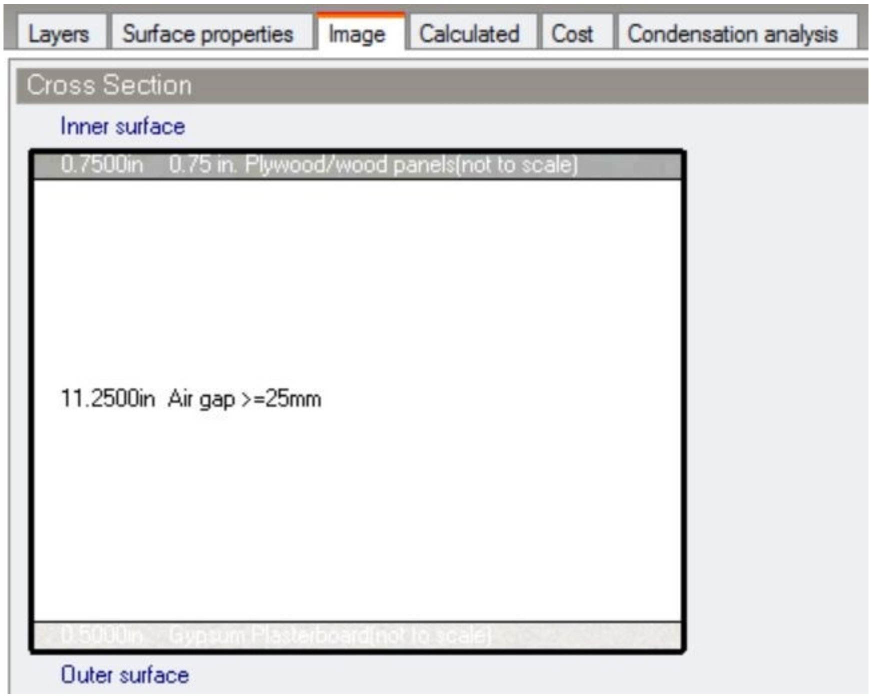
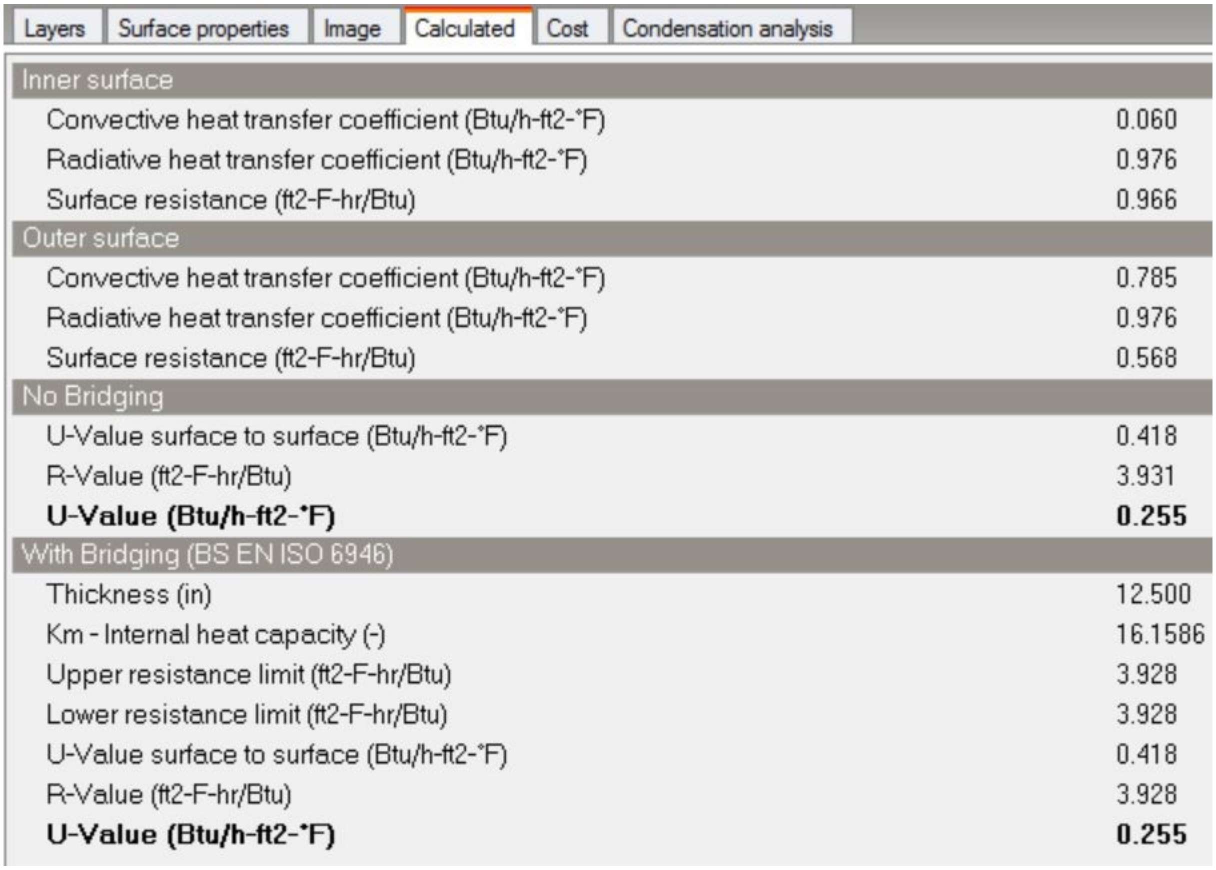
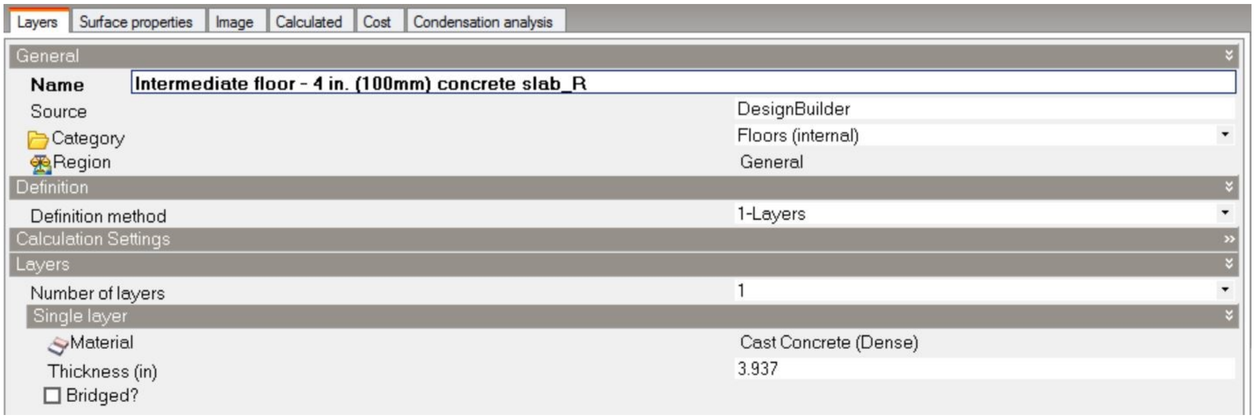


Figure: D-16 Lightweight internal floor, cross-section



Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.060
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.966
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.785
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.568
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.418
R-Value (ft2-F-hr/Btu)	3.931
U-Value (Btu/h-ft2-°F)	**0.255**
With Bridging (BS EN ISO 6946)	
Thickness (in)	12.500
Km - Internal heat capacity (-)	16.1586
Upper resistance limit (ft2-F-hr/Btu)	3.928
Lower resistance limit (ft2-F-hr/Btu)	3.928
U-Value surface to surface (Btu/h-ft2-°F)	0.418
R-Value (ft2-F-hr/Btu)	3.928
U-Value (Btu/h-ft2-°F)	**0.255**

Figure: D-17 Lightweight internal floor, R-value calculation



General

Name	Intermediate floor - 4 in. (100mm) concrete slab_R
Source	DesignBuilder
Category	Floors (internal)
Region	General

Definition

Definition method	1-Layers

Calculation Settings

Layers

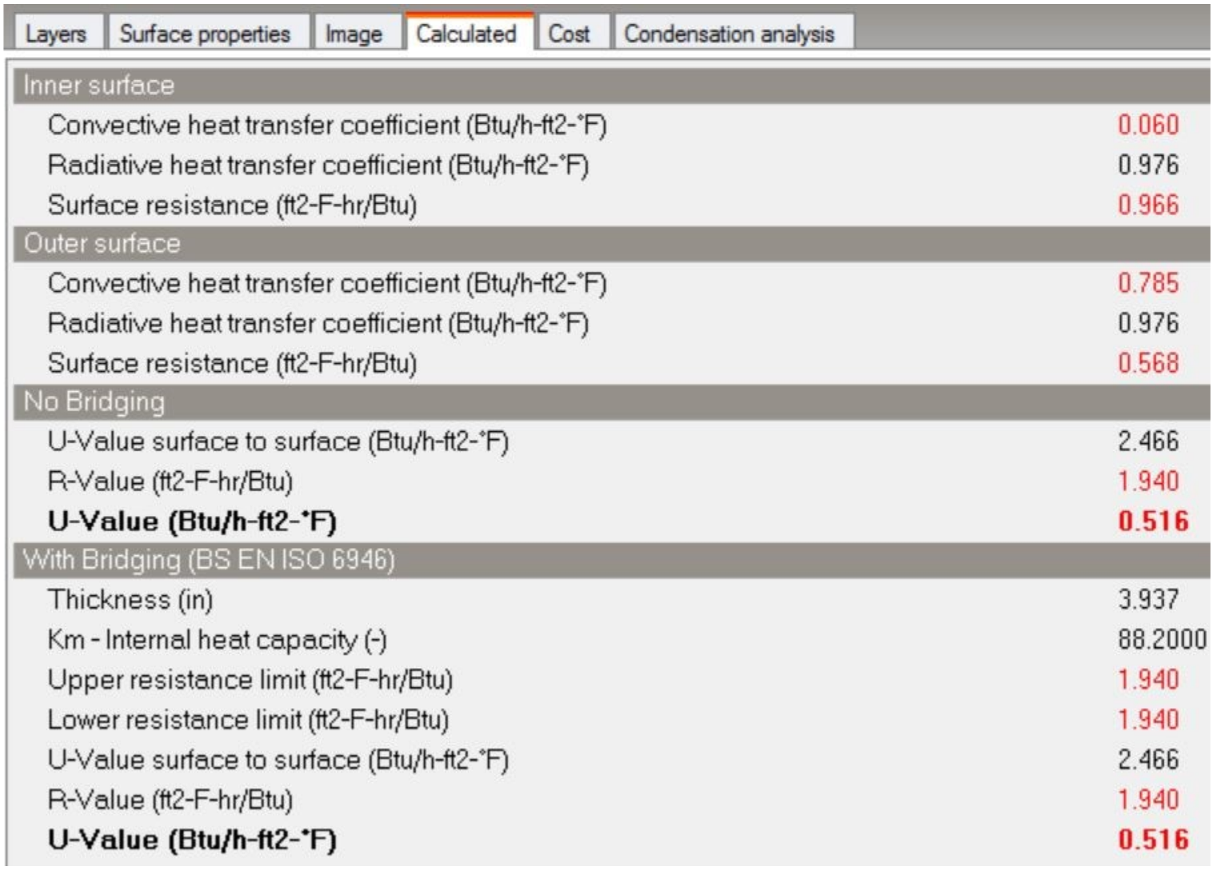
Number of layers	1

Single layer

Material	Cast Concrete (Dense)
Thickness (in)	3.937
☐ Bridged?	

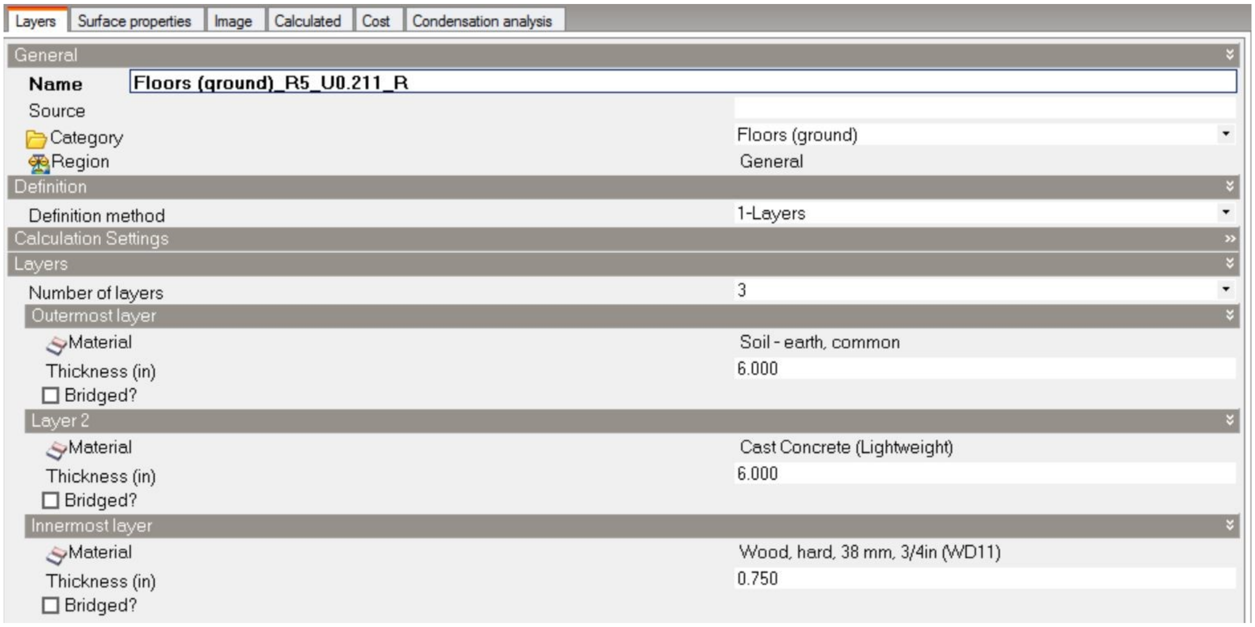
Figure: D-18 Heavy mass internal floor, general information

Figure: D-19 Lightweight internal floor, cross-section



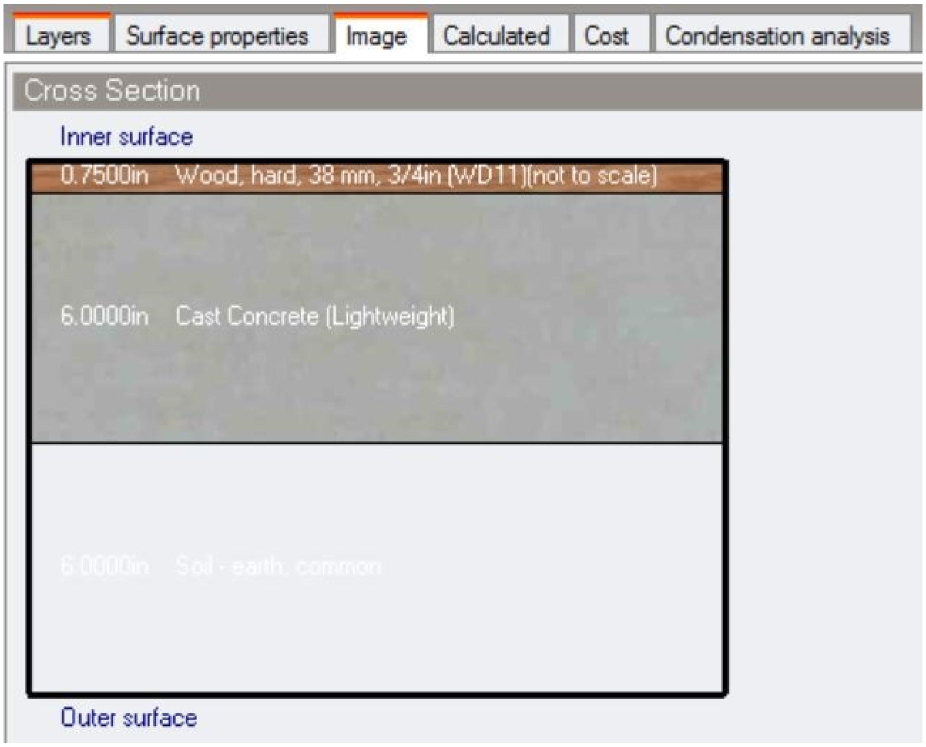
Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.060
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.966
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.785
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.568
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	2.466
R-Value (ft2-F-hr/Btu)	1.940
U-Value (Btu/h-ft2-°F)	**0.516**
With Bridging (BS EN ISO 6946)	
Thickness (in)	3.937
Km - Internal heat capacity (-)	88.2000
Upper resistance limit (ft2-F-hr/Btu)	1.940
Lower resistance limit (ft2-F-hr/Btu)	1.940
U-Value surface to surface (Btu/h-ft2-°F)	2.466
R-Value (ft2-F-hr/Btu)	1.940
U-Value (Btu/h-ft2-°F)	**0.516**

Figure: D-20 Heavy mass internal floor, R-value calculation



General	
Name	Floors (ground)_R5_U0.211_R
Source	
Category	Floors (ground)
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	3
Outermost layer	
Material	Soil - earth, common
Thickness (in)	6.000
☐ Bridged?	
Layer 2	
Material	Cast Concrete (Lightweight)
Thickness (in)	6.000
☐ Bridged?	
Innermost layer	
Material	Wood, hard, 38 mm, 3/4in (WD11)
Thickness (in)	0.750
☐ Bridged?	

Figure: D-21 IRC recommended ground floor for all models, general information



Cross Section

Inner surface

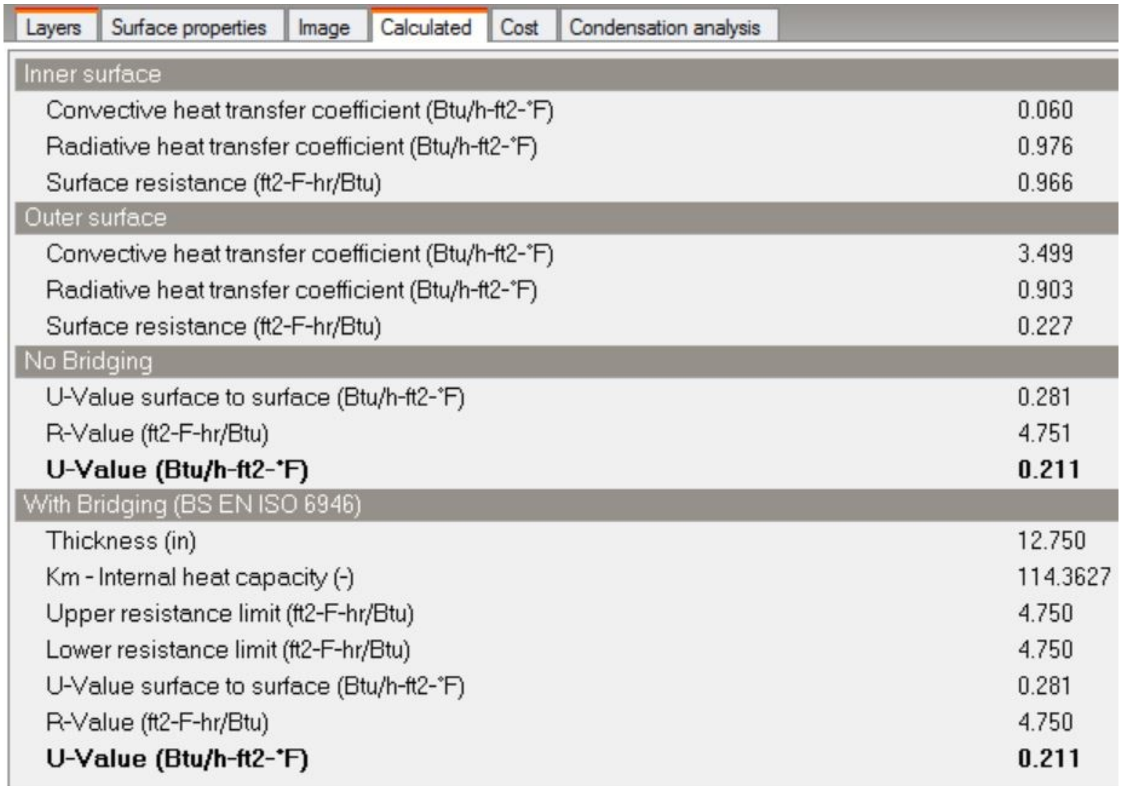
0.7500in Wood, hard, 38 mm, 3/4in (WD11)(not to scale)

6.0000in Cast Concrete (Lightweight)

6.0000in Soil - earth, common

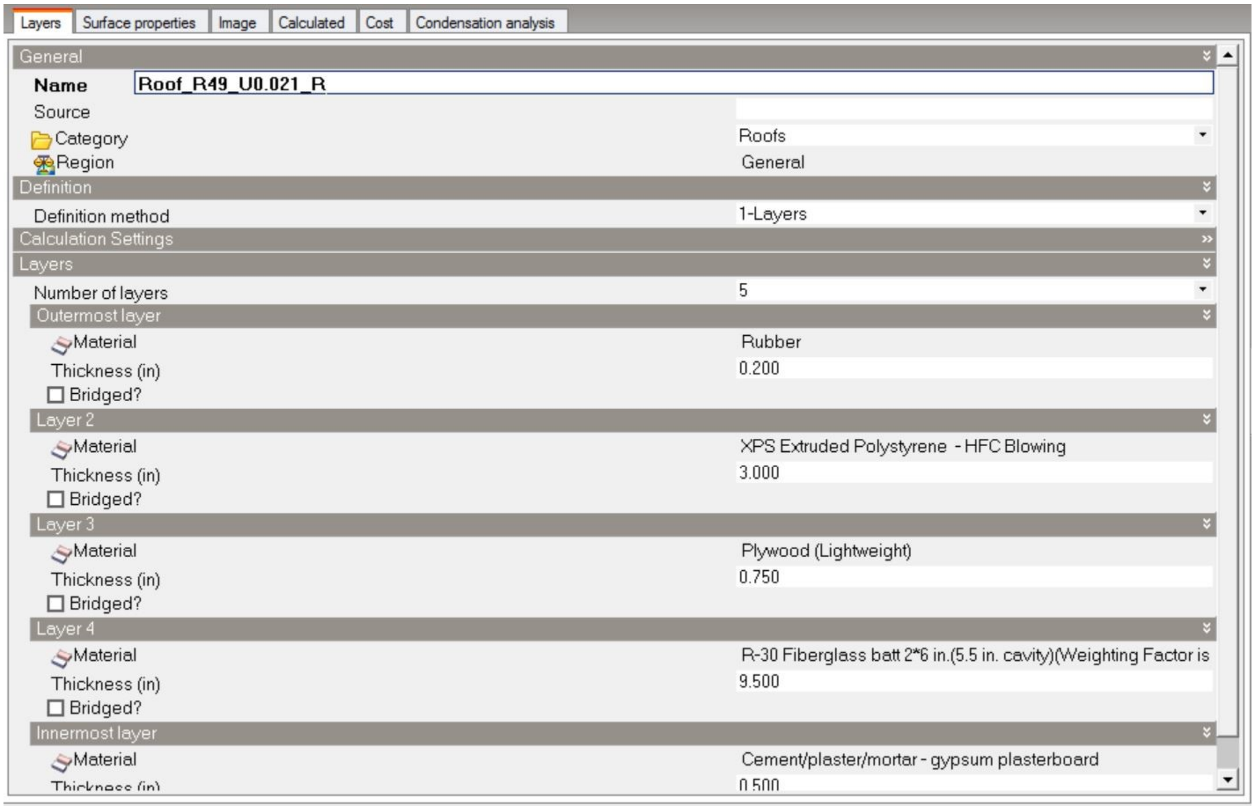
Outer surface

Figure: D-22 IRC recommended ground floor for all models, cross-section



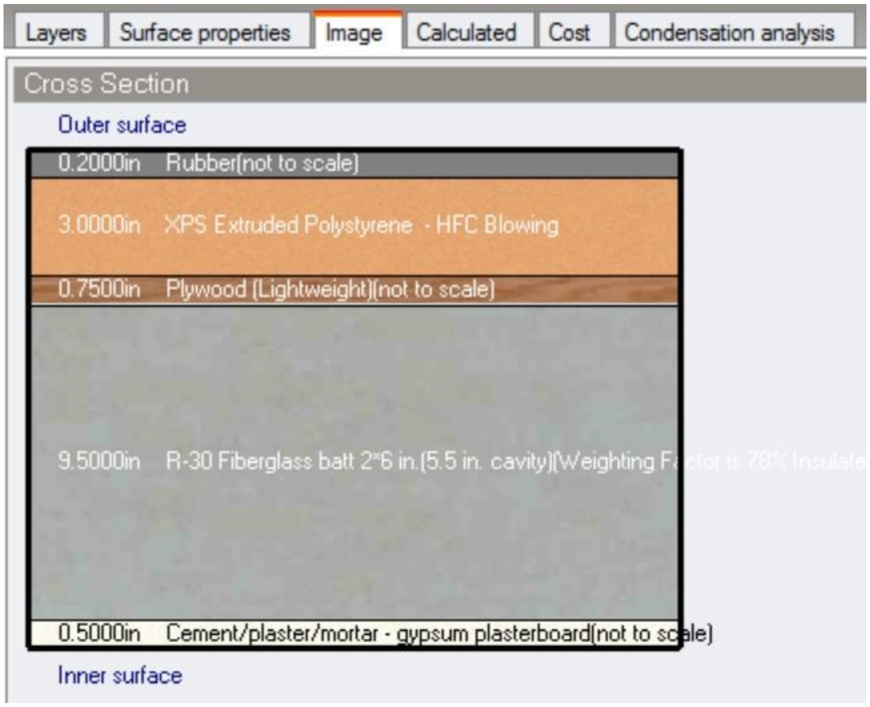
Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.060
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.966
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	3.499
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.903
Surface resistance (ft2-F-hr/Btu)	0.227
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.281
R-Value (ft2-F-hr/Btu)	4.751
U-Value (Btu/h-ft2-°F)	**0.211**
With Bridging (BS EN ISO 6946)	
Thickness (in)	12.750
Km - Internal heat capacity (-)	114.3627
Upper resistance limit (ft2-F-hr/Btu)	4.750
Lower resistance limit (ft2-F-hr/Btu)	4.750
U-Value surface to surface (Btu/h-ft2-°F)	0.281
R-Value (ft2-F-hr/Btu)	4.750
U-Value (Btu/h-ft2-°F)	**0.211**

Figure: D-23 IRC recommended ground floor for all models, R- value calculation



General	
Name	Roof_R49_U0.021_R
Source	
Category	Roofs
Region	General
Definition	
Definition method	1-Layers
Calculation Settings	
Layers	
Number of layers	5
Outermost layer	
Material	Rubber
Thickness (in)	0.200
☐ Bridged?	
Layer 2	
Material	XPS Extruded Polystyrene - HFC Blowing
Thickness (in)	3.000
☐ Bridged?	
Layer 3	
Material	Plywood (Lightweight)
Thickness (in)	0.750
☐ Bridged?	
Layer 4	
Material	R-30 Fiberglass batt 2*6 in.(5.5 in. cavity)(Weighting Factor is
Thickness (in)	9.500
☐ Bridged?	
Innermost layer	
Material	Cement/plaster/mortar - gypsum plasterboard
Thickness (in)	0.500

Figure: D-24 IRC recommended roof for all models, general information



Cross Section

Outer surface

0.2000in Rubber(not to scale)

3.0000in XPS Extruded Polystyrene - HFC Blowing

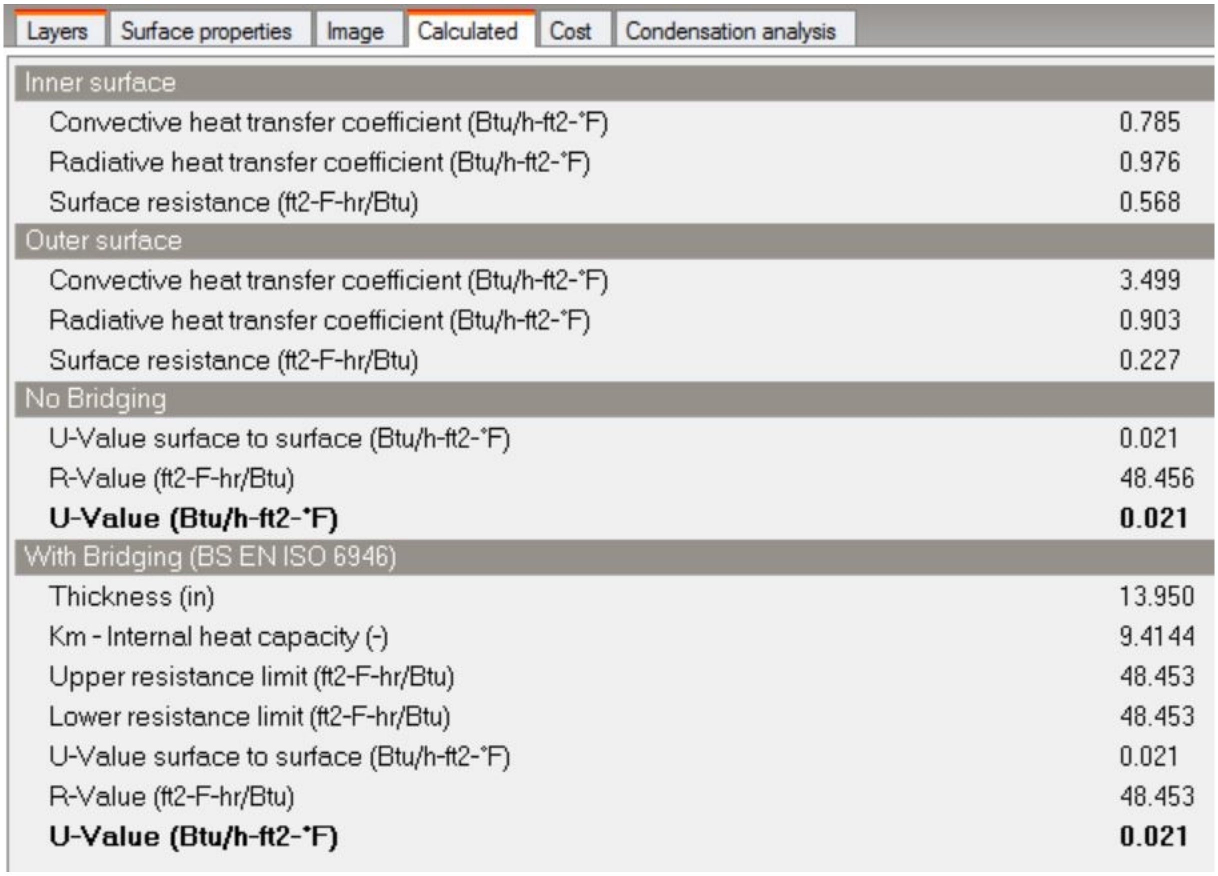
0.7500in Plywood (Lightweight)(not to scale)

9.5000in R-30 Fiberglass batt 2*6 in.(5.5 in. cavity)(Weighting Factor is 78% Insulate

0.5000in Cement/plaster/mortar - gypsum plasterboard(not to scale)

Inner surface

Figure: D-25 IRC recommended roof for all models, cross-section



Inner surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	0.785
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.976
Surface resistance (ft2-F-hr/Btu)	0.568
Outer surface	
Convective heat transfer coefficient (Btu/h-ft2-°F)	3.499
Radiative heat transfer coefficient (Btu/h-ft2-°F)	0.903
Surface resistance (ft2-F-hr/Btu)	0.227
No Bridging	
U-Value surface to surface (Btu/h-ft2-°F)	0.021
R-Value (ft2-F-hr/Btu)	48.456
U-Value (Btu/h-ft2-°F)	**0.021**
With Bridging (BS EN ISO 6946)	
Thickness (in)	13.950
Km - Internal heat capacity (-)	9.4144
Upper resistance limit (ft2-F-hr/Btu)	48.453
Lower resistance limit (ft2-F-hr/Btu)	48.453
U-Value surface to surface (Btu/h-ft2-°F)	0.021
R-Value (ft2-F-hr/Btu)	48.453
U-Value (Btu/h-ft2-°F)	**0.021**

Figure: D-26 IRC recommended roof for all models, R-value calculation

Appendix E - Programming in Python

The python code for the program used for data extraction is presented here:

```
import pandas as pd
import os
import numpy as np
import math

# Read CSV file
os.chdir(‘FILE_PATH_THAT_NEEDS_PROCESSING')
Name=['Month','Day','Year','Time','AP','Glazing','Int Nat Vent','Nat Vent','Ext
Infil','Lighting','Occupancy','Solar Gain Ext Windows','Air Temp','Radiant Temp','Operative
Temp','In Surf Temp','Ex Surf Temp',
        'Air Flow In','Air Flow Out','Outside Dry Bulb Temp','Wind Speed','Wind Direction']
Data=pd.read_csv(‘FILE_NAME',sep=',',skiprows=2,names=Name);

Mon=pd.unique(Data['Month'])
DataOut2={'Month':[],'Quarter':[],'Glazing':[],'Int Nat Vent':[],'Nat Vent':[],'Ext
Infil':[],'Lighting':[],'Occupancy':[],'Solar Gain Ext Windows':[]
        ,'Air Temp':[],'Radiant Temp':[],'Operative Temp':[],'In Surf Temp':[],'Ex Surf Temp':[],
        'Air Flow In':[],'Air Flow Out':[],'Outside Dry Bulb Temp':[],'Wind Speed':[],'Wind
Direction':[]}

for k in range(5,22):
    DataOut={'Month':[],'Quarter':[],'Mean':[]}
    variable=Name[k]
    print k
    #if k>7:break
    print variable
    for mnth in Mon:
```

```
        #if mnth >6:break
        data=Data[Data['Month']==mnth].reset_index(drop=0)
        day=pd.unique(data['Day'])
        tmpDf={'1':[],'2':[], '3':[],'4':[]}
        for dy in day:
            val=data[data['Day']==dy].reset_index()
            for quart in xrange(4):
                #ab=val.iloc[quart*6:(quart*6)+6]['Glazing']

                GlazAvg1qt=np.mean(val.iloc[quart*6:(quart*6)+6][variable])
                #print 'Glazeered',GlazAvg1qt
                if math.isnan(GlazAvg1qt)==True:
                    #print GlazAvg1qt
                    #print 'Data',val.iloc[quart*6:(quart*6)+6][variable]
                    break
                tmpDf[str(quart+1)].append(GlazAvg1qt)

        #print np.mean(tmpDf['1']),np.mean(tmpDf['2']),np.mean(tmpDf['3']),np.mean(tmpDf['4'])
        for i in xrange(4):
            DataOut['Month'].append(mnth)
            DataOut['Quarter'].append(i+1)
            DataOut['Mean'].append(np.mean(tmpDf[str(i+1)]))

    DF=pd.DataFrame(DataOut)
    DataOut2['Month']=DataOut['Month']
    DataOut2['Quarter']=DataOut['Quarter']
    DataOut2[variable]=DataOut['Mean']
    print len(DataOut2[variable]),len(DataOut2['Month']),len(DataOut2['Quarter'])
    #DF.to_csv(variable+'Mean'+'.csv')

pd.DataFrame(DataOut2).to_csv('PROCESSED_NEW_FILE_NAME')
```