ASSESSMENT OF THERMAL MASS PROPERTY FOR ENERGY EFFICIENCY AND THERMAL COMFORT IN CONCRETE OFFICE BUILDINGS

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Architecture
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

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ABSTRACT

The increasing use of concrete as a material propelled by the recent advancements in concrete technology is facing the prospect of its massive growth in the building sector worldwide. In addition to its positive structural characteristics, concrete has an inherent thermal mass feature that is known to save heating and cooling energies. However, such benefits need to be quantified so these benefits can be augmented and exploited. Concrete is also known to provide thermal comfort in a building, a prospect that can be related to its thermal mass property. While some studies have separately explored the effect of thermal mass's thickness or surface area on building energy and thermal performance in a limited way, only a few have focused on both factors in the same study in detail and for that matter their combined effects, and even fewer have taken into account the distribution of thermal mass in a building. With an integrated approach, this present research has aimed for addressing all three variables: the thickness and distribution of concrete thermal mass in the building envelope; the distribution of thermal mass in a building's configuration; and their effectiveness in reducing building energy consumption in office buildings and in improving its thermal comfort.

The research methodology mainly focused on the quantitative methods with the use of building energy simulation tools including eQUEST, Design Builder, Energy Plus, and Atherna Impact programs. The Department of Energy (DOE) benchmark office building was considered as reference building model and the architectural design variables, including wall thicknesses and exterior thermal amass area, were selected to represent primary thermal mass. The slab thickness and interior wall layouts were selected to represent the secondary thermal mass. The eight climatic conditions of 1A (very hot and humid); 2B (hot and dry); 3C (warm and marine); 4B (mixed-dry); 5A (cool and humid); 6A (cool and marine); 7 (cold and dry); and 8 (very cold) will be assumed as representatives of all 16 U.S. climate zones. Lastly, life cycle assessment (LCA) and life cycle cost (LCC) analyses were conducted for a selected number of case models.

This study has indicated that the primary thermal mass elements such as wall thickness and thermal mass area have more effects on building energy and thermal comfort performance compared to secondary thermal mass elements such as slab thickness and interior walls. Therefore, the main thermal mass-related design emphasis needs to be on its implementation in the building envelope. Energy efficiency and thermal comfort are generally conflicting criteria in building design in that the more the energy is saved, the less is the thermal comfort. Therefore, a design challenge is to determine the optimal combination of energy saving and thermal comfort. In terms of the optimization of energy usage and thermal comfort, this research shows that better energy performing thermal mass scenarios also have better thermal comfort performance. The utilization of thermal insulation along with a primary thermal mass, i.e., wall thickness, can also enhance the energy saving effects of thermal mass. In terms of LCA, an increase in wall thickness, for example, has relatively improved the environmental impacts of the building and has helped reduce the cost of building operation in its life cycle.

For future research, the effects of design form and building height on the effectiveness of thermal mass in improving building energy and thermal comfort performance can be studied. Furthermore, different types of perimeter wall assemblies and glazing, especially with low-e coating can be combined with thermal mass to study the benefit from other energy saving recommendations in conjunction with thermal mass. In terms LCC, for instance, besides the cost of concrete materials, assembly, maintenance and demolition costs associated with concrete should be determined to assess the actual benefits of thermal mass in comparison with its additional costs.

To my father (RIP), my mother and my sister whose support is never forgotten

ACKNOWLEDGEMENTS

I would like to express my deep appreciation and gratitude to my advisor, Professor Mir Ali, for the superb mentorship he provided to me throughout my doctoral education. Professor Ali's intellectual heft is matched only by his exemplary kindness and modesty, and I have been truly fortunate to have had the opportunity to work with him.

I would also like to thank my Ph.D. committee members, Professors Rick Strand, Scott Murray, Paul Armstrong and Norah El-Gohary for the valuable guidance and the friendly collegiality that each of them offered to me over the years. In a similar vein, I would like to recognize Professors David Chasco and Brian Deal for their generous support and collaboration throughout my doctoral studies.

Finally, I would like to express my gratitude to my family whose selfless support has always been my source of hope and motivation.

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LIST of SYMBOLS

A_i = interior surface area of thermal mass (m^2)
A_0 = exterior surface area of thermal mass (m^2)
C_m = heat capacity of the thermal mass (J/kg K)
C_p = heat capacity of air (J/kg K)
E = heat generation rate (W)
g = acceleration of gravity (m/s^2)
h_i = interior convective heat transfer coefficient (W/m^2 K)
h_o = exterior convective heat transfer coefficient ($W/m^2 K$)
M = mass of the thermal mass (kg)
Q_{cl} = cooling load (W)
t = time (s)
T_E = temperature rise due to internal heat gain (K)
T_i = indoor air temperature (K)
T_m = thermal mass temperature (K)
T_o = outdoor air temperature (K)
T_{set} = indoor air setting temperature at daytime (K)
$\tilde{T}_{\mathrm{o}}$ = mean outdoor temperature (K)
$D\tilde{T}_{\mathrm{o}}$ = amplitude of outdoor air temperature fluctuation (K)
β = phase shift (s)
λ_{i} = interior convective heat transfer number
λ_{o} = exterior convective heat transfer number
ξ = cooling load ratio
ξ_{t} = total cooling load ratio
ρ = air density (kg/m^3)
τ = time constant (s)
ω = frequency of outdoor temperature variation (1/s)

LIST of ABBREVIATIONS

ASHRAE: American Society of Heating, Refrigerating and Air conditioning Engineers

AK: Alaska

AT: Atlanta

AZ: Arizona

BC: Base Case

CA: California

CC: Central Core

CFC: Chlorofluorocarbon

CO_2: Carbon Dioxide

DOE: Department of Energy

FL: Florida

Ft: foot/feet

GWP: Global Warming Potential

HFC: *Hybrid fiber-coaxial*

HVAC: Heating, Cooling and Air-conditioning

IL: Illinois

In.: inches

ISO: International Organization for Standardization

IWL: Interior Wall Layouts

LA: Los Angeles

LCA: Life cycle assessment

LCC: Life-cycle cost

LCCA: Life Cycle Cost Analysis

LEED: Leadership in Energy and Environmental Design

MJ: Mega-joules
MN: Minneapolis
MT: Montana
MRT: Mean Radiant Temperature
ND: North Dakota
NM: New Mexico
OECD: Organization for Economic Co-operation and Development
ODP: Ozone Depletion Potential
OR: Orlando
PMV Predicted Mean Vote
PPD: Predicted People Dissatisfied
PV: Photovoltaic
SCL: Split Core Long side
SCM: Supplementary Cementing Materials
SCS: Split Core Short side
ST: Slab Thickness
TDB: Dry-bulb Temperature
TES: Thermal Energy Storage
TMA: Thermal Mass Area
Tswing: Temperature Swing
TR: Toronto
TX: Texas
UCLA: University of California at Los Angeles
U.S.: United States
U.S. EIA: United States Energy Information Administration

USGBC: U.S. Green Building Council

VAV: Variable Air Volume

WCED: World Commission on Environment and Development

WT: Wall Thickness

WWR: Window-to-Wall Ratio

CHAPTER 1

INTRODUCTION

As the world population continues to increase from its present 7 billion mark, the demand for our limited natural resources such as water, coal, oil, and natural gas increases as well. With time, this trend can lead to a gradual depletion of these resources, which in turn will become a greater challenge for future generations who will have to deal with even higher population densities and fewer resources. Moreover, our lifestyle is contributing to the era of an ever-increasing amount of emission of toxic gases and other pollutants that harm our environment.

As a result of limited natural resources and greenhouse gas emissions caused by fossil fuels, great emphasis is lately being placed on sustainability in building design and construction as a strategy to deal with these increasingly growing problems. Thermal mass benefits fit into the bigger picture of sustainable design to improve building energy performance.

1.1 Sustainability in design and construction

The World Commission on Environment and Development (WCED) defines sustainability as meeting the needs of present generations without compromising the ability of future generations to meet their own needs (WCED, 1989) According to the Organization for Economic Co-operation and Development (OECD), sustainable design has five major objectives: resource efficiency, energy efficiency, pollution prevention including indoor air quality as well as harmonization with environment, and integrated and systemic approaches (OECD, 2002).

In the area of design and construction, sustainability has its own applications. Newman defines sustainable architecture as an environmentally-conscious design approach, which saves energy and utilizes construction materials responsibly (Newman, 2001). Others consider the overall benefit of sustainability to be energy efficiency, design flexibility, resource conservation, and acceptable indoor environmental quality (Donaldson & Lippe, 2002). Again, the term sustainability, even in the construction sector, is tied to our efforts to save energy as one of the most prominent design factors. According to Hamzah and Yeang (2000), design in accordance with nature or "ecological design" is another interpretation of sustainability in general, and sustainable design and construction in particular. Yeang (1997) has also incorporated the principles of sustainability in the "bioclimatic" tall buildings that he pioneered. These types of buildings seek to create a place, which is responsive to local climates, and able to deliver a high level of comfort for occupants, and save energy through passive strategies. These ecological factors help improve the quality of indoor environment and save input energy because the available ambient resources are fulfilling the buildings' energy demands.

Cho (2004) sees the main objective of sustainable design of buildings, especially tall buildings, to be the reduction of energy consumption, which can be achieved by making use of regional climatic conditions. In his view, development of design methodology for tall buildings in relation to regional climatic conditions can be an important contribution of architects during the early phases of the design process. This view regarding sustainable design promotes the idea of climatic and passive design solutions.

Furthermore, holistic approach toward sustainable design in buildings can begin with so-called "integrated design approach" that take architects', engineers', value engineers' and energy experts' viewpoints into account from very early stages of design (Sobek, 2008). This integrated concept applies in lieu of traditional linear design approaches, which consist of schematic design, design development, construction documents, and construction phase.

Sobek has also introduced the “Triple Zero Concept”, which discusses zero energy, zero emission and zero waste design approach (Sobek, 2008). Zero energy design may include the reduction of building energy consumption, less use of fossil fuels and higher use of renewable resources. Zero emission discusses reduction of buildings’ emissions from the materials in their life-cycle. This approach encourages using local materials to minimize the sick-building syndrome phenomenon and energy used for transportation. Zero waste mainly focuses on reusing and recycling of building materials and documenting all building components and promotes “easily demountable construction” (Sobek, 2008).

In 1993, the U.S. Green Building Council (USGBC) was formed to address the issue of environmental and energy effects of the building industry. The USGBC introduced the Leadership in Energy and Environmental Design (LEED) rating criteria for buildings, which has eight categories, namely Sustainable Site, Location & Linkages, Water Efficiency, Energy & Atmosphere, Innovation & Design Process, Awareness & Education, Indoor Environmental Quality, and Materials & Researches (USGBC, 2009).“Materials and Resources” is one of these LEED criteria that can be indirectly related to the thermal mass property of materials. Even though the LEED criteria extensively address many of the building components and their related energy matters, they do not offer specific recommendations in terms of sustainability of building materials per se, and further research and studies need to be conducted in this regard. Under “Energy & Atmosphere” and “Indoor Environmental Quality”, the effect of thermal mass can be related to LEED standards in terms of its energy savings and indoor thermal comfort attributes (section 1.3 and 1.4).

It should be noted that maximizing the amount of LEED credits does not necessarily guarantee the overall sustainability of the building, which may need a detailed evaluation carried out for all aspects of sustainability. Ali and Dimick noted, “Depending on the climate, location, and size of the project, certain structural materials may be more sustainable than others …. Therefore, engineers must understand the effects that their choice of structural material will have on energy consumption, not only in terms of production, transportation, and installation, but also during the operation and deconstruction of a building” (Ali & Dimick, 2009). It is known that structure can potentially have a significant influence on the sustainability of a building in terms of weight of building, spacing and layout, as well as interior and exterior design of buildings. Given these parameters, it is critical to improve the current knowledge about structural materials, and sustainable structure that can contribute to the LEED criteria (Ali, 2009). Among commonly-used structural materials, concrete is experiencing an increasing demand worldwide because of its unique structural, architectural and energy performance characteristics. Energy modeling includes the entire building and hence concrete’s thermal mass, although the latter has positive impact on energy efficiency, yet such benefits remain un-recognized.

1.2 Concrete as a sustainable material

Concrete is “the world’s most consumed man-made material” (Naik, 2008). In 2002, about 2.7 billion m^3 of concrete were produced worldwide. Concrete by itself is a sustainable material. It has a relatively low inherent energy requirement, is produced with little waste, its resources are plentiful on earth, has a high thermal mass and is completely recyclable (Naik, 2008). Concrete is a durable and dependable material, and due to its compatibility has good energy performance characteristics. It also brings flexibility to the design and construction and is environmental friendly. Given the currently increasing movement toward industrialization and urbanization around the world, the use of concrete will keep growing.

It is well known that concrete, along with its unique structural characteristics, has an intrinsic thermal mass property that can improve building energy and thermal comfort performance. Although the thermal mass of concrete is known to contribute to the energy efficiency and hence sustainability of buildings, its quantitative assessment has not received as much attention as it deserves. This study intends to shed some light on this topic based on comparative energy analyses of concrete buildings.

In the next section, an overview of energy consumption profile in the United States, especially in the building industry will be presented, which further highlights the importance of energy savings and the use of thermal mass as an inexpensive and effective energy saving solution in buildings.

1.3 Building energy use

In the year 2010 the power energy used in the United States was 98,003 quadrillion Btu, which is about 200% increase since 1949 (U.S. Energy Information Administration, 2011). Such growth has not entirely resulted due to manufacture sector or transportation, but rather by the building industry (Ichinose, Shimodozono, & Hanaki, 1999). In fact, in the United States, the building sector is responsible for more than 40% of total energy consumption (Buildings Energy Data Book, 2011). According to the USGBC, the U.S. building sector consumes more than 60% of the electricity used in the country (USGBC, 2009), which is one of the many facts that highlight the importance of the energy efficient design concept in this industry. Figure 1.1 developed by the United States Energy Information Administration (U.S. EIA) shows the supply and demand for energy in 2010. The numbers in this figure represent the percentage of total energy supply (left hand) and energy demand (right hand). As shown, coal, natural gas, crude oil, and renewable energies are among the most common energy resources, and buildings, manufactures and transportation are the main energy consuming sectors.

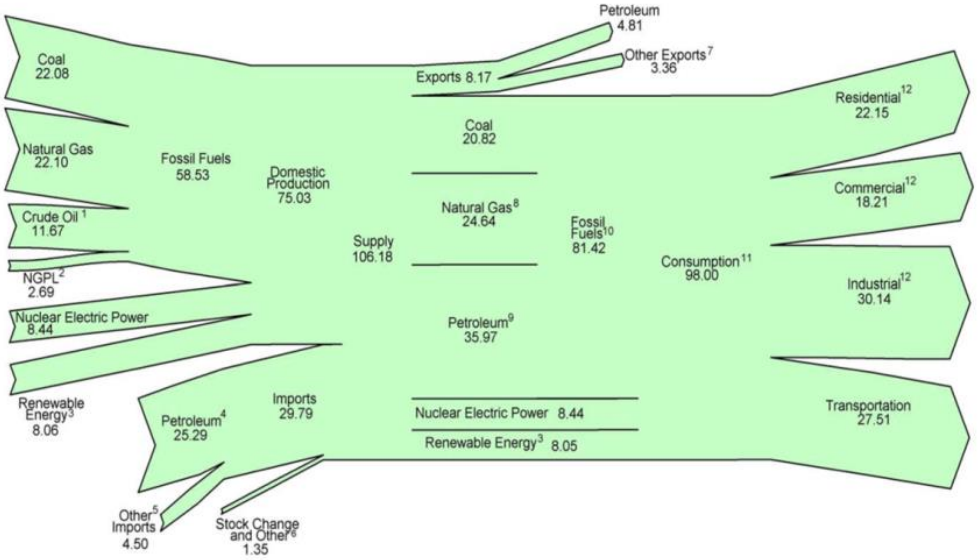


Figure 1.1 U.S. Energy Supply and Demand Percentages in 2010 (*Source: U.S. EIA, 2010*)

Figure 1.2 shows that only 8% of total U.S. energy production comes from the renewable energies of which hydroelectric power, wood and biofuels are the main contributors. It should be noted that given the harmful environmental impact of fossil fuel energy resources, the contribution of renewable energies to the U.S. energy profile can be and should be strengthened and increased.

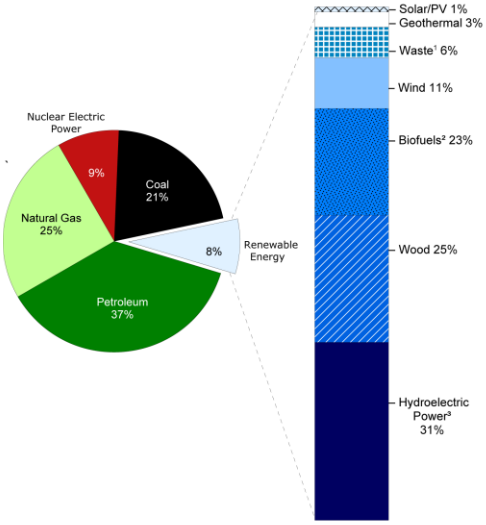


Figure 1.2 Renewable energy as share of total primary energy consumption (*Source: U.S. EIA, 2010)*

Figure 1.3 demonstrates the end-use shares of total U.S. energy consumption of which residential and commercial building are responsible for more than one-third. It is also shown in Figure 1.4

that the increase of energy use by all energy consuming sectors including manufacture, transportation and buildings over the past 60 years has been significant. As a matter of fact, as compared to 1950s, the amount of energy consumption has doubled in 2010.

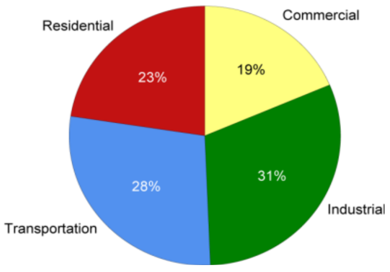


Figure 1.3 End-use sector shares of total U.S. energy consumption, *Source: U.S. EIA, 2010*

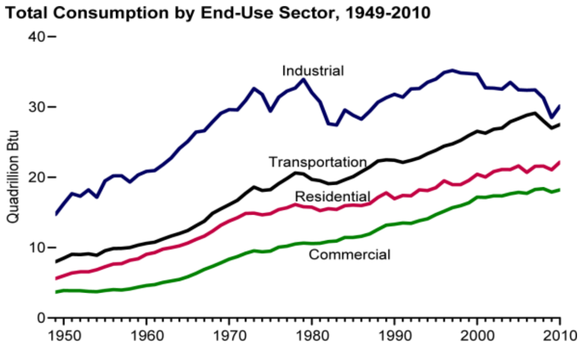


Figure 1.4 Total annual consumption by end-use sector, 1949-2010, *Source: U.S. EIA, 2010*

Among all building types, office buildings consume large quantities of energy. In fact, as shown in Figure 1.5, office buildings have the highest energy use among all building types. Retail and service, education and health care facilities all have lower energy usage as compared to the office buildings.

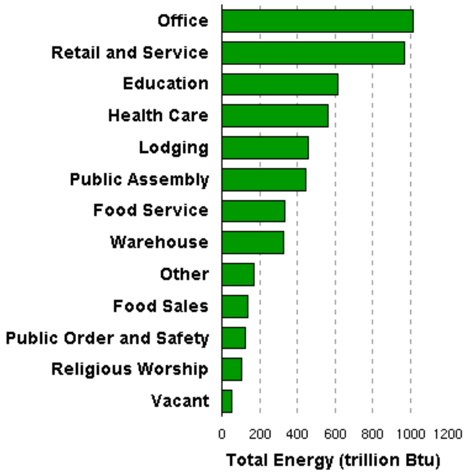


Figure 1.5 Building type total annual energy consumption in 2010 (*Source: U.S. EIA, 2010)*

Figure 1.6 shows 66% of office buildings' on-site energy use comes from electricity only and natural gas contribution does not exceed 25%. It is known that space cooling and heating have significant effects on electricity and gas consumption. As shown in Figure 1.7, heating and cooling, in which the use of concrete thermal mass has significant impact, together are responsible for 35% of total office buildings' energies.

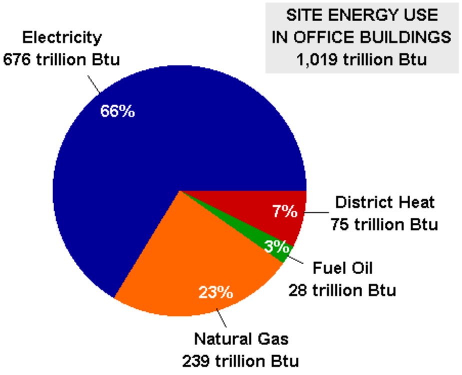


Figure 1.6 Site energy use in office buildings (type of energy source), *Source: U.S. EIA, 2010*

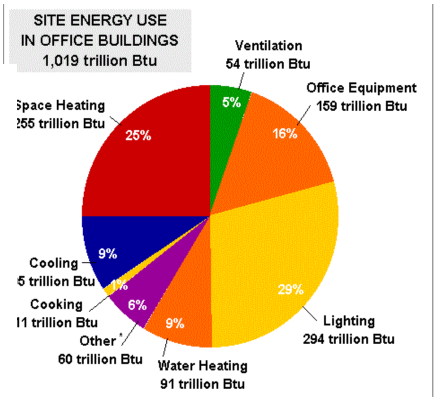


Figure 1.7 Site energy use in office buildings (end-user sectors), *Source: U.S. EIA, 2010*

The use of electricity in office buildings is shown in Figure 1.8. It is noted that about 17% of total electricity usage in office buildings is related to space heating and cooling, considering the cost of energy (Figure 1.9), they are responsible for 15% of total energy cost in office buildings. It is noted that the use of thermal mass that helps reduce building heating and cooling demands can significantly reduce building energy cost.

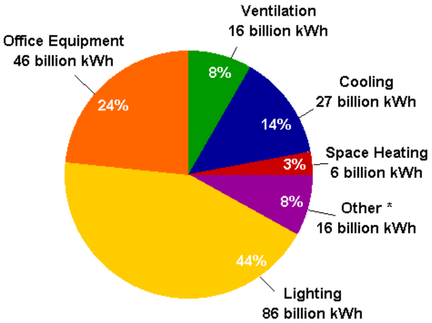


Figure 1.8 Site electricity use in office buildings, *U.S. EIA, 2010*

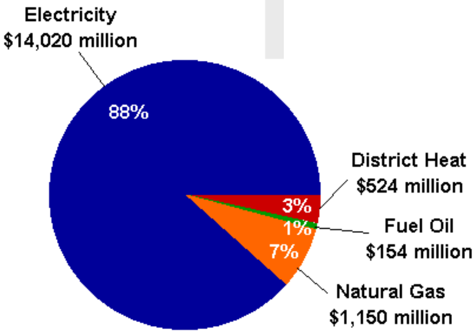


Figure 1.9 Cost of energy in office buildings, *U.S. EIA, 2010*

Furthermore, an analysis of 250 office buildings in the U.S. and Canada (Elmahdy, 1982; Syska & Hennessy, 1977) shows that, on average, the office building consumes between 26 and 104 kWh/ft^2 per year. Another survey (Piette, Wall, Gardiner, 1986) of the office buildings, that won awards in the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) Energy Awards Program, shows that improved design and operation can reduce the energy consumption in these buildings to 18 kWh/ft^2 yr. (Zmeureanu and Fazio, 1988).

One way of achieving lower energy consumption is to make better use of the thermal storage in the building mass. Relatively little is known about the effect of thermal mass on the energy consumption in office buildings, which significantly differ from residential buildings in size, form, internal loads, control, occupancy profiles and schedules (Zmeureanu and Fazio, 1988). This research aims at addressing this issue and comprehensively studying the impact of thermal mass on energy and thermal comfort performance of office buildings.

Because of high heat gains from lighting, people, equipment, and solar insolation during occupied periods, a typical office building in a cold climate with 6500 heating degree days, for instance, has a daytime cooling load from mid-March through mid-November. During the period mid-March through mid-May and mid-September through mid-November, the daytime cooling requirement is often satisfied by the building ventilation system in economizer mode since daytime outside air temperatures below 72°F frequently occur during these times of the year (Brown, 1990).

However, an office building also typically experiences nighttime heating loads when the building is unoccupied during these time periods. The high thermal-storage-design buildings store heat gains from lighting, people, equipment, and solar insolation with limited rise in indoor air temperature during occupied periods. Therefore, the operation of the economizer ventilation cooling is limited in the high thermal mass design buildings in the spring and fall periods because the indoor air temperature does not rise to the cooling set-point building designs. In the high thermal storage design buildings the heat stored in the building thermal mass during the day is released to fulfill the nighttime heating loads, thereby reducing the amount of energy required from the heating system (Brown, 1990). These are some of the advantages the high thermal mass design can bring to the energy efficiency of an office building.

1.4 Thermal comfort in buildings

Human body is constantly producing heat, which helps maintain the body temperature constant. This heat production depends upon our activity levels as well as metabolism. The human bodies also dissipate heat to the surrounding environment to maintain their temperature. The heat transfer mechanism to and from the body occurs mainly through conduction, convection (evaporation) and radiation via skin.

1.4.1 Thermal comfort

ASHRAE Standard 55 -2010, defines thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 55, 2010). Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. The environmental conditions required for comfort are not the same for everyone. However, extensive laboratory and field data have been collected that provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable. Thermal comfort could be monitored and maintained through both quantifiable and non-quantifiable parameters.

1.4.2 Thermal comfort factors

The quantifiable parameters of thermal comfort could be classified in three main categories including air-related, surface-related and human-related factors (Strand, 2008). The air factors include temperature, humidity and velocity of air. The primary effects of air temperature are related to convection and evaporation phenomena. The air humidity directly affects the heat loss from the human bodies since high humidity leads to less ability of human body to eject heat, which in turn, could result in thermal discomfort. The air velocity helps increase the rate of heat loss through the skin, which facilitates the heat dissipation from a body.

The surface factors are primarily related to the radiation phenomenon that is crucial for maintaining thermal comfort. For instance, given the same air set-point temperature, when the outside is colder, the inside also feels colder meaning that the same temperature does not provide the same level of thermal comfort. Another surface factor is the proximity. In other words, the distance to surrounding surfaces as well as the size of these surfaces can affect occupant perception of thermal comfort. The third category of quantifiable thermal comfort indices is called human factors, which in turn, has two subcategories—metabolic rate and clothing. Humans' metabolic rate changes in accordance with their activity levels. For instance, while sleeping, our metabolic rate is about 0.7 MET (one MET=18.4 Btu/h ft^2, for average adult with a body surface area of 19.6 ft^2); however, walking on the level for 4 mph will result in 3.8 MET (Stein, Reynolds, Grondzik & Kwok, 2010). Humans' clothing level (measured in Clo ranging from 0 to 1.0 where 1.0 Clo = typical business suit in 1941) is another influential factor that affects our perception of thermal comfort.

The psychological factors, e.g., feeling happy or angry are non-quantifiable thermal comfort parameters, and could affect our perception of thermal comfort. Our fitness level could also play a role in heat production. In other works, people with larger muscles normally tend to produce more heat while resting as compared to others. Age and gender could be influential factors in terms of metabolic rate and body heat production (Strand, 2008).

1.4.3 Thermal comfort models

As mentioned before, the perception of thermal comfort is influenced by the variables that affect the heat and mass transfer in our energy balance model. The most common approach to characterizing thermal comfort for the purposes of prediction and building design has been to correlate the results of psychological experiments to thermal analysis variables. According to ASHRAE Standard 55-2010, if 80% of occupants are satisfied with the level of comfort, the thermal comfort has been provided. Furthermore, the Predicted Mean Vote (PMV) versus Predicted People Dissatisfied (PPD) developed by Fanger measures the level of comfort through a qualitative evaluation (ASHRAE 55, 2010).

In this model (Figure 1.10), the occupant perception of thermal comfort is measured from scale 0 to ± 2 represented by PMV, where 0 means thermally neutral condition, positive number imply warm/hot and negative numbers indicate cool/cold conditions.

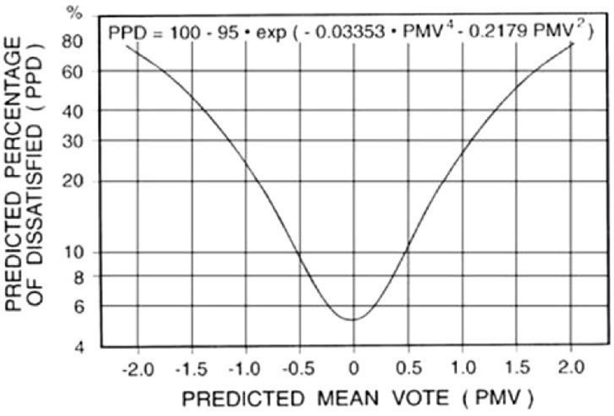


Figure 1.10 PMV versus PPD, *Source: ASHRAE Standard 55-2010*

As shown, even at level 0 (neutral) 5% of people are still dissatisfied with the comfort conditions.

1.4.4 Thermal comfort zone

ASHRAE Standard 55-2010 defines comfort zone as a “range of temperature and humidity conditions in which humans will likely be comfortable” (ASHRAE 55, 2010). As shown in Figure 1.11, less clothing (lower Clo) could allow us to tolerate a warmer environment.

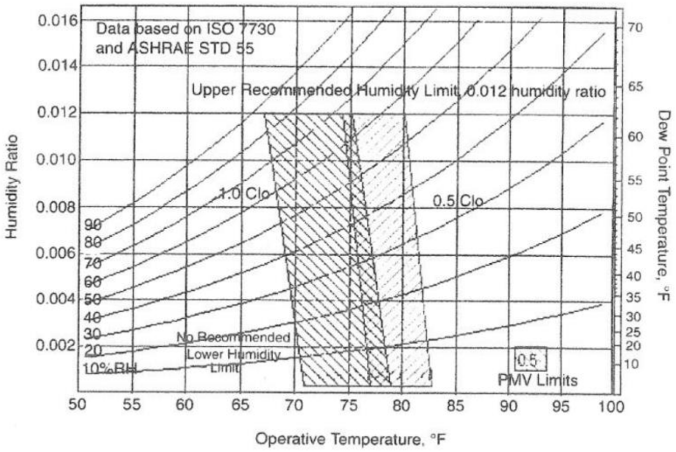


Figure 1.11 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

The range of operative temperatures presented in Figure 1.11 is for 80% occupant acceptability. This is based on a 10% dissatisfaction criteria for general (whole body) thermal comfort based on the PMV-PPD index, plus an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort. Figure 1.11 specifies the comfort zone for environments that meet the above criteria and where the air speeds are not greater than 40 ft./min. Two zones are shown—one for 0.5 Clo of clothing insulation and one for 1.0 Clo of insulation. These insulation levels are typical of clothing worn when the outdoor environment is warm and cool, respectively (ASHRAE 55, 2010).

1.4.5 Thermal comfort indices

Dry-bulb (TDB) and wet-bulb temperatures, relative humidity, mean radiant temperature (MRT) that is equivalent surface temperature for particular location characterizing radiant exchange with actual surroundings, and operative temperature which is average of TDB and MRT are the main thermal comfort indices (Strand, 2008).

1.5 Life cycle assessment

Life cycle assessment (LCA) is a methodology for assessing the environmental effects associated with a product over its life cycle—from raw material acquisition through production, use, and disposal (Goedkoop, De Schryver & Oele, 2007). Performing an LCA is one of the possible methods of assessing a product's environmental impacts and the potential effects that it has on the natural environment. The International Organization for Standardization (ISO) has developed international standards that describe how to conduct an LCA, which consists of three separate phases (Marceau & VanGeem, 2008).

The three phases of LCA are commonly referred to as (1) life cycle inventory analysis, (2) life cycle impact assessment, and (3) life cycle interpretation. The results of an LCA can be used to help choose among competing alternatives that have higher beneficial attributes. The first phase consists of a collection of the energy and material inputs and the emissions to air, land, and water resulted from the manufacture of the product and operation of the process. The second phase is an assessment of the potential social, economic, and environmental impacts associated with those inputs and emissions. The third phase is the interpretation of the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

In particular, the LCA of buildings is another important factor in regard to sustainability. As shown in Figure 1.12, virgin resources initially turn into building materials, and then building construction and operation begin. As the last phase of building life cycle, deconstruction of buildings could result in large amounts of material waste.

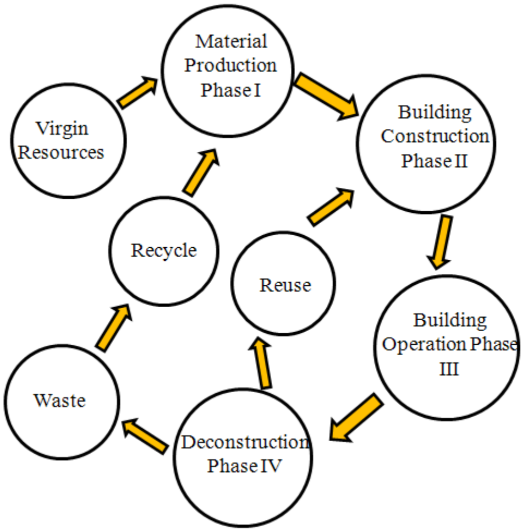


Figure 1.12 Life cycle assessment model *(Source: Ali & Dominick, 2009)*

Depending on the type of materials, they could either be recycled or reused in different building construction phases. Concrete as a structural and energy-conserving material has great potentials to be fully recycled (Ali & Greenwell, 1998). In terms of its production, the possible harmful environmental impact associated with the production of Portland cement could be offset through replacing cement by other Supplementary Cementing Materials (SCM) such as fly ash and other potentially “green” ingredients (Malhotra, 2004).

Thus far, the fundamental of sustainability, building energy use, thermal comfort, and LCA in relation to concrete thermal mass have been discussed to form the foundation of this research. In the following section, the specific research questions this study aims to address, the scope, hypotheses and research methodology will be presented.

1.6 Justification, scope and objective of research

The growing demand for energy around the world is contributing to an era of ever diminishing natural resources, in which the building industry plays a major role. Also, because of the use of fossil fuels to generate energy, greenhouse gases are emitted to the atmosphere leading to global warming. The present-day approach to reduce energy consumption mainly depends upon active mechanical methods and increasingly the use of renewable energy sources with solar panels, Photovoltaic (PV) cells, geothermal applications, and wind turbines. Simultaneously, passive approaches such as solar gain through daylighting and other alternate carbon-free sources are also being exploited.

The increasing use of concrete as a material propelled by the recent advancements in concrete technology is facing the prospect of its massive growth in the building sector worldwide. In addition to its positive structural characteristics, as well as other high-performance properties, concrete has an inherent thermal mass feature that is known to save heating and cooling energies and to improve thermal comfort in buildings, where its contribution could be measured by rigorous analysis as it is a function of the thickness, surface area, and location of the concrete elements within a building. However, such benefits need to be quantified so these benefits can be augmented and exploited. Concrete is also known to provide thermal comfort in a building, a prospect that can be related to its thermal mass property. While some studies (Mathews et al., 1991; Antonopoulos & Koronaki, 1998; Balcomb, 1983; Antonopoulos & Koronaki, 2000; Sodha et al., 1992; Shaviv et al., 2001) have separately explored the effect of thermal mass's thickness or surface area on building energy and thermal performance, only a few have focused on both factors in the same study and for that matter these combined effects, and even fewer have taken into account the distribution of thermal mass in a building. With an integrated approach, this present research has aimed to address all three variables: the thickness of concrete thermal mass in the building envelope; the concrete surface area exposed to either ambient environment or internal heat; and the distribution of thermal mass in a building's configuration.

More specifically**,** this research explores the effectiveness of concrete thermal mass in reducing building energy consumption in office buildings and in improving its thermal performance in terms of occupant comfort during a building's operation. It will evaluate the effect of thickness, surface area, and location of concrete thermal mass represented by architectural design variables such as wall or slab thickness, window-to-wall area ratio, and horizontal configurations on buildings' energy and thermal behavior.

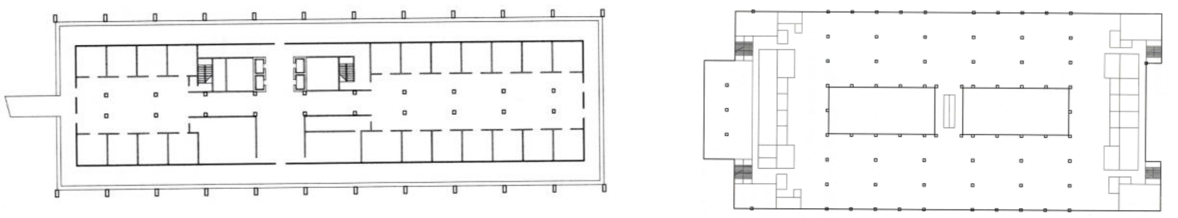
This study has focused on the sensible heat storage (i.e. change of sensible temperature), and exclude the latent or phase change heat storage (i.e. change of material phase from solid to liquid sate or vice versa). It is conducted for reinforced concrete office buildings in eight different U.S. climate zones chosen in such a way as to represent all sixteen U.S. climates (ASHRAE 90.1, 2004). While these climate zones represent typical U.S. climate conditions, lessons learned from this research can also be applied to other regions of the world with similar conditions.

This research marries the architectural and technological aspects of concrete thermal mass, and provides building architects and engineers with specific recommendations on an optimized distribution of thermal mass in office buildings to save energy and improve thermal comfort.

1.7 Research assumptions

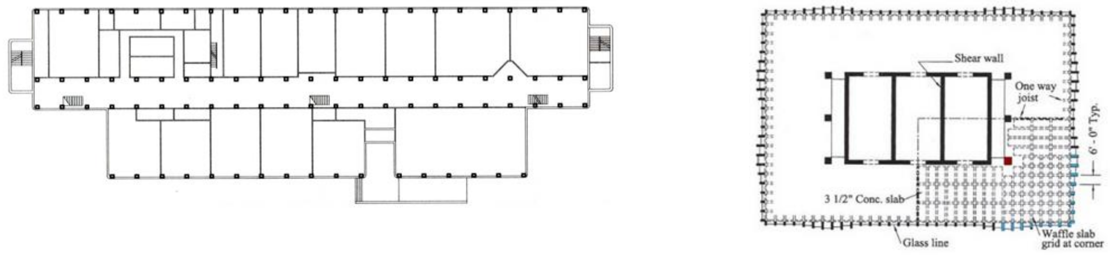
The building models investigated in this study are assumed to be air-tight, and the effects of insulation remain constant for all cases due to the comparative nature of this study. Although all building models are equipped with HVAC systems, the effect of these systems on building energy and thermal performance will be excluded as a variable of this study; therefore, the main focus of study will be on the effect of concrete thermal mass on building energy and thermal performance. The effects of sun direction, wind flow, vegetation, heat island, surrounding buildings, terrain, etc. are also excluded as a variable of this research. The annual and monthly heating and cooling energy consumptions as well as the combination of these two parameters represented by total energy consumption are the measurement indices for building energy performance, for such performance, similarly, the annual and monthly average of air, radiant and operative temperatures are assumed as the measurement indices for building thermal performance. The psychological aspects of thermal comfort such as culture, background of occupants, etc. as well as non-quantifiable thermal comfort parameters such as color, gender, age etc. have been excluded as comfort variables in this study. The sensory perception of building occupants has also been excluded as a variable in this study. It is also assumed that the heat transfer phenomenon uniformly occurs through concrete thermal mass, regardless of its location.

The Department of Energy (DOE) benchmark office building is considered as reference building model. The architectural design variables in the buildings for each category are as follows: wall thicknesses: 4 and 8 in., slab thicknesses: 4, 6 and 8 in., and window-to-wall area ratios: 20 and 40%. In addition, the building's horizontal design configurations will be taken to represent concrete thermal mass in four scenarios: (1) only concrete slabs and exterior walls; (2) slabs and core walls; (3) slabs, core walls and other interior walls, and (4) the whole concrete building consisting of exterior, interior and core concrete walls. Figure 1.13 shows a few examples of existing buildings similar to the four horizontal design configurations mentioned before.



John Deere Administrative Headquarters, Moline, Illinois

Lockheed Building 157, Sunnyvale, CA



Robert Wallace Earth Science Center, Manitoba, Canada

One Shell Plaza, Houston, TX

Figure 1.13 Architectural layouts of different buildings

According to the ASHRAE Standard 90.1-2010, the eight climatic conditions of 1A (very hot and humid), 2B (hot and dry), 3C (warm and marine), 4B (mixed-dry), 5A (cool and humid), 6A (cool and marine), 7 (cold and dry), and 8 (very cold) will be assumed as representatives of all sixteen U.S. climate zones. A matrix is developed to include all combinations of different climate zones and architectural design variables in which the effect of every design parameter is studied in different locations. Chapter 8 discusses this matrix and it results in details. As far as the thermal comfort indices are concerned, for this research, the air, surface and operative temperatures have been selected to monitor the level of comfort in different simulation scenarios.

Regarding the LCA analysis, among all three phases of this assessment mentioned in Section 1.5, only the Phase I — life cycle inventory analysis — has been conducted in this study.

In general, to maximize the sustainability of a building, an integrated planning approach is essential. This is the appropriate way to address conflicting interests such as energy efficiency and thermal comfort. Therefore, an integrated approach consisting of both passive techniques (e.g.

glazing, insulation, thermal mass, etc.) and active measures (e.g. more efficient heating and cooling systems, etc.) can be considered to achieve best possible outcome

1.8 Research methodology

A quantitative research approach including computer simulations has been used to assess the energy and thermal performance of buildings. The eQUEST, Energy Plus, and Athena computational programs are the main simulation tools at various levels of this study, where the modeling of buildings has been done by the Design Builder program, except for eQUEST, which has built-in modeling capabilities. This research is conducted in two major steps, of which one is a preliminary study and the other is the main body of the research. The preliminary study was intended to set the stage for the detailed main study.

1.8.1 Preliminary study

In this step initially the extent of concrete thermal mass effect on building energy performance in selected climate zones are compared with other building materials including steel and masonry to numerically assess the comparative advantage of concrete as a thermal mass material. Then, the variation of a selected group of building design variables including wall thickness and window-to-wall area ratio are analyzed to determine which variables and to what extent they contribute to the building's energy and thermal performance.

1.8.2 Main study

The variation of architectural design variables including wall and slab thickness, window-to-wall area ratio, and building horizontal layouts in terms of their effects on building energy and thermal performance are integrated through a comprehensive analysis. The outcome of each variation is then compared with the reference model. Initially, each category of building design variables including wall thickness, slap thickness, window to wall area ratio and plan layouts are separately evaluated to determine the potential trends of energy savings and in thermal performance improvements. Then, analyses of combinations of different design variables that can lead to a higher building energy and thermal performance are conducted.

As an added feature, after achieving the best case energy and thermal performance scenarios in different locations, their life cycle performance is evaluated against the building reference models using the Athena Impact program. The life cycle analysis is an auxiliary feature of this research in order to gain additional insights into the long term contribution of concrete thermal mass to the overall energy and thermal performance of office buildings.

In Chapter 2, the thermal mass theory is described along with literature review as well as benefits and applications of thermal mass.

1.9 Summary

This chapter reviews the fundamentals of sustainability, energy use and thermal comfort in the built environment. It also discusses this current doctoral research, its assumptions, scope, and methodology. Built environment is responsible for more than 40% of total United States annual energy consumption, which makes it a crucial sector with respect to energy saving measures. Built environment also plays a critical role in providing thermal comfort for occupants. This study will evaluate the effects of architectural design variables on building energy and thermal comfort performance with respect to concrete thermal mass.

CHAPTER 2

FUNDAMENTALS OF THERMAL MASS

Thermal mass is a significant inherent property of a material, and can be defined as the ability of the material to absorb, store, and release heat when needed (U.K. Concrete Industry, 2010). Heavy weight materials usually provide high levels of thermal mass that could effectively regulate the temperature fluctuations in buildings. As a general phenomenon shown in Figure 2.1, thermal mass absorbs heat and provides air circulation during the day via the buoyancy phenomenon, in which the warmer air, in contact with the thermal mass wall, rises and enters the adjacent room through openings near the top, while the colder air leaves the room through openings at the bottom thereby getting heated by the thermal mass. This phenomenon continues throughout the day.

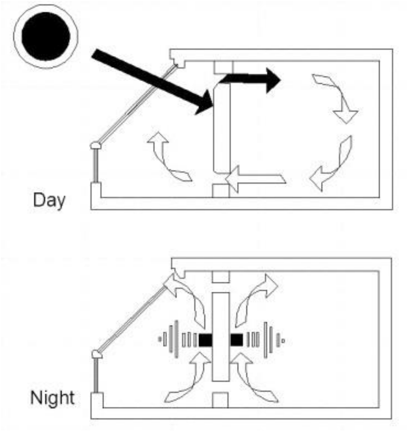


Figure 2.1 Thermal mass phenomenon *(adapted from: http://www.hhocarfuelcell.com/solar-power/solar-heating/passive-solar-heating-and-cooling/)*

However, at night, the absorbed heat is released to the surrounding environment, which could be very useful especially in hot and arid regions, where the outdoor night temperature is usually low. During summer, thermal mass delays heat transfer from outside to the inside; stabilizes the internal temperature; and reduces its fluctuations, which in turn, reduce the building energy use by lowering the cooling loads in air-conditioned spaces (U.K. Concrete Industry, 2010). In the evening, due to lower external air temperatures, night ventilation in conjunction with thermal mass could facilitate the removal of accumulated heat in the building.

At the beginning of the following day, the cooled building mass functions as a heat sink. The cooled mass can effectively lower the building cooling loads provided the building envelope is well-insulated (Balaras, 1996), and it can possibly reduce the energy consumption of the building, since it will reduce the operation time of HVAC systems.

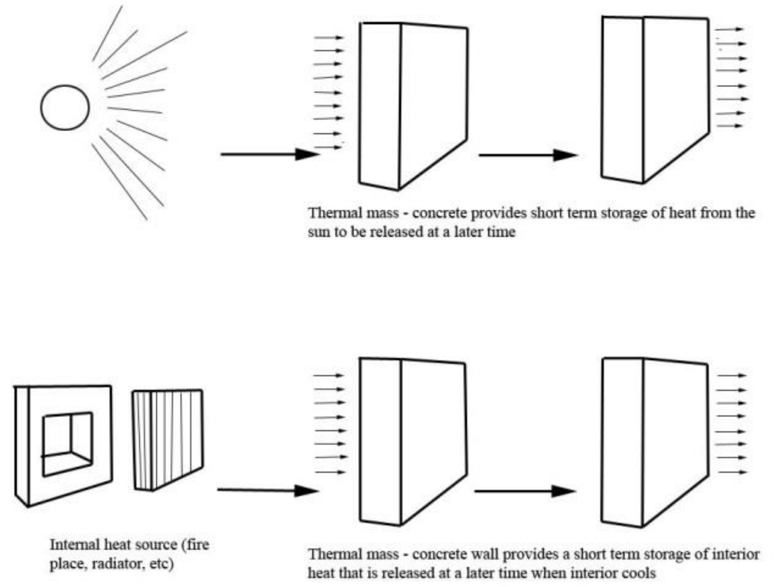


Figure 2.2 Thermal mass concrete and heat transfer (*Source: Schokker, 2010)*

Figure 2.2 shows the performance of thermal mass walls delaying the heat transfer in both summer and winter times (Schokker, 2010). Thermal mass materials such as concrete have also considerable contribution to building energy use in winter times as well. During winter, the south facing windows, integrated with high thermal mass materials, could help absorb and store heat. At night, stored heat is released into the building, which reduces the heating loads of space. The process is similar to what happens in summer nights, however, this characteristic is more beneficial in winter allowing windows and openings to remain closed, which in turn, increases the air-tightness of buildings.

Furthermore, high thermal mass materials such as concrete could also delay the peak internal temperature for several hours, which may occur in the afternoon after occupants have left the building. This characteristic of thermal mass is especially beneficial in office buildings which are the target of this study. Since the heat gain from occupants and equipment has already diminished, the building envelope stops collecting additional heat. As a result of the delayed peak temperature and the reduced heat gain, the required cooling energy considerably decreases.

2.1 Thermal Mass Theory

2.1.1 Heat balance

The heat balance concept indicates that the sum of zone loads and air system output equals the change in energy stored in the thermal zone (Energy Plus, 2011). The fundamental heat balance equation accounts for the thermal mass as follows:

(2.1)

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \bar{Q}_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{surface}} \bar{m}.C_p (T_{si} - T_z) + \bar{m}_{\inf}\, C_p (T_\infty - T_z) + \bar{Q}_{sys}$$

where

$\sum_{i=1}^{N_{sl}} Q_i =$ sum of the convective internal loads

$\sum_{i-1}^{N_{surface}} h_i A_i (T_{si} - T_z) =$ convective heat transfer from the zone surface

$m_{\inf} C_p (T_\infty - T_z) =$ heat transfer due to infiltration of outside air

$\sum_{i=1}^{N_{surface}} m_i C_p (T_{si} - T_z) =$ heat transfer due to interzone air mixing

$\bar{Q}_{sys} =$ air system output (kw)

$Q_i =$ convective internal loads *(kw)*

$m_i =$ zone air mass (kg)

$m_{\inf} =$ infiltration air mass (kg)

$T_{si} =$ zone surface temperature $(^\circ C)$

$T_z =$ zone air temperature $(^\circ C)$

$T_\infty =$ outdoor air temeprature $(^\circ C)$

$C_z \frac{dT_z}{dt} =$ energy stored in zone air (kwh)

$C_z =$ capacitance $= \rho_{\mathrm{air}} \mathrm{C_p} \mathrm{C_T} \, (kJ/K.m^3)$

$\rho_{air} =$ zone air density (kg/m^3)

$\mathrm{C_p} =$ zone air specific heat *(kJ/kg K)*

$\mathrm{C_T} =$ sensible heat capacity multiplier

The capacitance C_Z is typically used that of the zone air only. However, thermal masses that are assumed to be in equilibrium with the zone air could be included in this term. Therefore, the thermal mass and the time lag for heat transfer through it is accounted for through the basic heat balance method.

2.1.2 Heat storage

The ability of a material to store heat is directly dependent upon its mass and specific heat.

As shown in Figure 2.3, the larger the storage mass, the smaller the temperature swings, and mC_p, which is the heat capacitance of the storage based on mass, clearly represents such fact. The equation (Kreith & Kreider, 1981) used to generate the curves in Figure 15 is:

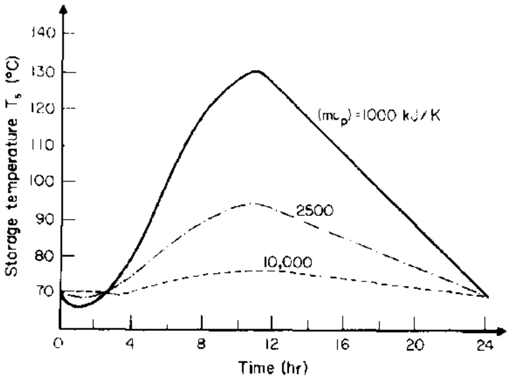


Figure 2.3 Storage temperature history for different storage sizes, (*Source: Kreith & Kreider, 1981)*

(2.2)

$$T_s = T_{so} - \frac{1}{(mC_p)_x} - (L_0 t - \frac{2tQ_{uo}}{\pi} \sin^2 \frac{\pi t}{2})$$

where

T_s = storage temperature ($^{\circ}C$)

T_{s0} = storage temperature at $t = 0(^{\circ}C)$

m = mass of the storage material (kg)

L_0 = energy demand on the system (kJ/hr)

C_p = specific heat of the storage material ($kJ/kg\ K$)

t = lengh of the day (hr)

Q_{u0} = peak energy delivery rate to storage (kJ/Nr)

This equation illustrates the fact that the larger the storage capacitance, the smaller the fluctuations of storage temperature.

Heat can be stored in a material as sensible heat, latent heat, or a combination of both. Sensible heat storage requires a rise in temperature of martial. Latent heat storage, on the other hand, requires a material phase-change at a constant temperature (Hariri & Ward, 1988).

A thermal mass system is a thermally open system. In other words, there is a free energy flow to and from the system. According to the First Law of Thermodynamics, the net change in the energy of a thermally open system equals to the net energy crossing the boundary of the system (Stein et al., 2010). “If this law is applied to the energy input and output of the open system, excluding kinetic energy storage and potential energy storage, the general equation of energy storage for an open system is obtained” (Hariri & Ward, 1988).

A simple expression for the amount of energy stored in a material can be shown as (Hariri & Ward, 1988):

(2.3)

$$E_{st} = \rho C_p \frac{\partial T}{\partial t} V$$

where

E_{st} = stored energy (J/s)

ρ = density of medium (kg/m^3)

C_p = specific heat at constant pressure of medium, (J/kg K)

T = temperatur e (K)

t = time (s)

v = volume of medium (m^3)

This equation indicates the amount of energy storage in a material depends on material property, especially its density and specific heat. A high thermal mass material should have both high density and specific heat (Hariri & Ward, 1988).

2.1.3 Sensible heat storage

Every material stores heat as its temperature rises and it releases the heat later on as it cools. This is called sensible heat storage if no change of phase takes place in this process (Hariri & Ward, 1988). The amount of energy stored in a material depends on the amount of material as well as its ability to store heat (heat capacity). This energy can be expressed as:

(2.4)

$$E = \int_{T_0}^{T_1} m C_p \, dT$$

where T_0 and T_1 are the initial and final temperatures respectively; m is the heated mass and C_p the specific heat capacity of the mass (Hariri & Ward, 1988). Along with heat capacity, thermal conductivity also needs to be considered. A material cannot be suitable for sensible heat storage if it discharges quickly. The ability of a material to store heat depends upon thermal diffusivity, α, which is an indicator of heat transfer through a material. In other words, the higher the thermal diffusivity, the quicker the heat transfer through a material as shown in this equation:

(2.5)

$$\alpha = k/\rho C_p$$

where

k = thermal conductivity in W/m K

ρ = density in kg/m^3

Hear can be added or withdrawn from a sensible heat storage material. This can be achieved by having a highly heat conductive material, such as metals, or a heat transfer layer can be established between the material and other mediums surrounding the material (Hariri & Ward, 1988). There are several materials that can satisfy the requirements for a sensible heat storage material like concrete, steel, adobe, stone and bricks (Hariri & Ward, 1988).

2.2 Thermal mass characteristics

There are several factors that affect the thermal mass behavior of concrete as documented in the following:

2.2.1 Thermal diffusivity

The term “thermal diffusivity” refers to heat transfer through a material and is defined in heat transfer analysis by thermal conductivity divided by volumetric heat capacity (Schokler, 2010). A high thermal diffusivity shows that heat transfer through a material will be quick, and not considerable amount of heat will be stored in the material. As a matter of fact, the depth that the diurnal heat waves’ penetration within a material depends upon its thermal diffusivity (Balaras, 1996).

Concrete has a low thermal mass diffusivity, which means it slows the heat transfer through the material; stores a large amount of heat; and is less sensitive to temperature differences in the surrounding environment. The heat capacity, on the other hand, is the product of material mass density and its specific heat.

It should be noted that materials with higher thermal diffusivities can store heat at a greater depth within the substance than materials with lower thermal diffusivities (Balaras, 1996). In fact, the heat stored beyond a certain thickness does not transfer to the indoor air until the following day. This phenomenon can be undesirable during the cooling season simply because the release of heat during the early hours if the next day can result in occupants’ thermal discomfort. In addition, more energy would be needed to dissipate the stored heat from the walls, which can lead to higher cooling loads (Balaras, 1996). .

2.2.2 Heat capacity

Heat capacity is defined as the amount of heat needed to raise the temperature of a given mass by one degree. Since it is the product of mass and its specific heat, and concrete absorbs heat slowly, it has a higher heat capacity than many building materials including steel.

Table 2.1 shows the comparison between heat capacity and thermal diffusivity of different materials. Note that high heat capacity and low thermal diffusivity, renders concrete as a significant thermal mass material (Schokler, 2010)

Table 2.1 Heat capacity and thermal diffusivity of materials, *Source: Schokler (2010)*

Material	**Heat capacity,** $\mathrm{J/(kg \times K)}$	**Thermal diffusivity,** $\mathrm{m^2/s}$
Concrete	728.07	5.38 to 7.53
Iron	384.84	172
Aluminum	741.94	1270
Plaster	696.87	3.77 to 6.46
Wood	2700.79	1.18
Water	4195.07	1.51
Air	998.50	237

2.2.3 Insulation

The location of insulation on a wall mass could affect the thermal performance of wall construction. For concrete walls, a more effective way for reducing heat transition across the walls is to place the insulation on the outside of the walls; therefore, the wall mass will be in direct contact with the interior conditioned air. This arrangement can result in a better performance than placing insulation on the inside face of the wall, or for that matter within the wall (American Concrete Institute, 2002) because it allows thermal mass to directly interact with and be exposed to the internal heat generated inside the building. Therefore, the heat could be stored in the wall with no interference from insulation.

Generally speaking, both thermal mass and insulation are effective in the thermal performance of a building (Subbarao, Burch, Hancock & Jeon, 1986). However, insulation materials can adversely affect the performance of the thermal storage capacity of a wall (Burch, Cavanaugh & Licitra, 1985) because it disrupts the thermal interaction between thermal mass and indoor or outdoor air. It also should be noted that since thermal mass stores and releases heat, it interacts with the building operation at a greater degree than a layer of insulation (Byrne & Ritschard, 1985).

2.2.4. Daily temperature changes

Daily temperature change could also influence the effect of concrete thermal mass. The thermal mass material could delay and reduce peak temperatures as indicated in Figure 2.4, which shows a thermal lag for an 8-in thick concrete wall. As shown in this figure, the concrete thermal mass has created a significant thermal lag, which not only delays the effect of peak temperatures, but also reduces the amplitude of heat gain. Because of concrete’s considerable thermal mass and its ability to delay the penetration of heat through the walls, the peak outdoor air temperature will not considerably affect the indoor conditions. At night, when the outdoor temperature is relatively low, the wall mass starts releasing the heat into the inside spaces, which in turn moderates the effect of low ambient temperatures on the indoor conditioned space.

During the seasons when large daily temperature swings exist, concrete thermal mass would show an even better performance since its thermal capacity would be more effectively utilized. In heating seasons, in addition to solar heat, thermal mass also collects the heat generated inside the space by office equipment and mechanical systems. This stored heat will later be released into the conditioned space, which in turn will reduce the building’s required heating loads.

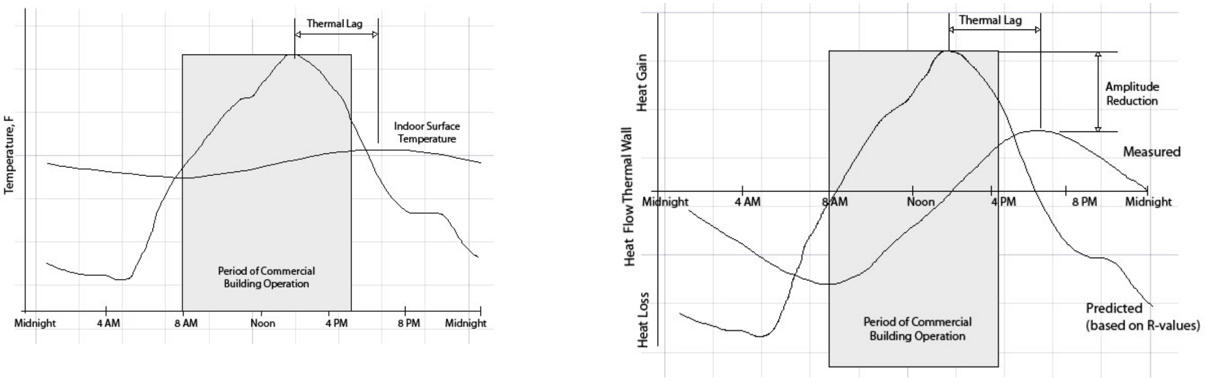


Figure 2.4 Thermal lag for 8 in concrete wall (left); thermal lag and amplitude reduction for 8 in concrete wall (right) , *Adopted from: American Concrete Institute (2002)*

During the cooling seasons, however, the stored heat needs to be dissipated; therefore, night ventilation strategies are used, which include circulation of cooler outdoor air over the heated wall mass. The cooled wall mass, which allows for the lower indoor temperature during the following day, reduces cooling loads and delays the peak loads.

2.2.5 Building height and occupancy

Building design and operation will also impact the thermal performance of a building. In low-rise residential buildings, heating and cooling loads are affected by the thermal performance of the building envelope itself. In fact, the type of wall construction and climatic conditions are the main variables affecting the thermal energy consumption of low-rise buildings.

High-rise commercial and residential buildings, on the other hand, have to deal with a considerable internal heat gain in addition to the climate and wall construction variables in regard to the thermal performance of buildings. Large internal heat gains from equipment, lighting, occupants as well as solar heat transmitted through windows require thermal mass to absorb the heat, and reduce the thermal loads of buildings.

The peak cooling load in commercial buildings usually occurs in the afternoon; therefore, if thermal mass could delay the peak load from the afternoon to the evening when there is low or no occupancy in the building, the thermal load of the conditioned space will substantially reduce. This phenomenon occurs because the potential overlap between the peak temperature and the peak occupancy has been avoided. It should be noted that, generally speaking, the benefits of thermal mass in commercial buildings, e.g. office buildings, is considerably greater than its contribution to the building energy performance in low-residential buildings (American Concrete Institute, 2002). As a matter of fact, when the outdoor conditions, e.g. ambient temperature, are suitable for passive cooling strategies, such as natural ventilation, these techniques can be utilized to reduce the cooling loads in office buildings (Balaras, 1996).

In summary, for the thermal mass materials such as concrete to effectively store heat, they need to possess a proper density, high thermal capacity, and a high thermal conductivity; therefore, heat may penetrate through all the material during the specific time of heat charging and discharging.

2.3 Thermal Mass and Transient Heat Transfer

Unlike the steady-state conductive heat transfer, the heat conduction through a thermal mass material, such as concrete, is a transient phenomenon, which shows the effect of time in the conduction process. Figure 2.5 compares the heat transfer through an ideally non-thermal mass material and a material that possess high thermal mass property.

The left column represents a hypothetical material that does not have thermal mass capacities. The right column, on the other hand, demonstrates how the heat transfer process is affected by the presence of thermal mass of a material like concrete. As shown in this figure, the initial rate of heat transfer as seen by the temperature gradient at the right side of the material is inversely proportional to the thermal mass of materials. With time, the temperature gradient and thus the heat transfer rate does not change when there is no thermal mass as seen in the left column. In other words, from times T_1 to T_4, no change of slope is observed. However, as seen in the right column, as a result of thermal mass properties, the slope of heat transfer line generally changes with time.

As a matter of fact, the right column images show how the heat transfer is delayed due to the influence of thermal mass. At T_1, a minimal temperature slope is observed at the right face of the material that extends to the left face because the heat transfer is being stored by the material. Therefore, the heat transfer rate at the right face of the material is delayed dramatically. As time passes, at T_4 the temperature gradient increases, corresponding to an increase in the heat transfer rate, and becomes almost equal for both cases; however, the heat transfer delay that occurred in the presence of thermal mass is beneficial not only to delay the heat transfer and store the heating energy inside the material, but also to moderate inside temperatures and potentially save air-conditioning energy.

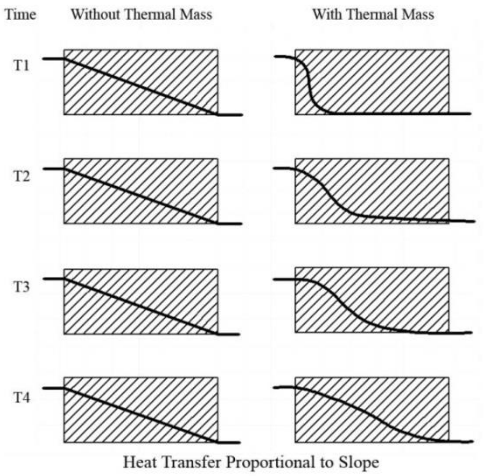


Figure 2.5 The effect of thermal mass on heat transfer, *Courtesy of: Professor Rick K. Strand*

Figure 2.6 shows the effect of thermal mass on the temperature difference between the surface layer of a material and the depth of the material (Nicholls, 1981).

t_{0m} = temperature amplitude at surface, C°
τ = time, s
τ_o = period of oscillation, s
α = thermal diffusivity (k/c), m^2/s
η = an integer

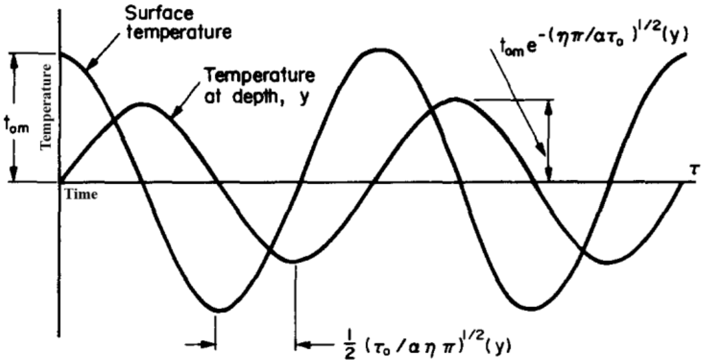


Figure 2.6 Temperature variation with depth y during periodic heat conduction in semi-infinite body,
(Source: Nicholls, 1981)

As shown, the time required for heat to penetrate the thermal mass material will not only delay the heat transfer, but it will also significantly reduce the "amplitude of the temperature with time" (Nicholls, 1981).

2.4 Thermal mass applications

The concept of thermal mass has many applications in the design and construction of buildings. In fact, passive heating strategies such as direct solar gain or roof pond systems heavily rely on the utilization of thermal mass properties to store and transfer heat. This phenomenon keeps the indoor temperature convenient and helps the air circulate inside the room by providing natural ventilation. A few examples are presented here to demonstrate the role of thermal mass in different applications.

The direct solar gain is one of the passive heating strategies, which can be used to fulfill the heating demands of buildings. If the building envelope is made of masonry thermal storage materials made up of concrete block, brick, stone, or adobe, the heat can be absorbed in the envelope during the day and released to the interior space at night as shown in Figure 2.7.

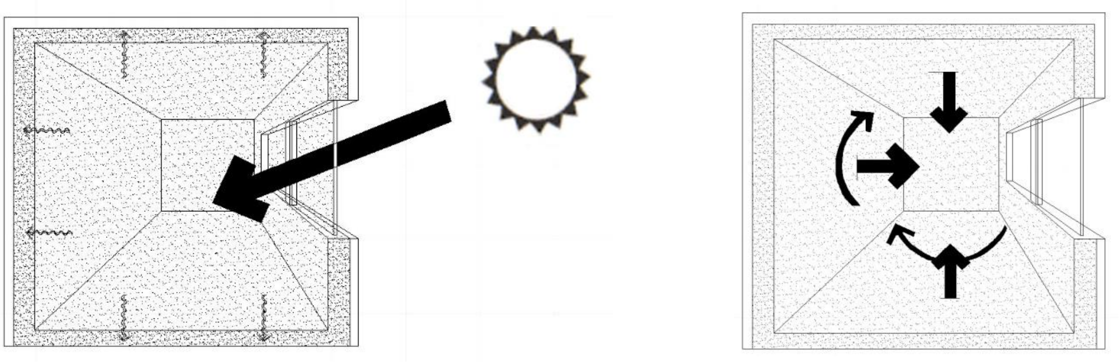


Figure 2.7 Masonry heat storage, direct gain systems, (*adapted from: Mazria, 1980)*

As shown in Figure 2.8, the concept of thermal mass wall—“Trombe Wall”—could help improve the energy and thermal performance of buildings by considerably absorbing the heat and releasing it into the space. Moreover, adding vents to a Trombe Wall system will lead to the distribution of heat by natural convection, which will be most effective during daytime, especially early evening (Mazria, 1980). In this passive heating system, the solar radiation initially hits the thermal mass wall adjacent to the glass, is converted to heat, and then the heat is transferred to the air, which is trapped between the wall and glass. If the upper vents are opened, the rising warmed air enters the room through them at the top of the wall, while the cool air leaves the room through the lower vents at the bottom of the wall. This phenomenon will cause air circulation, which effectively ventilates the space. In winter, this strategy could help introduce warm air into the room during the day, and provide comfortable temperature for the building. At night, the stored heat is released to the space and warms it up.

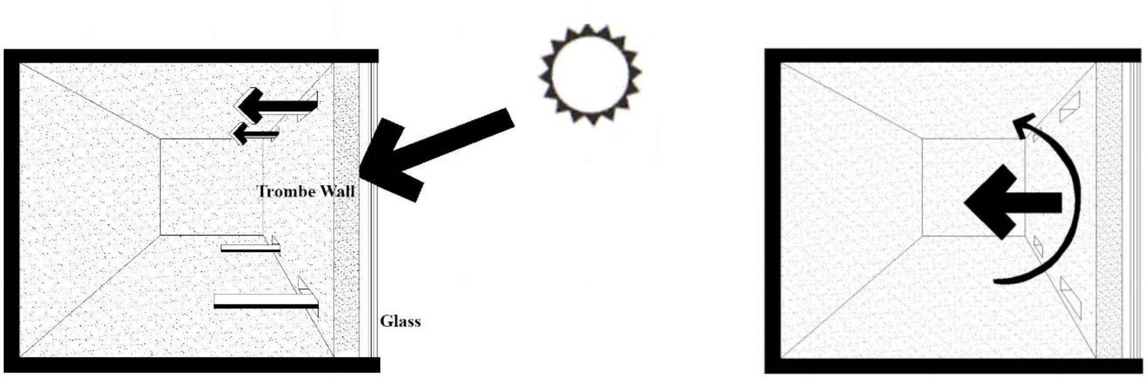


Figure 2.8 Indirect gain - masonry thermal storage wall, *Adopted from: (Mazria, 1980)*

To enhance the performance of the Trombe Wall system, the indirect solar gain technique could also be improved by a better utilization of the direct method (Mazria, 1980). In fact, as shown in Figure 2.9, an attached greenhouse (or sun house), which is a combination of direct and indirect solar gain strategies could further benefit this passive heating strategy. The greenhouse is directly heated by solar radiation; however, the room adjacent to the greenhouse receives the heat through the wall thermal mass separating these two spaces. During daytime, the wall absorbs the heat, which is transferred to the space adjacent to the sun house. In this system, the greenhouse serves as an expanded thermal mass wall system, where instead of having two glasses spaced a few centimeters apart, the entire sun house plays the role of heat absorbance and heat transfer. Placing vents at the top and bottom of the thermal wall could further help circulate the air that is already warmed up in the greenhouse space.

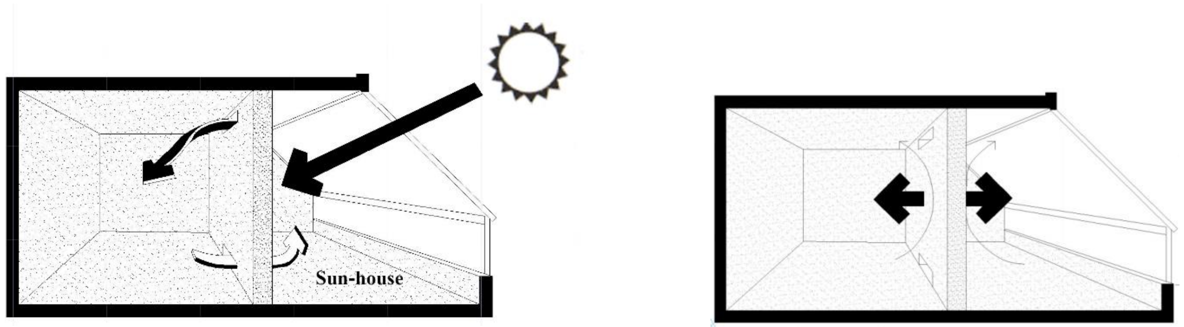


Figure 2.9 Indirect gain - attached sun-house, *Adopted from: (Mazria, 1980)*

Another extension of the thermal mass strategy is the use of a roof pond system, where the thermal mass—water—is located on the roof of the building (Mazria, 1980). In order to benefit from the water thermal mass, water ponds usually enclosed in plastic bags are located at the top of the roof, which is also the ceiling of the room below. As shown in Figure 2.10, in winter, the water ponds are exposed to the direct sunlight during the day to absorb heat; however, they are concealed with an insulating panel at night to maintain the stored heat, and prevent it from being released back to the outside air. The collected heat is then radiated from the celling to the space below, and keeps it warm at convenient temperatures.

Direct heat gains usually take place in the outer layer of a building envelope, which is exposed to solar radiation (Balaras, 1996). The interior surfaces can also benefit from direct heat gain through absorbing incident solar radiation that enters the building through fenestrations. Indirect heat gains, on the other hand, usually occur inside the building. They are resulted from the energy that is transferred inside the building from direct gain layers. It should be noted that direct gain surfaces are more effective in terms of thermal storage capacity and performance than indirect layers (Balaras, 1996).

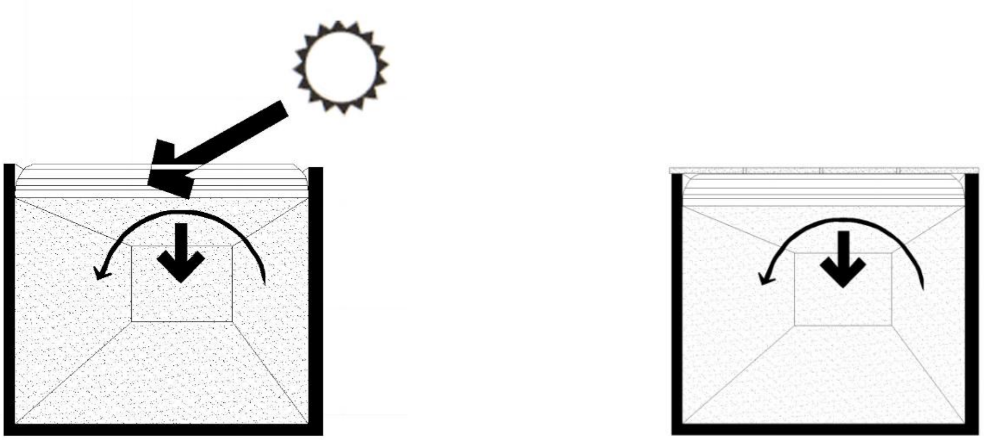


Figure 2.10 Indirect gain - roof pond - heating cycle, *Adopted from: (Mazria, 1980)*

During summer, on the other hand, the ponds are covered during the day to protect them from direct sunlight; however, they will be exposed to the outside during the night to be cooled down by natural convection or radiation as shown in Figure 2.11. During the following day, the cooled water ponds will maintain the inside temperature well below the high outside air temperature.

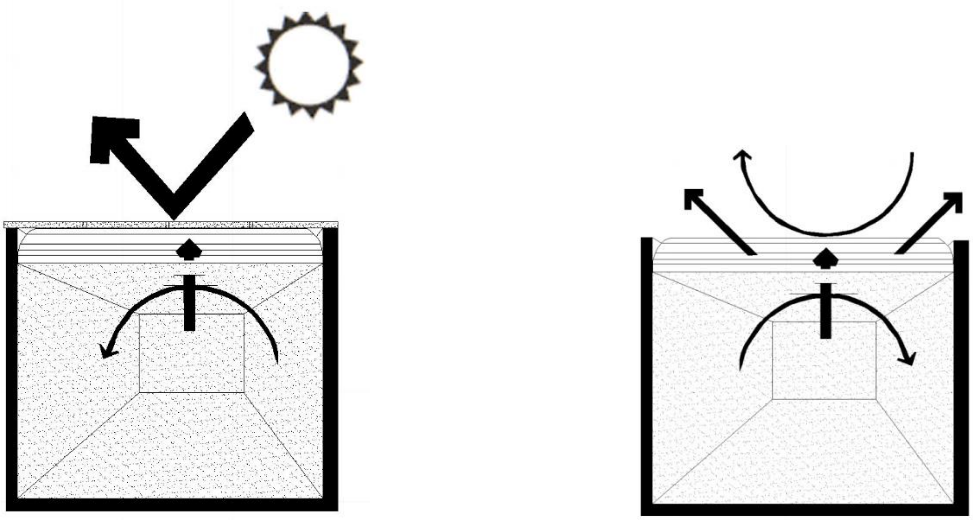


Figure 2.11 Indirect gain - roof pond - cooling cycle, *Adopted from: (Mazria, 1980)*

2.4.1 Wind towers

The thermal mass property of masonry materials could also assist in providing the natural ventilation for buildings. One of the prominent applications of thermal mass is called “Wind Catchers” or “Wind Towers”, which have been mainly used in Middle-Eastern countries with arid climates to ventilate the interior spaces by making use of natural convection.

Wind towers operate as follows: because of thermal mass properties, the wind catcher’s masonry walls absorb the heat during the day, which will be transferred to the cool ambient air at night. During night, because of the warmer air’s lesser density at the top of tower, an upward air draft is created, which can draw up the air from inside the building through the tower and release it to the outside. This phenomenon will allow for the cool ambient air to enter into the space through other openings at lower levels such as doors or windows. The continuation of this process throughout the night can result in a relatively constant cool air circulation, and therefore natural ventilation inside the building (Bahadori, 1978).

Figure 2.12 shows an example of wind catchers, and how the air circulates through the towers and enters the interior spaces (Bahadori, 1985).

Nevertheless, during day, the operation of wind catchers is somewhat different than night, especially when there is no wind. In fact, the more interesting role of masonry thermal mass comes into play when there is no wind, which means that natural ventilation will heavily rely on the thermal buoyancy phenomenon driven by the thermal mass concept. Due to the thermal mass properties of the tower walls, the hot ambient air becomes cool and denser in contact with them, which have been sufficiently cooled during the previous night; therefore, an air downdraft is created. The cooled denser air ventilates the space and finally leaves the building through other openings such as windows and doors causing air circulation and natural ventilation inside the room.

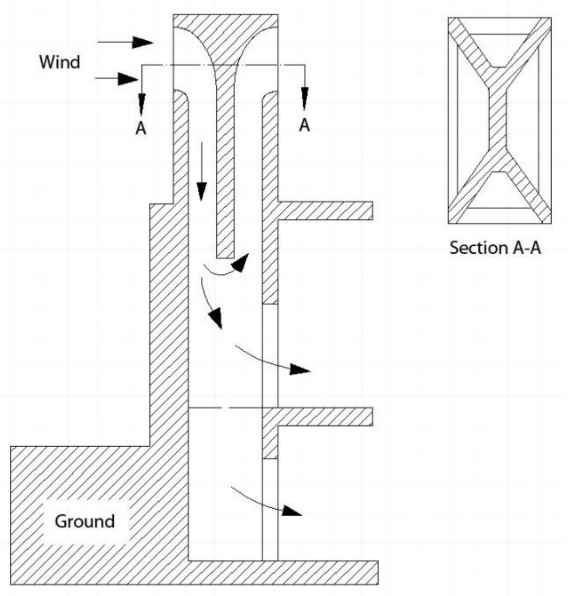


Figure 2.12 Wind Catchers, *Adopted from: (Bahadori, 1985)*

Later during day, in the absence of wind when the temperature of the upper part of the towers reaches that of the ambient air, the wind catcher starts operating like a chimney. The temperature of the air that comes in contact with the heated tower walls increases; therefore, its density decreases. Consequently, the hot air rises and causes an air updraft, which in turn helps circulate the inside air. When there is wind during day, the rate of ventilation increases, which can considerably ventilate the building (Bahadori, 1978).

2.4.2 Thermal energy storage

Another application of thermal mass phenomenon is thermal energy storage (TES) system. It has several advantages: "(1) the TES may act as a reserve unit, (2) the efficiency of energy conversion can be improved by TES, and (3) in the case of electric space heating and hot water production, favorable rates can be obtained by shifting the electricity consumption to off-peak hours using TES systems" (Hariri & Ward, 1988). This study shows that low, medium and high temperature storage mediums require different storage capacities. A substance with a high melting-point temperature should be utilized for a high temperature storage application such as office buildings (Hariri & Ward, 1988). Water is a great example of a medium for low and medium temperature systems. It can function as a heat exchanger simply because it is both the transport fluid and heat storage medium (Hariri & Ward, 1988).

2.4.3 Thermo-Deck system

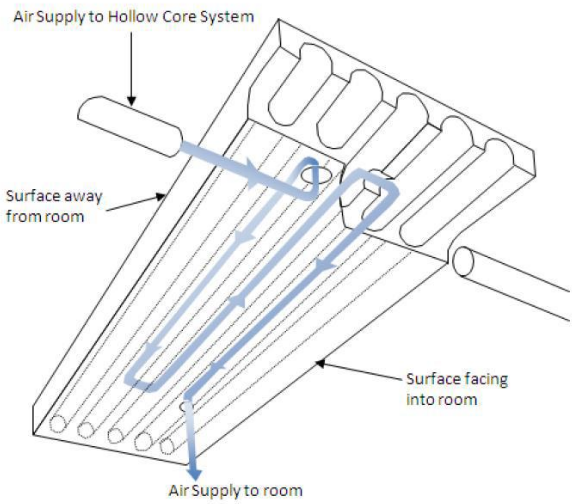


Figure 2.13 Thermo-Deck system, *Source: (Barton, 2002*)

The Thermo-Deck System uses the concrete hollow core slab as air duct and heat storage mass (Figure 2.13). During the summer, the concrete slab is cooled at night, which makes it be able to function as a heat sink during the following day. This can reduce the building cooling loads. The concrete slab can also function as a heat exchanger as well, which can result in reducing the ambient air temperature when it enters the room (Zmeureanu and Fazio, 1988).

2.5 Influence of thermal mass on energy performance

According to Willoughby (2002), the use of thermal mass could bring several advantages to a working or living environment. First, it could save energy, reduce the building's carbon footprint, and improve comfort conditions in both summer and winter. There is a potential to save up to 11% of energy in buildings by making proper use of thermal mass properties of building materials (Willoughby, 2002). The author points out that, in addition to energy benefits, the thermal mass could also improve the sound insulation both within and between dwellings.

Figure 2.14 demonstrates the ability of thermal mass to absorb direct or indirect heat from different sources including solar radiation and internal gains from cooking, lights, appliances and so forth. In this figure, the primary thermal mass is directly exposed to the solar gain through windows; however, the secondary and tertiary thermal masses that are not directly exposed to sunlight can absorb the solar heat indirectly and even remotely, respectively. This triple thermal mass concept can help maximize the advantages that the thermal mass property can bring to the building, such as, higher energy savings and thermal comfort (Willoughby, 2002).

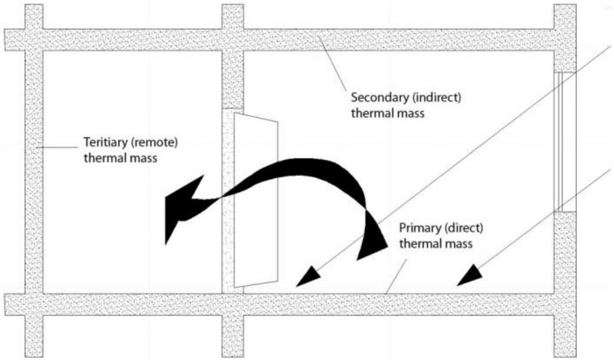


Figure 2.14 Classification of thermal mass, *Adopted from: (Willoughby, 2002*)

As a matter of fact, unlike other direct renewable energy saving measures such as PVs, green roofs, or geothermal, no significant initial costs are associated with the use of thermal mass, which is often present in a building for architectural and structural reasons. Basically, by modifying the already existing building elements including exterior and interior walls or slabs, energy consumption in a building can be reduced during both heating and cooling seasons.

In office buildings, the maximum cooling loads depend upon various factors including internal gains from office equipment, interior lighting and occupants as well as heat radiations from interior surfaces (Braun, 2003). Therefore, it can be said that building surfaces can have a large impact on building cooling demands. As a matter of fact, the thermal capacity of a concrete building envelope can be 2-4 Wh/◦F per square foot of floor area, which is "equivalent of energy storage on the order of 1 hr. for every ◦F of thermal mass's pre-cooling" (Braun, 2003). "Opportunities for reducing operating costs through use of building thermal mass for cooling are due to four effects: reduction in demand costs, use of low cost off-peak electrical energy, reduced mechanical cooling resulting from the use of cool nighttime air for ventilation precooling, and improved mechanical cooling efficiency due to increased operation at more favorable part-load and ambient conditions" (Braun, 2003).

Buildings with high thermal mass have potentials to provide significant energy savings because of their ability to receive and store heat from all heat generating sources such as lights, occupancy, solar and people during daytime and release the heat when the building is unoccupied (Brown, 1990). However, one may argue that the cost of building high thermal mass envelopes may cancel out some energy and cost benefits resulting from them. According to Brown (1990) "the initial cost for the optimized thermal storage design is lower than the initial costs for office buildings employing light construction, since the lower initial cost of the down-sized HVAC system for the optimized thermal storage design offsets the increased cost of wall and floor systems incorporated in the optimized design".

Zhu et al. (2009) investigated the energy effects of concrete mass walls as compared to wood frame construction in Las Vegas, Nevada. They conducted an experimental study for two identically-sized houses with different types of construction —concrete mass walls versus wood frame ones. They found that the heating load was considerably lower in the house with concrete thermal mass; however, the cooling load showed a moderate increase with respect to the wood frame building. One of the potential reasons pointed out by the authors was that in a desert climate such as Las Vegas, due to high ambient temperatures and strong sunlight, too much heat would be stored in concrete walls to be dissipated back; therefore, the cooling loads would increase.

Another study conducted by Kalogirou et al. (2002) using the TRNSYS program—an energy simulation software—presented the effect of thermal mass on heating and cooling loads in Cyprus. According to this study, the diurnal temperature variations in Cyprus make it an ideal location for the application of thermal mass. This study found that, as the outcome of using thermal mass, the heating loads decreased by 47%, whereas a slight increase of cooling loads was observed. Moreover, a recent study conducted by Ghoreishi and Ali (2011) show that concrete thermal mass could save 7% to 10% of maximum cooling loads in different climatic conditions in the United Sates. In another study, Ghoreishi and Ali (2013) have shown that the use of thermal mass in office buildings could lead to up to 22% heating energy savings in climates with high cooling degree days.

Another study conducted by Barnaby et al. (1980) simulated the hollow core slabs and their thermal mass behavior for a 970,000 square-foot building in Sacramento, CA. According to this study, the hollow-core system could result in energy savings of up to 13% as well as cooling peak load reductions of up to 30%. Tamblyn (1980) has even shown that a hollow core slab can be more effective than a flat slab in terms of energy savings. According to his studies hollow core slabs can save up to a 25% of chiller demand while a minimum air temperature fluctuation take place during the building's occupied hours. A simulation study using Enerpass program and conducted by Allen et al. (1984) has investigated the effect of hollow core concrete slabs on building energy performance in a passive solar house in Ottawa, Canada. This study has shown that this system can lead to 13% of energy savings for the studied building. In a study on a six-story office building in Johannesburg, South Africa, Birrer (1984) has shown that using the hollow-core slab system can reduce the building cooling loads by about 16 Btu/hr. ft^2.

In the presence of a composite concrete and steel floor system, where a combination of return air plenum and heat storage mass is used, the concrete floor can act as a heat sink (Monette, 1984). In this study, the simulation research using Transheat and Hotcan programs showed that such system can result in 6%-25% of annual energy savings.

Sand-mass is another application of thermal mass, "where a slab foundation of sufficient thickness to serve as the building thermal mass is used along with the poured cement in interior wall and floor construction" (Brown, 1990). This study has shown that the sand mass systems could lead to a considerable energy savings in regards to both annual energy savings and down-sizing of HAVC systems. According the finding of this study, an annual operating savings of $3,781 to $4,465 can be achieved. Furthermore, an estimated savings of $18,000 for cooling equipment and $5,000 for heating equipment can be achieved since the high thermal mass can help down-size the HVAC equipment and reduce the initial investment on the system.

Nighttime temperature setback could potentially reduce building energy use. Burch et al. (1984) conducted a paramedic study where the effects of wall thermal mass on heating energy demands was evaluated. The study has shown that as a result of nighttime temperature setback, the heating savings could be as much as 11% to 37% in different climates.

Fallahi et al. (2010) have studied another application of thermal mass in conjunction with double-skin façade (DSF) systems. The study was conducted to evaluate the effect of thermal mass in DSFs in terms of building enemy reductions. According to this study, a considerable energy use reduction is achievable when thermal mass is implemented in the air channel of mechanically ventilated DFS systems instead of venetian blind slats. As a matter of fact, the energy reduction can be as large as 21% to 26% in summer and 41% to 59% in winter as compared to DSFs system with venetian blind slats

As indicated before, one of the advantages of using thermal mass is to shift the peak load to later hours when there is less or no occupancy in the office building; therefore, a potential overlap of peak load and peak temperature could be avoided. Yongjun et al. (2013) have carried out a review on the energy effects of thermal mass and have reported that the load shifting phenomenon, as a result of thermal mass, could result in more than a 30% reduction of daily peak load and an 8.5% to 29% reduction of overall energy cost.

Another study integrated two common TES strategies: one of which was to install ice storage tanks and have them charged at night (when the cost of electricity is lower) and discharged during the day, and second was to “utilize the thermal mass of the structural building materials to pre-cool the building at night” (Hajiah & Krarti, 2012). This research has found that in the presence of both building thermal mass and active TES system, one may obtain up to 40% reduction of the overall energy costs of buildings (Hajiah & Krarti, 2012).

2.6 Thermal comfort

In addition to building energy performance, concrete thermal mass could play a major role in providing thermal comfort for office buildings' occupants. High mass buildings significantly limit high indoor air and surface temperature variations and sustain a steadier thermal environment as compared to light constructions. Concrete thermal mass can increase thermal comfort in three scenarios (Balaras, 1996): one would be during mild weather seasons including spring and fall, the other scenario is during times and seasons when large ambient temperature variations take place. The last scenario would be in areas where large temperature swings between daytime and nighttime exists.

Brown (1990) has conducted a study on the effect of using thermal mass on indoor air temperature and heating and cooling loads. The study indicates that high thermal mass can maintain the indoor temperature above the nighttime setback temperature of 50°F (ambient temperature below 20°F), whereas such benefit is not available in low thermal mass building. The same mechanism has been shown to help reduce cooling demands in summer time. In other word, due to the presence of high thermal mass, the indoor temperature incases as a much slower pace than that in low thermal mass buildings. Therefore, the building cooling demands can be shifted to hours when the building is unoccupied (after working hours). This delayed cooling demand can be later on satisfied by natural ventilation or economizer operation in hours when the outside temperature is below 76°F (Brown, 1990). This will further reduce the building cooling energies.

A comparative study on the effect of thermal mass on thermal comfort has been carried out by Ogoli (2003). This study has focused on high and low thermal mass buildings at the equator. It has shown that in the month of February when the maximum ambient temperature was above 91 °F, the indoor maximum temperature in the high thermal mass building did not exceed 77.7 °F, which is a significant in terms of providing thermal comfort for occupants (Ogoli, 2003),

2.6.1 Thermal comfort: steady-state versus adaptive models

Thermal comfort has been discussed since 1930s. There have been two main approaches to thermal comfort: the steady-state model and the adaptive model (Taleghani, et al., 2013). In Chapter 1, the PMV and PPD models were introduced and discussed in the Section 1.4.3. These thermal comfort models are called steady-state models since “they use a steady-state heat balance for the human body predicting the mean vote on an ordinal category rating scale of thermal comfort of a population of people” (University of Strathclyde, 2014). Fanger (1970) defined PMV as the “index that predicts, or represents, the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing levels”. The satisfaction with thermal comfort is a condition where most occupants experience “thermal neutrality” and do not express discomfort with thermal conditions (van Hoof, 2008). After the oil crisis of 1973, the research focused on how to optimize the indoor thermal conditions before getting uncomfortable (van Hoof, 2008), and the PMV model has since been the basis for research and studies on steady-state thermal comfort.

Adaptive model, on the other hand, which is mainly based on “the theory of the human body's adapting to its outdoor and indoor climate” is another model type of thermal comfort (Taleghani, et al., 2013), which has been increasingly popular among scholars ad researcher as compared to the heat balance approach, i.e. steady-state model (Halawa & van Hoof, 2012). In the adoptive model approach, building occupants have more control over their personal thermal environment. This approach in particular has been adapted for naturally-ventilated buildings where building users have access to operable windows and have more freedom to “adjust their clothing insulation (Halawa & van Hoof, 2012)

There are several reservations in regards to using the Fanger model (de Dear, 2004). First reservation is about “unnatural way of judging the thermal sensation through unnatural laboratory-type research” (de Dear, 2004). Second concern would be the fact that these “engineering” approaches do not consider subjective thermal comfort factors such as cultural background or “social contextual dimension” of thermal comfort. Lastly, they mainly focus on mechanically-ventilated buildings and do not necessarily address the energy saving considerations (Nicol & Humphreys, 2002).

Furthermore, regarding thermal comfort, the author had a meeting with Professor Joy Malnar, from University of Illinois at Urbana-Champaign, School of Architecture in April 2014. Her viewpoint toward the topic of thermal comfort was mainly concerning cultural-related aspects of thermal mass. In other words, building occupants’ social and cultural background can play a major role in their perception of thermal comfort. For instance, the people who have lived their entire lives in cold climates may have a higher degree of tolerance toward cold weather in similar way that people from tropical regions may have easier time living in a climate with hot and humid weather conditions.

2.7 Thermal mass and night ventilation

In cooling seasons, the heat stored in the building thermal mass during the day, which helps reduce cooling loads and improves thermal comfort, needs to disappear at night; otherwise, it will release heat into the building the following days and increase the indoor temperature, especially in the morning, and consequently cause thermal discomfort and increase building cooling loads. This could simply erase some of the energy and comfort benefits gained by the concrete thermal mass. One potential solution to counter this phenomenon is to use the nighttime ventilation, preferably with cool outside air, to remove the heat from the building mass.

The nighttime ventilation strategy is even more effective and can reduce energy use of mechanically-ventilated buildings in locations where large daily temperature swings exist (Balaras, 1996). Especially, the office occupancy when the building is usually unoccupied at night is a great application for this strategy because the building can be cooled down with nighttime cooling techniques. “Air-conditioned buildings can also be precooled during off-peak hours, for considerable energy savings. Resulting small indoor temperature variations have also a positive influence on occupant thermal comfort” (Balaras, 1996).

Balaras (1996) has also shown that in high thermal mass buildings, when the indoor temperature is set at 75 °F, the cooling energy consumption can be less than that in lightweight low thermal mass structures. The night time ventilation can also reduce the cooling loads by 27% to 36% (Balaras, 1996).

Balaras (1990) also conducted a study on a simulated high thermal mass building acting as an environmental chamber while a nighttime cooling operation was added to the simulation. The outdoor conditions were set as low temperatures and high humidity at nighttime and hot and dry conditions during the daytime. This study showed that nighttime cooling could be even much more efficient than 24 h cooling. As a matter of fact, it could result in more than 50% reduction of the total cooling-related electricity use (Balaras, 1990).

During an experimental study, Ruud et al. (1990) researched the effect of nighttime cooling on building cooling loads. The case study was the Independent Life Insurance building in

Jacksonville, Florida. According to this study, the building pre-cooling did not result in a significant reduction in peak cooling demands; however, “an 18% reduction of cooling energies during the daytime was achieved”.

Givoni (1983 & 1984) also conducted a study on high thermal mass building that are cooled at night, when the ambient temperature was between 66°F and 93°F. The cooled structure, as a result of nighttime ventilation, would act as heat sink in the following day reducing the building cooling demands. For spaces for which the nighttime cooling technique was utilized, the maximum temperature did not exceed 78°F; whereas for unventilated spaces it was found to be 83°F. In generally, the nighttime ventilation was found to reduce the room air temperature by nearly 15% of the ambient temperature.

Studies have also shown that the effectiveness of nighttime cooling can depend upon “the temperature swing (Tswing) at the site, and it is not directly related to the relative humidity of the site” (Shaviv, Yezioro & Capeluto, 2001). It has been shown that when the nighttime ventilation rate is small, or the building is a low thermal mass structure, a high Tswing is needed to have an effective nighttime cooling strategy. In summary, the cooling demand reduction would depend on “the amount of thermal mass, the rate of night ventilation, and the Tswing between day and night” (Shaviv, Yezioro & Capeluto, 2001).

In Chapter 3 that follows, the phase I of this research that involves the comparison between energy effects of different building materials will be presented. In addition, the first section of the phase II focusing on the effect of concrete building envelope on building energy and thermal comfort performance will be discussed.

2.8 Summary

This chapter reviews the fundamentals of thermal mass, its properties and applications. It also studies the literature review concerning thermal mass effects on building energy and thermal comfort performance. Based on literature review, thermal mass is shown to have considerably improved building energy performance. In other words, buildings' heating and cooling demands could be noticeably reduced in the presence of thermal mass. Thermal mass could also help moderate the indoor temperature variations; therefore, a more thermally comfortable environment could be provided for building occupants.

CHAPTER 3

THERMAL MASS and BUILDING ENERGY PERFORMANCE

As indicated in Chapter 1, this research has been conducted in two phases, first of which briefly focuses on a broader topic of thermal mass in its role for improving building energy performance and the second specifically relates to the effect of concrete thermal mass on building energy and comfort performance in details. This chapter focuses on the first phase of the research, which in turn, has two parts. First part addresses the effect of thermal mass property of different common building materials including steel, concrete and masonry on building energy use as a prelude to the second part, which studies the extent of concrete thermal mass impact on building energy performance in different U.S. climate zones

3.1 Part I: Thermal mass property of different building materials

The HVAC systems are primarily used to provide thermal comfort and indoor air quality for occupants with an optimized and reasonable degree of energy use. The selection of air-conditioning and heating systems highly depends on the climatic conditions of a building's location. Depending upon temperature, humidity, and other environmental factors, different strategies could provide various comfort levels in the building. The Climate Consult program developed at the University of California at Los Angeles (UCLA) uses the weather information of many locations around the world to suggest the appropriate climate-responsive strategies to provide comfort for occupants (UCLA, 2014). The required weather information is also provided by the U.S. Department of Energy.

ASHRAE Standard 62.2-2010 categorizes the climate zones of the United States into seven categories (Figure 3.1). It also has three different variations of moist, dry, and marine conditions to further define different climatic zones (ASHRAE Standard 62.2, 2010). The ASHRAE Standard 90.1-2010 also introduces the same seven categories along with cities and counties and their climate zones (ASHRAE Standard 90.1, 2010).

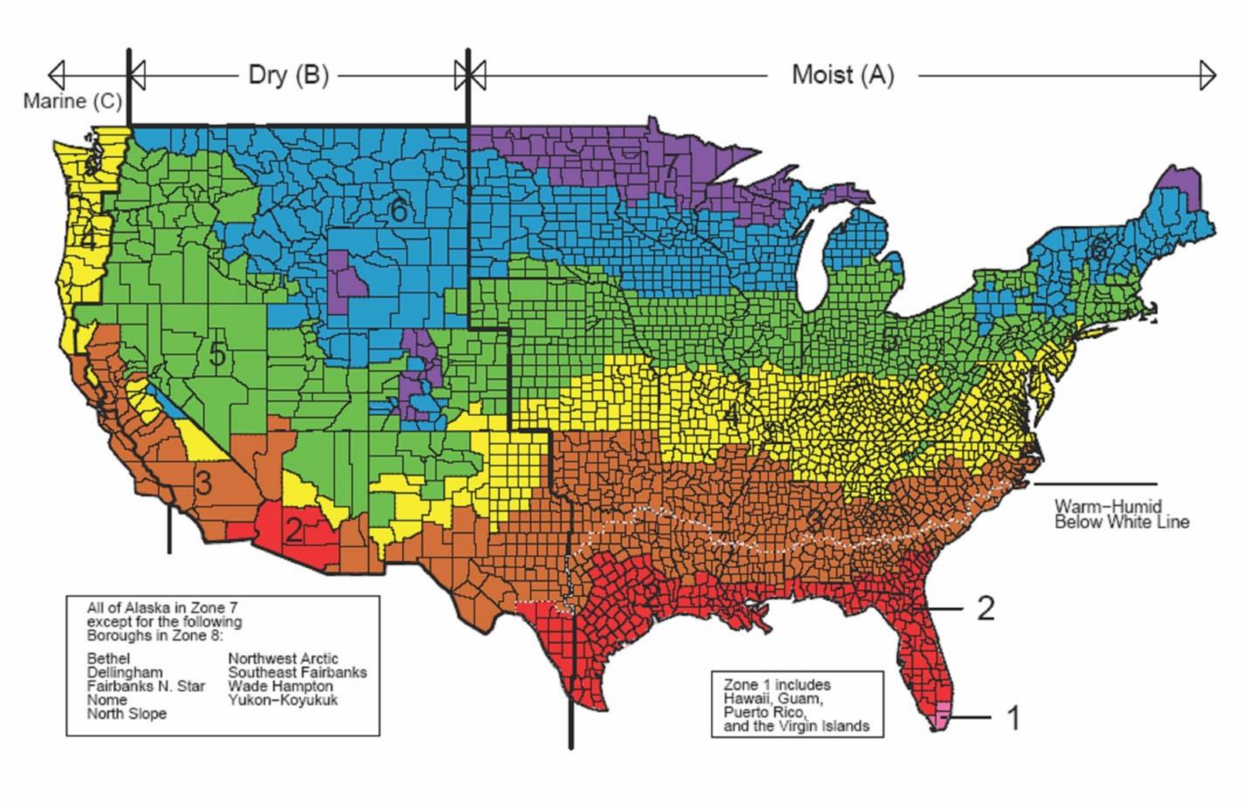


Figure 3.1 U.S. climate zones

In order to investigate the passive conditioning strategies by the Climate Consult program, six different American cities, i.e. Phoenix, AZ, Houston, TX, Tucson, AZ, Minneapolis, MN, Billings, MT, and Fargo, ND, were chosen as representative of the six climatic conditions including hot and dry, hot and humid, very hot, cold and humid, cold and dry, and very cold, respectively.

The results of this analysis suggest that natural ventilation is adequate only for less than 10% of the year, which causes this ventilation strategy not to be completely reliable for conditioning the space. It is also noted that in most of the locations studied, conventional heating and cooling as well as humidification are required for more than 50% of the year. These results highlight the necessity of mechanical air-conditioning, heating and cooling in the United States. Therefore, the use of mechanical air-conditioning is almost always necessary, and the required energy consumption needs to be taken into account. These findings further suggest the importance of thermal mass properties of building materials, especially concrete, to save energy and reduce heating and cooling loads.

3.1.1 Energy simulation and analysis

To investigate the relative degree of application of different structural materials used in buildings, a survey was conducted. The survey included internet search and personal communications with building professionals from different regions of the world. The findings of the survey are summarized in Table 3.1. As shown, concrete is the most widely used building material worldwide. Therefore, any improvements on its thermal and environmental performance would greatly contribute to the sustainability of buildings

Table 3.1 Commonly used building materials worldwide

	Low Rise Building			**High Rise Building**		
	Residential		*Commercial*	*Residential*		*Commercial*
North America						
United States	Wood/brick		Steel/concrete	Concrete		Steel/concrete
Canada	Wood/brick		Steel/concrete	Concrete		Steel/concrete
Central America						
Mexico	Concrete		Concrete	Concrete		Steel/Concrete
Panama	Concrete		Concrete	Concrete		Steel/Concrete
South America						
Brazil	CMU, cast in place concrete, brick veneer		CMU, cast in place concrete, brick veneer	Concrete		Concrete
Argentina	CMU, cast in place concrete, brick veneer		CMU, cast in place concrete, brick veneer	Concrete		Concrete
Europe						
Germany	Pre-fabricated concrete panel, hollow brick		Pre-fabricated concrete panel, hollow brick	Concrete		Concrete
United Kingdom	Masonry/brick		Hollow brick	Concrete		Steel
France	Masonry/brick		Hollow brick	Concrete		Concrete
East Asia						
China	Concrete/brick			Concrete		Concrete/Steel
South Korea	Concrete/brick			Concrete		Concrete/Steel
Middle East						
United Arab Emirates	Masonry/steel		Masonry/steel	Concrete		Concrete
Iran	Masonry/steel		Masonry/steel	Concrete/Steel		Concrete
Turkey	Masonry/steel		Masonry/steel	Concrete		Concrete
Saudi Arabia	Masonry/steel		Masonry/steel	Concrete		Concrete
South Asia						
India	Concrete/brick		Concrete/brick	Concrete		Concrete
Pakistan	Concrete/brick		Concrete/brick	Concrete		Concrete
Bangladesh	Concrete/brick		Concrete/brick	Concrete		Concrete
Africa						
Egypt	Concrete/brick		Concrete/brick	Concrete		Concrete
South Africa	Concrete/brick		Concrete/brick	Concrete		Concrete

Furthermore, in order to study and measure the thermal performance of concrete in different climates in the United States as indicated in Table 3.2, a simulation study was conducted, and the eQUEST program was used for the energy simulation.

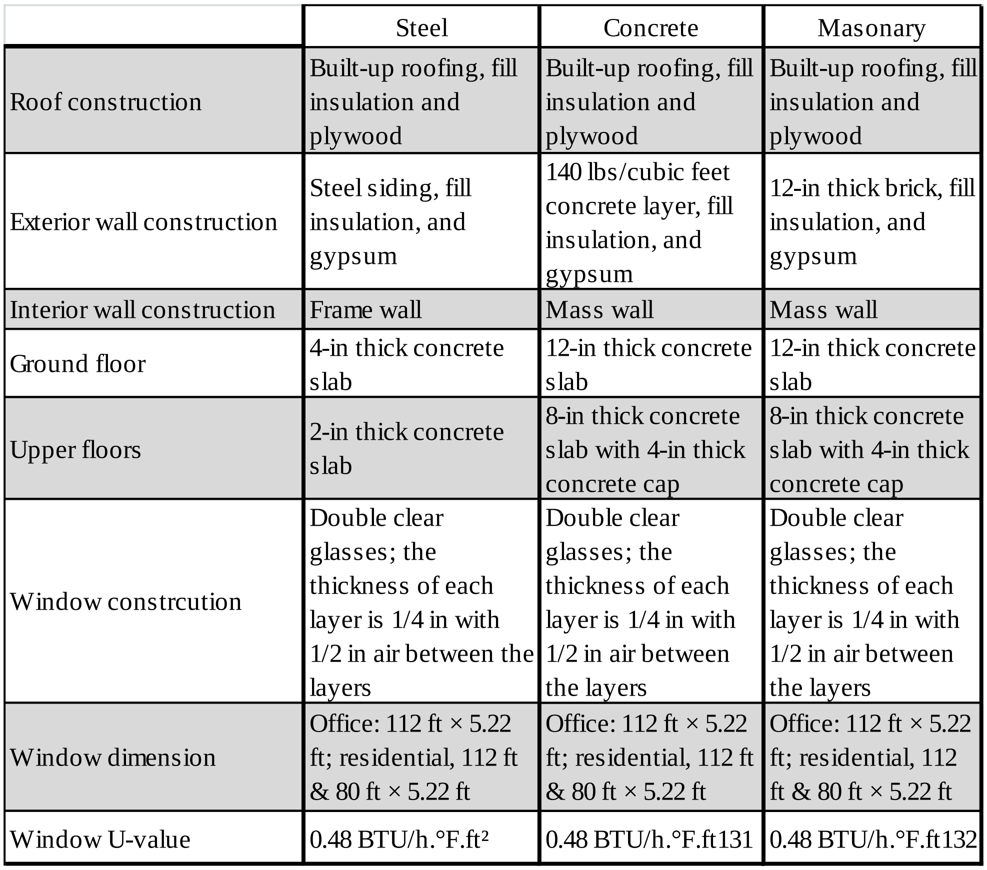
Table 3.2 Six different U.S. climate zones

City	**State**	**Climate**
Phoenix	AZ	Hot and dry
Houston	TX	Hot and humid
Tucson	AZ	Very hot
Minneapolis	MN	Cold and humid
Billings	MT	Cold and dry
Fargo	ND	Very cold

Adopting concrete, steel, and masonry as the common building materials, three major parameters were considered to analyze and compare the effect of thermal mass under different conditions. These parameters were climate zone, building occupancy, and building height. Moreover, among all building types provided by the eQUEST program, two types of building occupancies—residential and office—were chosen. In addition, the architectural and mechanical features of buildings given by the eQUEST program remained unchanged for all variations of climates for both residential and commercial buildings.

The building configurations and layout were also maintained constant. Two plans were selected: a square plan with 12,500 sq. ft. footprint with the floor to ceiling height of 9 ft. in all office building cases and a rectangular plan with the same floor area and floor-to-ceiling height in all residential building cases. The square and rectangular footages were set by the eQUEST. The maximum annual cooling load was selected as the measurement index for the energy performance of the building to compare the performance of office and residential buildings among each category. Table 3.3 shows the construction specifications of building models. It should be noted that different slab thicknesses were chosen for this study although very thick slabs may not be common in professional practices. Similar to the Climate Consult simulation, the same locations shown in Table 3.2 were selected to conduct this analysis

Table 3.3 Building model specifications



	Steel	Concrete	Masonary
Roof construction	Built-up roofing, fill insulation and plywood	Built-up roofing, fill insulation and plywood	Built-up roofing, fill insulation and plywood
Exterior wall construction	Steel siding, fill insulation, and gypsum	140 lbs/cubic feet concrete layer, fill insulation, and gypsum	12-in thick brick, fill insulation, and gypsum
Interior wall construction	Frame wall	Mass wall	Mass wall
Ground floor	4-in thick concrete slab	12-in thick concrete slab	12-in thick concrete slab
Upper floors	2-in thick concrete slab	8-in thick concrete slab with 4-in thick concrete cap	8-in thick concrete slab with 4-in thick concrete cap
Window constrcution	Double clear glasses; the thickness of each layer is 1/4 in with 1/2 in air between the layers	Double clear glasses; the thickness of each layer is 1/4 in with 1/2 in air between the layers	Double clear glasses; the thickness of each layer is 1/4 in with 1/2 in air between the layers
Window dimension	Office: 112 ft × 5.22 ft; residential, 112 ft & 80 ft × 5.22 ft	Office: 112 ft × 5.22 ft; residential, 112 ft & 80 ft × 5.22 ft	Office: 112 ft × 5.22 ft; residential, 112 ft & 80 ft × 5.22 ft
Window U-value	0.48 BTU/h.°F.ft^2	0.48 BTU/h.°F.ft131	0.48 BTU/h.°F.ft132

In terms of the simulation study, as shown in Figure 3.2, initially, the maximum cooling loads in office and residential buildings in Phoenix for seven different building heights ranging from 5 stories to 60 stories were evaluated. Even though some fluctuations in cooling load for different building heights are observed, the magnitudes of these changes are minimal. Therefore, it is shown that height does not significantly affect the maximum cooling load per unit floor area given different types of materials, especially for the office buildings.

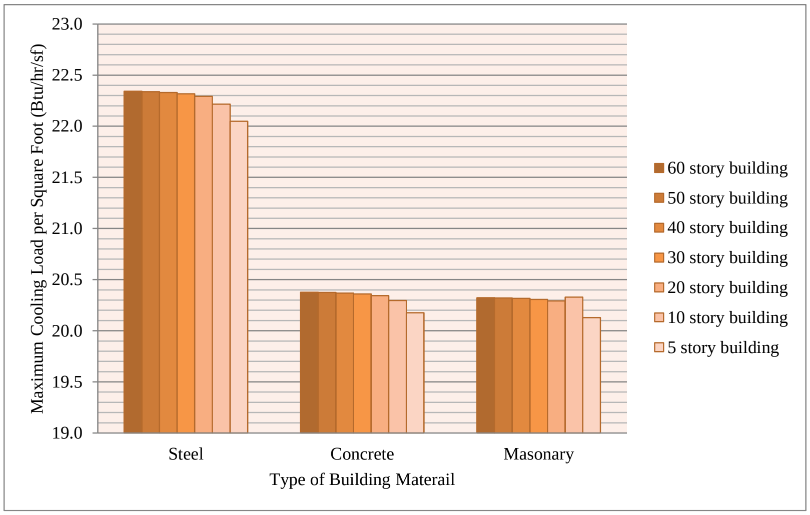


Figure 3.2 Impact of height on maximum cooling load for office (top) and residential (bottom) buildings in Phoenix, AZ

In residential buildings, however, it is noted that any change of height may affect the cooling load and reduce it to some degree but still not significantly. Therefore, height was excluded as one of the variables for the rest of the analyses and, a 30-story building of intermediate height with a footprint of 12,500 sq. ft. was selected for modeling. The default HVAC system for office buildings selected by eQUEST is a chilled cold-water coils system and a hot water coils system while for the residential buildings, the program sets no particular cooling system or electronic furnace.

Figure 3.3 shows the influence of thermal mass concrete, steel and masonry on maximum cooling load in office and residential buildings for the different climate zones.

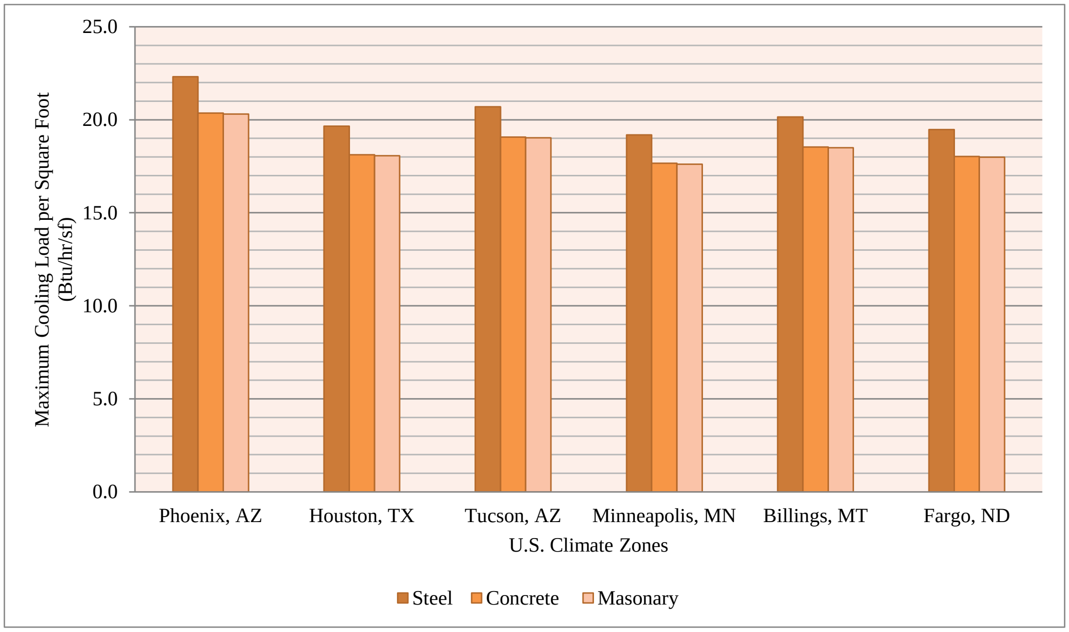


Figure 3.3 Maximum cooling load reduction in office (top), and residential (bottom) buildings

Moreover, the impact of concrete's thermal mass given different concrete wall thicknesses is shown in Figure 3.4, where the six different locations listed in Table 3.2 were considered to evaluate the thermal performance of concrete.

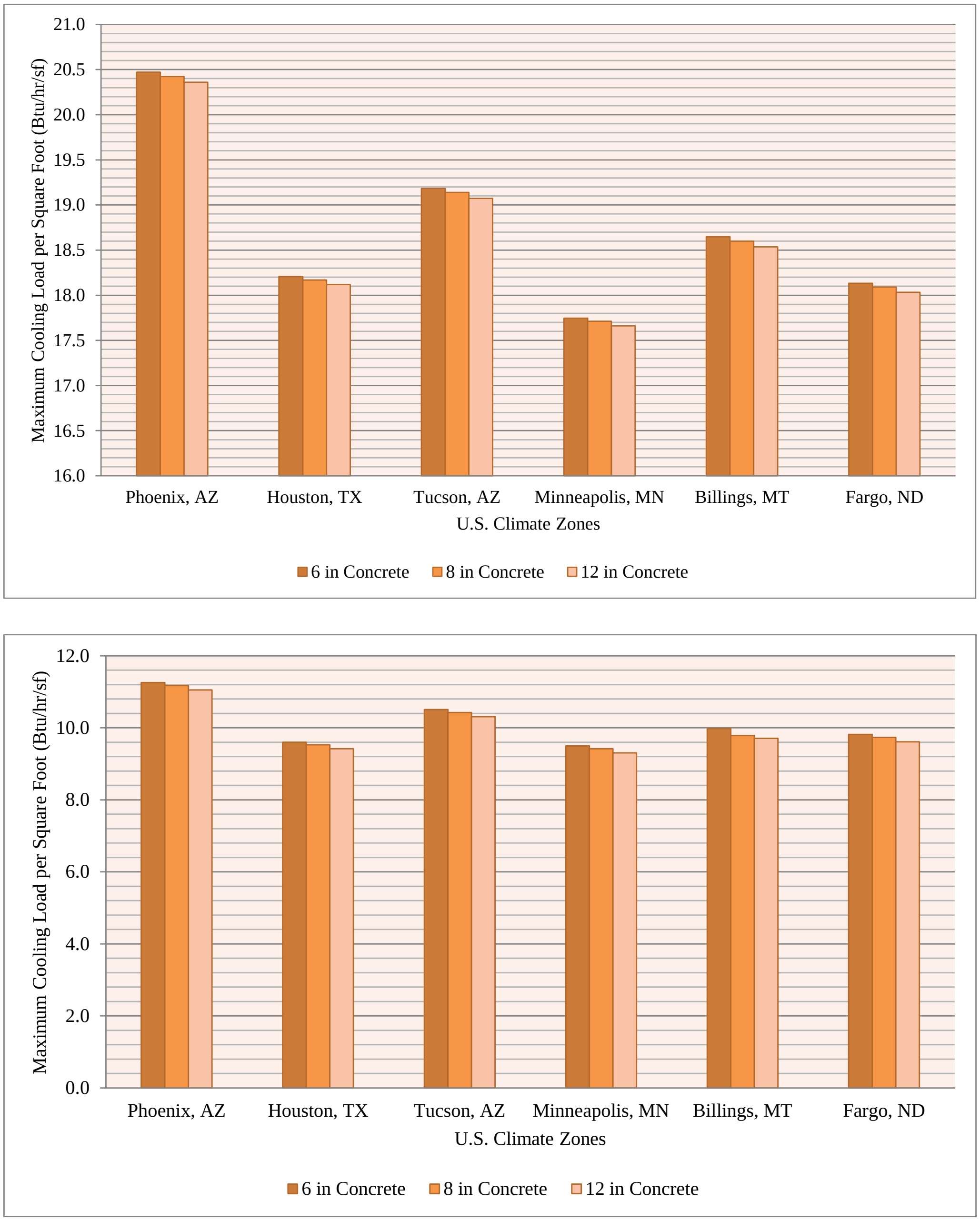


Figure 3.4 Effect of concrete wall thickness on cooling load reduction in office (top) and residential (bottom) buildings

3.1.2 Interpretation of results

Concrete and masonry showed relatively similar results in terms of maximum cooling load reduction in both office and residential buildings. Concrete reduces the maximum cooling load in the range of 7.41% to 8.78% in office buildings and 6.48% to 10.19% in residential buildings, with respect to steel.

In office buildings, the maximum cooling load reduction occurs in Phoenix by 8.47%, Billings by 8%, Minneapolis by 7.95%, Houston by 7.81%, Tucson by 7.82%, and finally, Fargo by 7.41%. In residential buildings, however, the highest reduction corresponds to Fargo by 10.19%, Billings by 9.04%, Houston by 8.10%, Phoenix by 7.52%, Minneapolis by 7.21% and Tucson by 6.48%. The difference in results between residential and office buildings can be caused by a number of variables such as internal thermal loads in office and residential buildings.

Furthermore, the volumetric increase of concrete shows a linear relationship with the cooling load reduction. In other words, as the thickness of concrete wall increases, the maximum cooling load decreases. In both office and residential buildings, the maximum reduction occurs with 12 in thick concrete walls, followed by 8 in and 6 in.

3.1.3 Additional remarks

In addition to structural and architectural properties, the thermal mass property of concrete is one of its main contributions to building energy performance. Due to its significant thermal mass, concrete reduces cooling and heating loads during summer and winter, respectively. According to the findings of this study for the investigated buildings' maximum cooling loads, concrete's thermal performance is different in office and residential buildings given different climate zones. In an office building, hot and dry locations showed a maximum cooling load reduction of 8.47%, and in very cold climates, a minimum reduction of 7.41%. In a residential building, on the other hand, the maximum cooling load reduction of 10.19% occurred in very cold locations while the minimum reduction of 6.48% was found to be in very hot locations.

3.2 Part II: Thermal mass of concrete in different climates

Part II of the phase I of this research evaluates the effects of thermal mass property of concrete on building energy use in different U.S. climate zones. To assess the influence of thermal mass on building energy performance, an investigation was carried out on a rectangular open-spaced building model. This design was chosen in accordance with the U.S. Department of Energy's (DOE) benchmark commercial building models (DOE, 2008). For simplicity, the same design was chosen for the residential models; although in reality, unlike office buildings' typical open-spaced designs, a residential plan may have more partitions inside the building.

Representing thickness, distribution and surface area of thermal mass, the buildings' wall thicknesses, heights, and window-to-wall area ratios were chosen as the variables to evaluate the impact of thermal mass on building energy performance. The annual heating and cooling energy consumptions per unit area of the building's floors and the combination of these two parameters were selected as the measurement indices of the building's energy performance. In fact, the heating and cooling requirements were represented by the amount of gas and electricity consumptions per kBtu, respectively. The energy simulation was also conducted through the Energy Plus program using the Design Builder as the interface software. In addition, six different locations in the U.S. representing six different climate zones shown earlier in Table 3.2 were chosen as follows: Phoenix, AZ (P): hot and dry; Houston, TX (H): hot and humid; Tucson, AZ (T): very hot; Billings, MT (B): cold and dry; Minneapolis, MN (M): cold and humid, and Fargo, ND (F): very cold.

It is known that office and residential buildings have different HVAC operational hours, different heating and cooling requirements given their considerably different internal gains, and different occupancy levels. Therefore, the energy performance is studied within each category of office and residential buildings.

3.2.1 The base case model

Table 3.3 describes the architectural, structural, and mechanical characteristics of the base case model for both office and residential buildings. These specifications were selected in compliance with the DOE benchmark models for commercial buildings, default occupancy schedules and activity, and the International Energy Conservation Code, where the latter two were set by the Design Builder and Energy Plus programs.

Table 3.4 The specifications of the base case model

	Office buildings	Residential buildings
Building dimension (ft)	150 × 80	151 × 80
Height (ft)	115	115
Window-to-wall ratio (%)	65	65
People density (people/m^2)	0.01	0.002
Wall U-value (BTU/h °F ft^2)	0.75	0.75
Window U-value (BTU/h °F ft^2)	1.02	1.02
Floor U-value (BTU/h °F ft^2)	0.61	0.61
Roof U-value (BTU/h °F ft^2)	0.6	0.6
Window type	Single pane clear 0.12 in	Single pane clear 0.12 in
Window dimensions (ft)	10 × 5	10 × 5
Heating set point (°F)	72	70
Cooling set point (°F)	75	77
Heating set back (°F)	53	53
Cooling set back (°F)	82	82
Heating-supply air temperature (°F)	95	95
Cooling-supply air temperature (°F)	53	53
Mechanical ventilation set point (°F)	50	50
HVAC schedule	7 am-7 pm	4 pm-11 pm (lounge), 10 pm-9
Lighting target (fc)	45	15
Office equipment (Btu/hr ft^2)	4.75	1.6

As shown in Table 3.4, for most design parameters, both office and residential buildings have relatively similar values, except for office equipment where the maximum internal gains per square meter in office buildings are three times more than residential ones. Furthermore, the lighting target for the office occupancy is significantly higher than that for a residential building, which is expected given the office building’s regular operations.

As shown in Figure 3.5, each floor of the building consists of two main thermal zones. One of these zones belongs to the core circulation area, while the other is defined by the open space around the core area. To assess the impact of thermal mass, three different external concrete wall thicknesses including 4 in, 8 in, and 12 in are chosen. However, the concrete slab thickness of 6 in is kept constant for all cases.

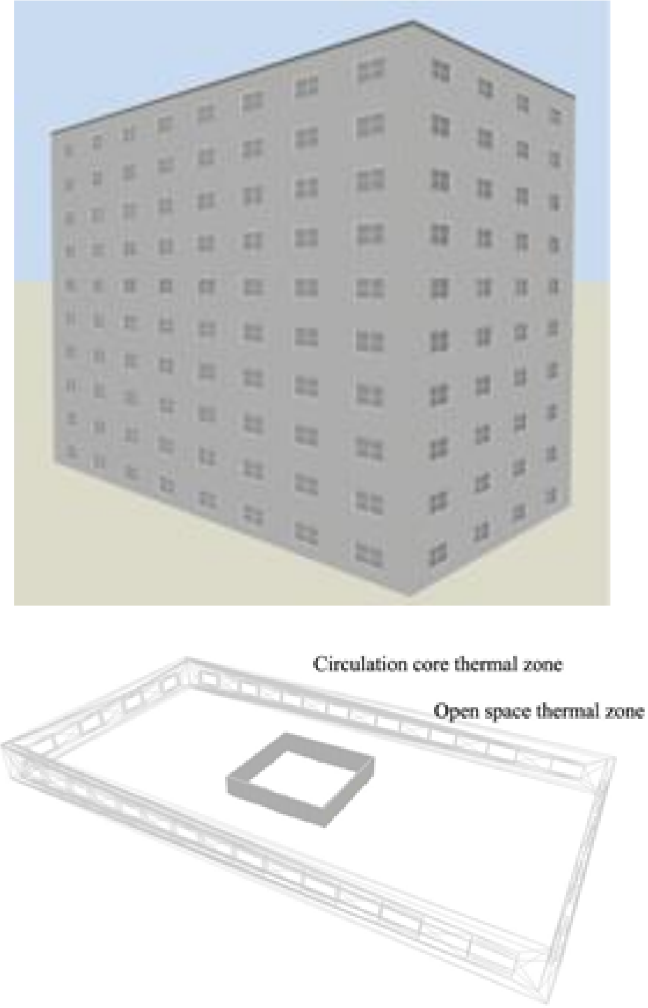


Figure 3.5 Base case model, three dimensional image (top), open space and core thermal zones (bottom)

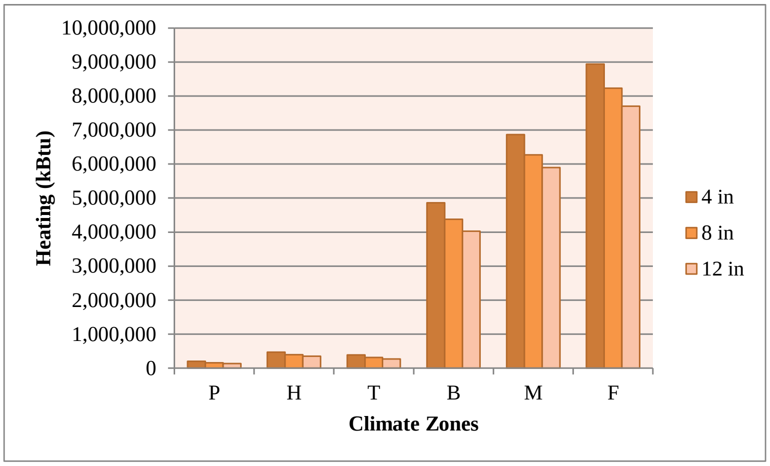
Selecting single-glazed windows over double-glazed ones allowed external concrete walls—not windows—to be the principal element of the building facade that delay heat transfer through the building envelope

To investigate the impact of concrete thermal mass solely, and to avoid any additional effects on the building’s thermal performance from insulation, the wall insulation was excluded from the building model. The operation of HVAC systems follows the Compact Schedule when such systems operate from 7 am to 7 pm. However, to further investigate the impact of concrete thermal mass on buildings' cooling demands, nighttime natural ventilation is introduced from 7 pm to 7 am the following day.

To explore the performance of thermal mass, the effect of increased wall thickness, window-to-wall area ratio and building height on the reduction of heating and cooling requirements is compared among different scenarios. In other words, for both office and residential buildings, the basic case is to have a 10-story concrete building with a wall thickness of 4 in and a window-to-wall area ratio of 20%. In the second and third cases, the wall thickness is changed to 8 in and 12 in, while other variables remain unchanged. For each case, the heating and cooling requirements are changed; therefore, by comparing these changes among the various scenarios, the effectiveness of concrete thermal mass can be determined given different external wall thicknesses. For 4 in wall thickness, the window-to-wall area ratio and building height were later changed to 30% and 20 stories, respectively, to further explore the energy performance for different design variables.

3.2.2 Heating energy demands

In terms of the effectiveness of thermal mass, the occupancy of buildings is a critical factor for energy consumption. For instance, whether the building is residential or commercial, the type of heating and cooling strategies, HVAC systems, and their operational schedules would be different, which in turn, will affect the building's energy consumption. Figure 3.6 demonstrates the heating energy demands in an office and a residential building for three different wall thicknesses and six different climate zones. It shows that the increase of wall thickness from 4 in to 12 in can result in a consistent reduction of heating energies in both building types.



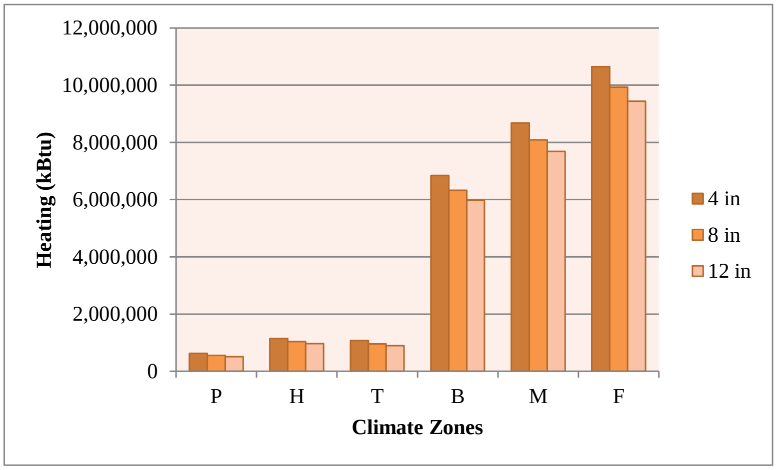


Figure 3.6 (cont.) Heating energy consumptions in 10-story office (above) and residential (below) buildings

Table 3.5 summarizes the effect of concrete thermal mass on the annual heating energy consumptions in office buildings. As shown in this table, there is a direct correlation between concrete thermal mass and buildings' heating requirements regardless of location, which indicates that as concrete thermal mass increases, the heating energy demands decrease. It is noted that, in both hot and cold climates, the increase in thermal mass leads to a reduction of heating requirements. However, the reduction of heating demands in office buildings, when the wall thickness (thermal mass) increases from 4 in to 8 in is nearly 30% more than when it increases from 8 in to 12 in.

Table 3.5 Thermal mass impact on the annual heating energy consumptions in office (left) and residential (right) buildings

10-story building, Win./wall area ratio: 20%		**The reduction of heating loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	21.1	15.2
	Houston, TX	15.6	11.9
	Tucson, AZ	19.8	14.4
	Billings, MT	10.0	8.0
	Minneapolis, MN	8.7	5.9
	Fargo, ND	7.9	6.4

10-story building, Win./wall area ratio: 20%		**The reduction of heating loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	11.1	7.1
	Houston, TX	9.8	6.4
	Tucson, AZ	10.8	6.8
	Billings, MT	7.6	5.6
	Minneapolis, MN	6.8	5.0
	Fargo, ND	6.7	4.9

Also, doubling the thickness of a wall from 4 in to 8 in leads to a 22% reduction of heating energy consumptions mainly in hot climates. Thus, the reduction of heating demands due to thermal mass is considerably higher in hot climates than it is in cold locations. Potential reasons supporting these phenomena can be explained as in the following:

- Temperature swings are considerably higher in hot climates, in which, the effects of thermal mass become predominant; and

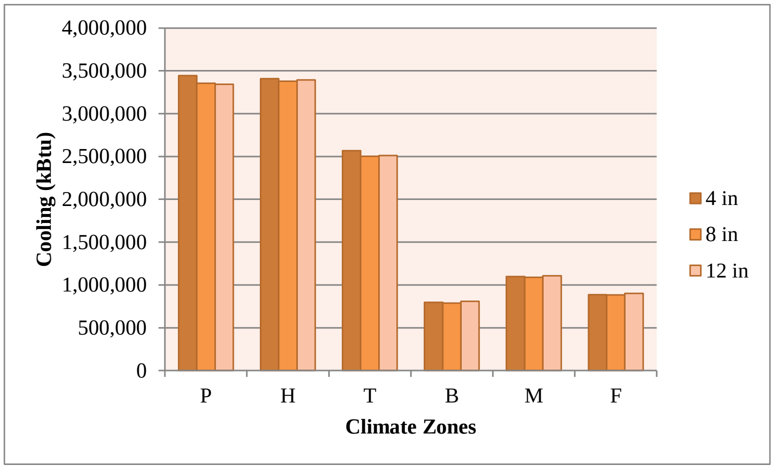
- Unlike the cold climate zones, all hot locations in this study are also primarily sunny, in which, further and longer exposure to the sun can improve and enhance the effect of thermal mass.

The same table also shows the reduction of heating energy demands due to the increase of thermal mass in residential buildings. In both hot and cold climates, the increase in thermal mass leads to the reduction of heating requirements. Similar to office buildings, the reduction of heating energy consumptions in residential buildings, when the wall thickness (thermal mass) increases from 4 in to 8 in, is nearly 30% higher than when it increases from 8 in to 12 in. Also, doubling the thickness of a wall from 4 in to 8 in leads to a 12% reduction of heating requirements in hot climates.

Residential buildings in hot locations show a higher reduction of heating energy consumptions (at any increase of wall thickness) than similar buildings in cold climates, which is consistent with the results for office buildings.

3.2.3 Cooling energy demands

Figure 3.7 shows the evaluation of cooling demands for both residential and office buildings. For both office and residential cases, the percent reduction is noted to decrease with the increase in wall thickness. It can be inferred that further increase will lessen the benefit of thermal mass for energy efficiency.



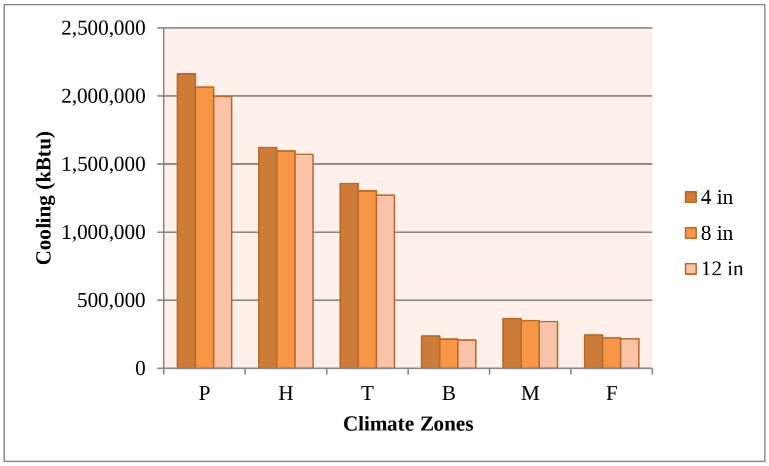


Figure 3.7 Cooling energy consumptions in 10-story office (above) and residential (below) buildings

According to the results of this study, as shown in Table 3.5, office buildings show a higher reduction of buildings' cooling energy requirements as thermal mass increases in hot locations when compared to cold ones. Furthermore, thermal mass effects in office buildings show rather interesting results in both hot and cold climates. In Table 3.6, beyond 12 in wall thickness, thermal mass increases the cooling demands rather than decreasing it for office buildings. In other words, 12 in can be an optimal wall thickness in terms of thermal mass impact on cooling demands. These results are supported by the findings from the experimental study in Nevada discussed earlier that showed an increase of cooling energy consumptions in the concrete framed construction (Zhu et al., 2009).

Moreover, in Phoenix, AZ (a hot and dry location) where the increase of thermal mass and the reduction of cooling energy consumptions have a linear positive correlation, when wall thickness increases from 4 in to 12 in, the decrease of cooling requirements is significantly larger, up to 8 times greater than when the wall thickness increases from 8 in to 12 in. For residential buildings, on the other hand, cold climates show a higher reduction of cooling demands due to the increase of thermal mass. Also, this reduction of cooling requirements in both office and residential buildings is higher when the wall thickness increases from 4 in to 8 in as compared to when it increases from 8 in to 12 in for both hot and cold climate zones.

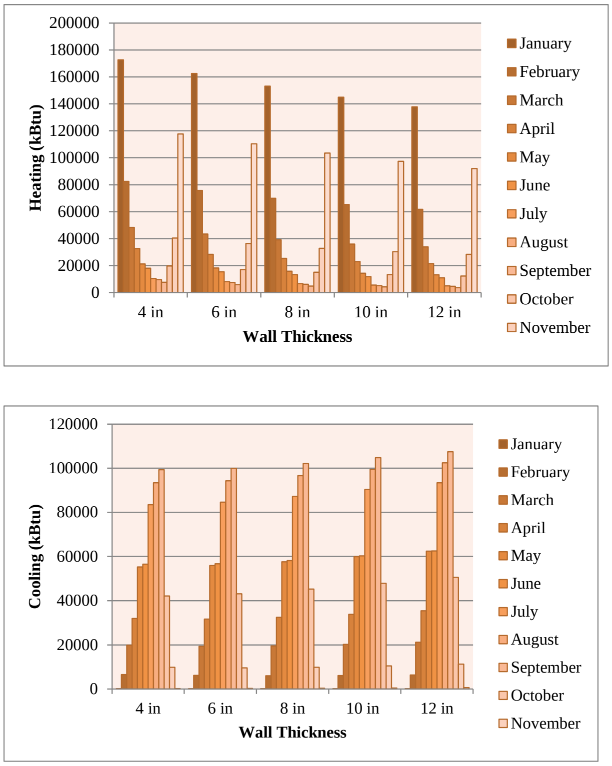
Table 3.6 Thermal mass impact on the annual cooling energy consumptions in office (above) and residential (below) buildings

	10-story building, Win./wall area ratio: 20%	**The reduction (increase) of cooling loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	2.6	0.3
	Houston, TX	0.8	(0.4)
	Tucson, AZ	2.6	(0.5)
	Billings, MT	1.1	(2.4)
	Minneapolis, MN	1.1	(1.9)
	Fargo, ND	0.4	(1.8)

	10-story building, Win./wall area ratio: 20%	**The reduction (increase) of cooling loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	4.5	3.3
	Houston, TX	1.6	1.5
	Tucson, AZ	4.0	2.4
	Billings, MT	9.2	3.0
	Minneapolis, MN	4.2	2.1
	Fargo, ND	8.2	3.8

3.2.4 Heating and cooling energy demands in mild weather

For mid climates, where temperature variations are less, the findings of this study have shown that as the thermal mass increases, the cooling requirements slightly increase as well, which is not expected given the nature of thermal mass.



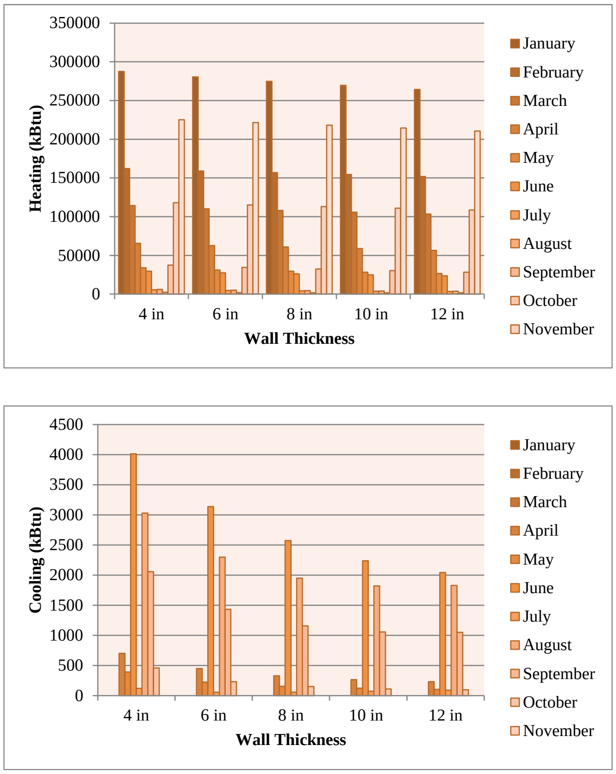


Figure 3.8 Heating (above) and cooling (below) energy consumptions in office buildings in San Francisco, CA

Figure 3.9 Heating (above) and cooling (below) energy consumptions in residential buildings in San Francisco, CA

To further investigate this interesting effect of thermal mass, the city of San Francisco, CA, a mild weather location, was also studied to obtain more information on this phenomenon. Figures 3.8 and 3.9 present the monthly results of this energy simulation. As shown in Figures 3.8 and 3.9, and Tables 3.7 and 3.8, as the wall thickness increases, the heating energy consumptions decrease for all months of a year, which was an expected. However, under similar conditions, the cooling energy consumptions increase.

Table 3.7 Thermal mass impact on the monthly heating (above) and cooling (below) energy consumptions in office buildings in San Francisco, CA

10-story building in San Francisco		**The reduction of monthly heating loads** (%)			
		Change in wall thickness			
		4 in - 6 in	6 in - 8 in	8 in - 10 in	10 in - 12 in
Months of year	January	5.8	5.8	5.4	5.0
	February	8.1	7.7	6.6	5.4
	March	10.1	9.8	8.0	5.9
	April	12.8	10.8	9.2	6.5
	May	14.3	13.0	9.7	7.7
	June	15.1	13.2	11.6	7.3
	July	23.6	18.4	15.5	10.8
	August	22.1	17.4	16.0	10.7
	September	23.1	17.8	14.4	11.8
	October	13.5	11.8	11.1	8.1
	November	10.2	9.5	7.9	6.3
	December	6.1	6.3	5.9	5.5

10-story building in San Francisco		**The reduction (increase) of monthly cooling loads** (%)			
		Change in wall thickness			
		4 in - 6 in	6 in - 8 in	8 in - 10 in	10 in - 12 in
Months of year	January	(2.6)	(14.6)	(39.2)	(32.0)
	February	6.3	1.9	(1.3)	(3.5)
	March	2.9	(1.2)	(3.5)	(4.7)
	April	0.8	(2.4)	(4.1)	(4.8)
	May	(1.0)	(3.1)	(4.1)	(4.2)
	June	(0.3)	(2.6)	(3.7)	(3.8)
	July	(1.3)	(3.1)	(3.5)	(3.4)
	August	(0.9)	(2.5)	(3.0)	(3.0)
	September	(0.6)	(2.2)	(2.6)	(2.6)
	October	(2.5)	(4.9)	(5.7)	(5.7)
	November	2.1	(2.8)	(6.0)	(7.5)
	December	(47.0)	(34.4)	(27.5)	(25.8)

Table 3.8 Thermal mass impact on the monthly heating (above) and cooling (below) energy consumptions in residential buildings in San Francisco, CA

10-story building in San Francisco		**The reduction of monthly heating energies** (%)			
		Change in wall thickness			
		4 in - 6 in	6 in - 8 in	8 in - 10 in	10 in - 12 in
Months of year	January	2.5	2.1	1.9	1.9
	February	1.8	1.4	1.5	1.7
	March	3.6	2.1	2.0	2.3
	April	4.7	2.9	3.3	3.9
	May	7.9	5.0	4.8	5.3
	June	7.6	4.8	4.8	5.4
	July	14.4	9.8	10.3	10.1
	August	16.7	8.8	9.7	9.6
	September	26.1	8.6	5.2	4.9
	October	7.4	6.2	6.5	6.6
	November	2.4	1.7	1.9	2.1
	December	1.7	1.5	1.7	1.8

10-story building in San Francisco		**The reduction of monthly cooling energies** (%)			
		Change in wall thickness			
		4 in - 6 in	6 in - 8 in	8 in - 10 in	10 in - 12 in
Months of year	January	N/A	N/A	N/A	N/A
	February	N/A	N/A	N/A	N/A
	March	N/A	N/A	N/A	N/A
	April	36.1	26.9	19.3	12.1
	May	42.5	30.9	21.3	14.0
	June	21.9	17.9	13.0	8.6
	July	51.3	(1.2)	(25.4)	(25.1)
	August	24.1	15.3	6.5	(0.3)
	September	30.4	19.2	8.7	0.5
	October	49.6	35.0	25.8	14.1
	November	N/A	N/A	N/A	N/A
	December	N/A	N/A	N/A	N/A

Residential buildings show similar performance results in terms of heating and cooling demand reductions. Except for a few cases where cooling energy consumptions increase during summer when the wall thickness increases, both heating and cooling requirements decrease as the wall thickness increases. Therefore, despite San Francisco’s mild climate, the energy performance of thermal mass is comparable to that of extreme climatic conditions, albeit to a lower degree.

3.2.5 Nighttime natural ventilation

In this study, following buildings' occupancy schedules, the HVAC operation hours were set mainly during daytime. However, to further investigate the observed increase of cooling demands and to consider the possible effect of nighttime excessive heat storage in the walls, nighttime natural ventilation from 7 pm to 7 am was also introduced to the building envelope. In this section, Minneapolis, MN was chosen since it showed a considerable increase of cooling energy consumptions when the wall thickness increased from 8 in to 12 in. Figure 3.10 and Table 3.9 show the results of the impact of increased wall thickness on cooling energy demands.

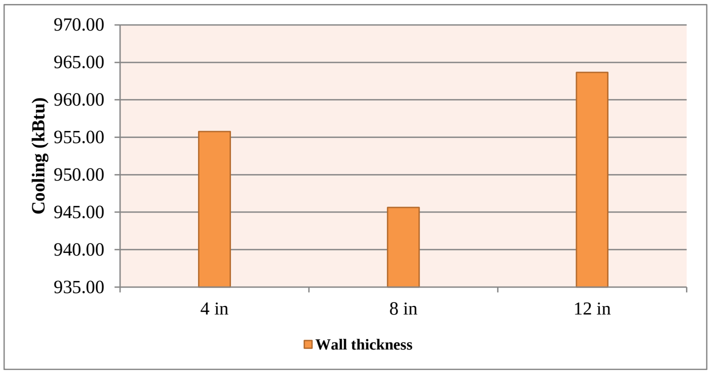


Figure 3.10 Effect of nighttime natural ventilation on cooling energy consumptions in a 10-story office building in Minneapolis, MN

Table 3.9 Thermal mass impact on cooling energy consumptions in the presence of nighttime ventilation in Minneapolis, MN

10-story building in Minneapolis	**The reduction (increase) of cooling loads** (%)	
	Change in wall thickness	
	4 in - 8 in	8 in - 12 in
Wall thickness	1.1	(1.9)

The effect of thermal mass concrete on cooling requirements was further studied for the mild climate of San Francisco, CA in the presence of nighttime natural ventilation by progressively increasing wall thicknesses from 4 in. to 12 in. in 2 in. increments. The results are shown in Figure 3.11 and Table 3.10.

Although some minor changes in overall magnitude of cooling energy demands were observed in San Francisco, the results did not indicate a considerable change of energy behavior of thermal mass compared to the former scenarios, when there was no nighttime ventilation, and the increase of thermal mass led to an increase of cooling requirements.

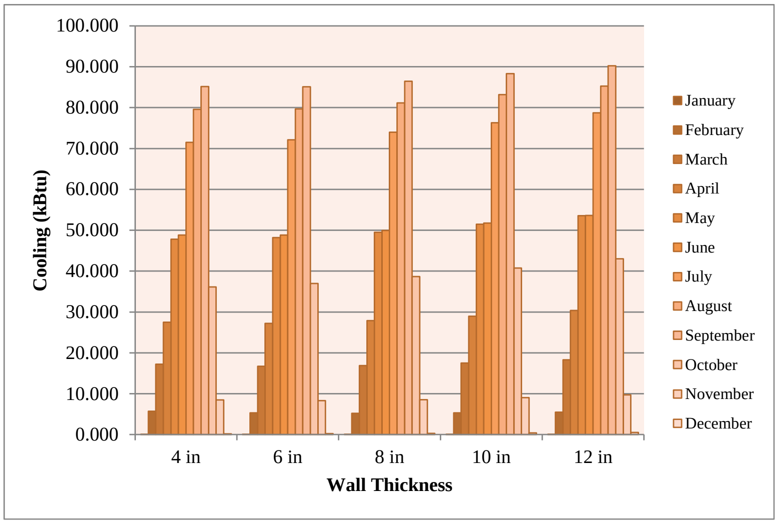


Figure 3.11 Effect of nighttime natural ventilation on cooling energy consumptions in a 10-story office building in San Francisco, CA

Table 3.10 Thermal mass impact on the monthly cooling energy consumptions in office buildings in the presence of nighttime ventilation in San Francisco, CA

10-story building in San Francisco		**The reduction (increase) of monthly cooling loads** (%)			
		Change in wall thickness			
		4 in - 6 in	6 in - 8 in	8 in - 10 in	10 in - 12 in
Months of year	January	(1.0)	(14.6)	(39.2)	(31.4)
	February	6.4	1.9	(1.3)	(3.4)
	March	2.9	(1.1)	(3.5)	(4.7)
	April	1.0	(2.3)	(4.0)	(4.8)
	May	(0.8)	(2.8)	(3.9)	(4.1)
	June	(0.1)	(2.3)	(3.6)	(3.6)
	July	(0.9)	(2.6)	(3.1)	(3.2)
	August	(0.2)	(1.8)	(2.5)	(2.5)
	September	0.1	(1.6)	(2.2)	(2.2)
	October	(2.3)	(4.5)	(5.4)	(5.5)
	November	2.1	(2.7)	(6.0)	(7.5)
	December	(47.8)	(34.3)	(27.5)	(25.6)

However, unlike the situation when there was no nighttime ventilation, the increase of cooling demands along with the increase of wall thickness relatively flattened out (i.e. was reduced) when the wall thickness increased from 8 in to 12 in.

3.2.6 Total heating and cooling demands

To evaluate the overall energy performance of buildings, total heating and cooling requirements of the buildings were studied. Figure 3.12 shows the results of building energy consumption for office and residential occupancies, different climate zones, as well as different wall thicknesses. As shown in Table 3.11, for both office and residential buildings, in cold climates as opposed to hot locations, considerably higher reductions of building energy consumption are observed due to the increase of thermal mass.

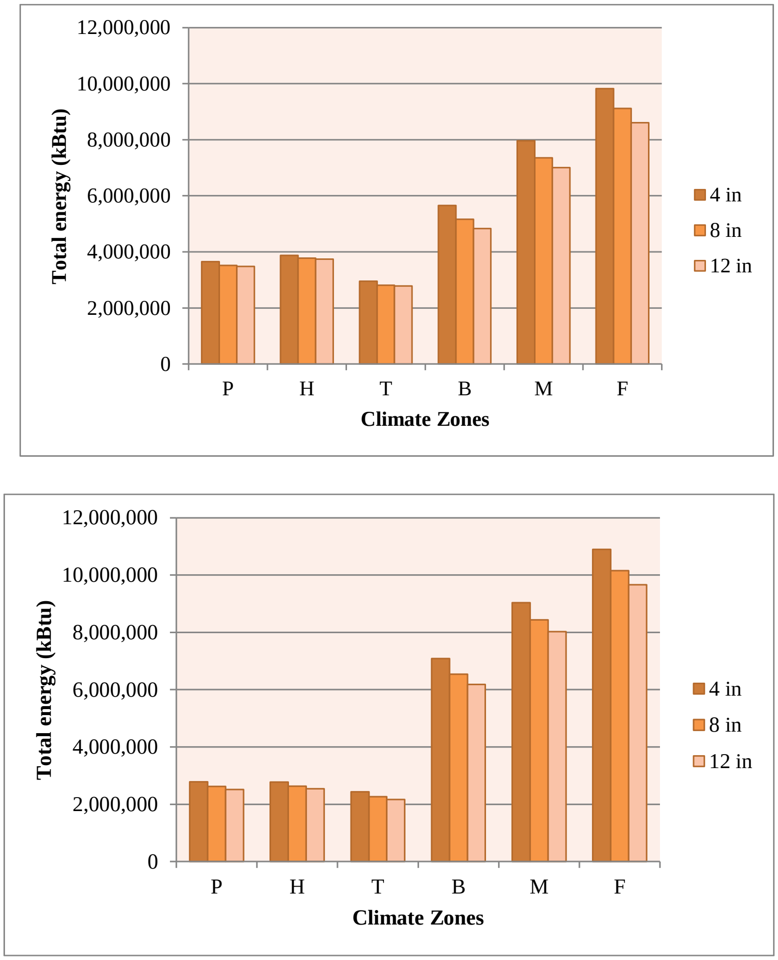


Figure 3.12 Total heating and cooling energy consumptions in 10-story office (above) and residential (below) buildings

In addition, in office buildings, when the wall thickness increases from 8 in to 12 in, the reduction of total energy consumptions is significantly higher in cold climates than it is in hot locations. Similarly, in residential buildings, when the wall thickness increases from 8 in to 12 in, the reduction of total heating and cooling requirements is higher in cold climates than in hot locations, with this higher reduction being presumably up to 30%.

Table 3.11 Thermal mass impact on the annual heating and cooling energy consumptions in office (above) and residential (below) buildings

10-story building, Win./wall area ratio: 20%		**The reduction of total heating and cooling loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	3.6	1.0
	Houston, TX	2.6	0.9
	Tucson, AZ	4.8	1.2
	Billings, MT	8.8	6.4
	Minneapolis, MN	7.7	4.7
	Fargo, ND	7.2	5.6

10-story building, Win./wall area ratio: 20%		**The reduction of total heating and cooling loads** (%)	
		Change in wall thickness	
		4 in - 8 in	8 in - 12 in
US Climate Zones	Phoenix, AZ	6.0	4.1
	Houston, TX	5.0	3.4
	Tucson, AZ	7.0	4.3
	Billings, MT	7.7	5.5
	Minneapolis, MN	6.6	4.9
	Fargo, ND	6.8	4.9

3.2.7 Peak heating and cooling energy demands

The peak amounts of heating and cooling demands can be additional parameters to measure the energy performance of buildings in order to investigate the effect of thermal mass on maximum heating and cooling loads, which in turn, affect the design of HVAC systems and equipment such as chillers, boilers and air-handling units.

Table 3.12 Thermal mass impact on the peak heating (above) and cooling (below) energy consumptions in office and residential buildings in Phoenix, AZ

10-story building		**The reduction of peak heating loads** (%)	
		4 in - 8 in	8 in - 12 in
Building Occupancy	Office	6.21	2.70
	Residential	8.57	2.10

10-story building		**The reduction of peak cooling loads** (%)	
		4 in - 8 in	8 in - 12 in
Building Occupancy	Office	4.03	0.98
	Residential	12.19	6.01

Table 3.13 Thermal mass impact on the peak heating (above) and cooling (below) energy consumptions in office and residential buildings Fargo, ND

10-story building		**The reduction of peak heating load** (%)	
		4 in - 8 in	8 in - 12 in
Building Occupancy	Office	4.09	4.62
	Residential	8.33	3.03

10-story building		**The reduction of peak cooling load** (%)	
		4 in - 8 in	8 in - 12 in
Building Occupancy	Office	4.73	1.85
	Residential	13.83	5.12

In this study, to evaluate the impact of thermal mass on peak heating and cooling requirements, Phoenix, AZ and Fargo, ND were chosen because they showed the highest annual heating and cooling energy consumptions among the locations that were investigated. Tables 3.12 and 3.13 show the results of peak heating and cooling demands in these locations.

As shown, in residential buildings, for both locations—Phoenix and Fargo—the increase of wall thickness from 4 in to 8 in and from 8 in to 12 in resulted in the reduction of peak heating and cooling demands ranging from 8% to 13%, respectively. In office buildings, this reduction in both Phoenix and Fargo is only 4%. Moreover, for both climates, in residential buildings, the reduction of peak cooling demands is higher than that for peak heating demand, by about 5%.

3.2.8 Internal gains in office and residential buildings

To further explain the difference of thermal mass's energy performance between office and residential buildings, this study was extended to evaluate the internal gains for both applications.

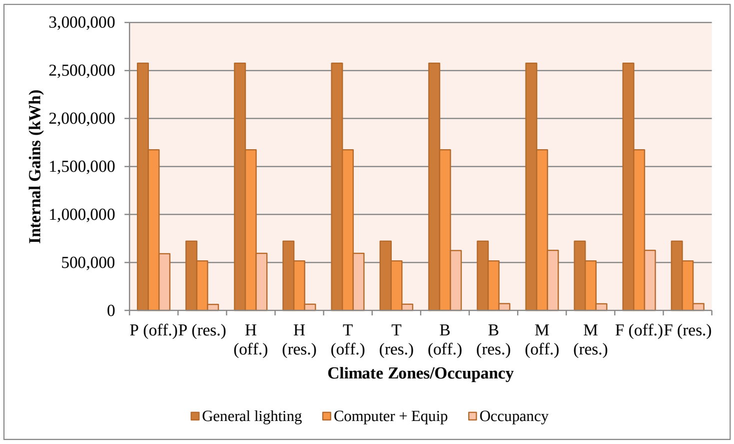


Figure 3.13 Internal gains for office (off.) and residential (res.) buildings

Figure 3.13 shows the annual results of internal gains due to the lighting, computer and equipment, and occupancy for a 10-story building with 4 in concrete walls. As shown in this figure, regardless of location, the amount of internal gains due to the general lighting and equipment in office buildings is almost three times that of residential ones. In addition, the internal gains resulted from the occupants is about ten times larger in office buildings than residential occupancies. These numbers can explain some of the performance differences observed in office and residential buildings. As shown in previous sections, the increase of required cooling energy consumptions in office buildings as the wall thickness increases beyond 8 in can be caused by the high level of internal gains in the office occupancy. Unlike the residential buildings where lighting, equipment, and occupants would not significantly affect the heating and cooling demands, high internal gains in office buildings could be maintained as the heat stored in the walls. With the increase of wall thickness, an excessive storage of heat needs to be dissipated, which could lead to higher energy consumptions.

3.2.9 Other influential design parameters

In addition to wall thicknesses, the impact of window-to-wall area ratios and building heights on the performance of thermal mass in reducing energy use was also investigated.

It is noted that in office buildings, the increase of window-to-wall area ratio from 20% to 30% can lessen the reduction of total heating and cooling requirements (as a result of the increases of wall thickness) of up to 30% in hot climates and 15% in cold ones. The increase of building height to 20 stories, on the other hand, did not result in a significant change of total heating and cooling demands (following the change in thermal mass). This finding may, however, change for tall and super-tall buildings.

Similarly, for residential buildings, the increase of building height did not result in a significant change of total heating and cooling energy consumptions when the wall thickness increased. However, the window-to-wall ratio of 30% lowered the reduction of total energy consumptions (following the increase in thermal mass) by 25% and 10% in hot and cold climates, respectively. It also should be noted that in both office and residential buildings, this reduced effect was mainly related to cooling requirements rather than heating demands, which did not show a significant change as a result of glazing variations.

3.2.10 Commentary on results

It can be stated that, generally speaking, extreme climates can better exploit the thermal mass properties of materials than mild climates. The findings discussed herein between office and residential occupancies, as well as the heating, cooling, and total energy consumptions (i.e., combining heating and cooling energy demands), suggest that the increase of thermal mass can generally reduce the heating and cooling requirements regardless of location and occupancy.

In office buildings, this reduction of energy consumptions, due to the increase of wall thickness from 4 in to 8 in, can range from less than 1% of cooling demands in cold climates to 22% of heating demands in hot locations. However, the increase of wall thickness beyond 8 in can lead to an increase of cooling requirements in office buildings regardless of location, which may not be ultimately beneficial. This increase of cooling requirements beyond 8 in wall thickness was also observed in mild climates such as San Francisco. Even introducing nighttime natural ventilation could not change this trend of increase in cooling demands.

For residential occupancy, the increase of wall thickness from 4 in to 8 in and from 8 in to 12 in in hot climates showed a greater reduction of heating demands of up to 5% than comparable buildings in cold climates. However, following the increase in wall thickness, buildings in cold locations showed a better cooling energy performance (about 5% more reduction) than similar buildings in hot climate zones.

In terms of total heating and cooling requirements, office buildings in cold climates showed a relatively higher reduction than similar buildings in hot locations; whereas residential buildings, in both hot and cold climates showed a similar reduction of total energy demands. As far as the peak heating and cooling energy consumptions are concerned, in residential buildings, the reduction of peak cooling demands is higher than the reduction of peak heating demands; however, in office buildings, these two reductions are nearly equal.

Furthermore, the increase of window-to-wall ratios from 20% to 30% can lessen the effectiveness of thermal mass in reducing building energy consumptions (mainly cooling requirements) of up to 30%. The increase of building height to 20 stories, on the other hand, has not shown a considerable impact on the energy performance of thermal mass in either application of office or residential buildings.

Chapter 4 will focus on the second phase of the research where a detailed study of the effect of concrete thermal mass on office building energy and thermal comfort performance will be presented. Office buildings were chosen for this phase of research since they are more challenging with respect to heating and cooling design given a significant presence of internal loads, which is not observed in residential buildings. The chapter begins with the assessment of primary concrete thermal mass including the thickness of perimeter wall on the building energy consumption and its thermal comfort.

3.3 Summary

This chapter reviews the preliminary phase of this research, which studies the effect of common building materials on building cooling performance and the impacts of concrete thermal mass on building overall energy performance. Generally speaking, extreme climates are shown to better exploit the thermal mass properties of materials than mild climates. Increase of thermal mass is seen to generally reduce the heating and cooling requirements regardless of location and occupancy. However, the increase of wall thickness beyond 8 in can lead to an increase of cooling requirements in office buildings. In office buildings, the increase of wall thickness can result in energy reduction of up to 22%. In residential building, the increase of wall thickness can result in a reduction of energy demands of up to 5%. Increase of window-to-wall ratios can lessen the effectiveness of thermal mass in reducing building energy consumptions; however, the increase of building height is shown not to have a considerable impact on the energy performance of thermal mass in either office or residential buildings.

CHAPTER 4:

PERIMETER WALL THICKNESS and BUILDING PERFORMANCE

As indicated in Chapter 2, the primary thermal mass, which is directly exposed to the solar heating, has greater impacts on building energy performance as compared to interior thermal mass elements. Secondary thermal mass, on the other hand, is located inside the building and indirectly exchanges heat with the surroundings.

As the main primary thermal mass, the building envelope plays a major role in regards to building energy and thermal comfort performance. The thickness and the area of the perimeter wall (as opposed to the area of fenestrations) are the two principal parameters of building envelope studied in this research. This chapter discusses the effectiveness of perimeter wall thickness on building energy and thermal comfort performance.

In this study, the thickness of perimeter wall was varied from 4 in (base case), to 8 in, 12 in, 16 in and 20 in. The energy simulation for each case is conducted and the energy use and thermal comfort results are compared among different cases.

4.1 The effect of building envelope on energy use and thermal comfort

Kosny et al. (1998) have shown that most effective thermal mass configurations are massive walls with thermal mass (concrete layer) being in good contact with the interior of the building, which confirms the chapter one discussion on relationship between thermal mass and insulation and the fact that thermal mass would be more effective in improving building energy and comfort conditions when it is in a direct contact with the interior space.

Shaviv et al. (2001) have compared different types of building construction with respect to thermal mass including 1) Light building (no thermal mass, like a mobile home), 2) Medium-light building (light walls, but heavy floor, like cement tiles on concrete floor, and concrete ceiling, 3) Semi-heavy building (heavy floor, ceiling and external walls—8 in concrete blocks—but light internal partitions including gypsum boards), and 4) Heavy building (heavy floor, ceiling, external and internal walls—10 cm concrete blocks, with plaster on both sides). According to this study, when the performance of the different heavy and light structures was compared, it was observed that the light structure behaves like a heat trap. The temperature obtained in such buildings was even higher than the maximum outside temperature. The medium light structure seemed to significantly improve the thermal behavior of the building, by reducing maximum indoor temperature. The semi-heavy structure showed further improvements in the performance of the building, and the improvement proceeds with the heavy structure, although it was shown to be less significant.

Balaras (1996) has shown that a 4 in to 8 in wall thickness is usable for heat absorption, storage and release on a daily basis. Thicker walls, up to 12 in, may provide longer periods of thermal storage. Thermostat setup during summer, is less effective in massive structures, because they take longer to cool down. Numerical simulations have also shown that the percent annual reductions in sensible heating and cooling loads, because of the thermal mass levels of the walls (floors and foundations were assumed to be massless); can be as high as 40% in mild climates.

4.2 Thermal mass analysis for energy and thermal comfort

To assess the influence of envelope thermal mass on building energy performance; a simulation was carried out on a rectangular-shaped open-spaced building model. The U.S. Department of Energy's (DOE) benchmark commercial building (Figure 4.1) models (DOE, 2008) was the basis for the base case model of this study (Figure 4.2). The annual and monthly heating and cooling energy consumptions as well as the combination of these two parameters represented by total energy consumption are the measurement indices for building energy performance. Similarly, the annual and monthly average of air, radiant and operative temperatures are assumed as the measurement indices for building thermal performance. In fact, the heating and cooling requirements were represented by the amount of gas and electricity consumptions per kBtu, respectively. The energy simulation was also conducted through the Energy Plus computer program using the Design Builder as the interface software. In addition, the eight climatic conditions of 1A (very hot and humid), 2B (hot and dry), 3C (warm and marine), 4B (mixed-dry), 5A (cool and humid), 6A (cool and marine), 7 (cold and dry), and 8 (very cold)

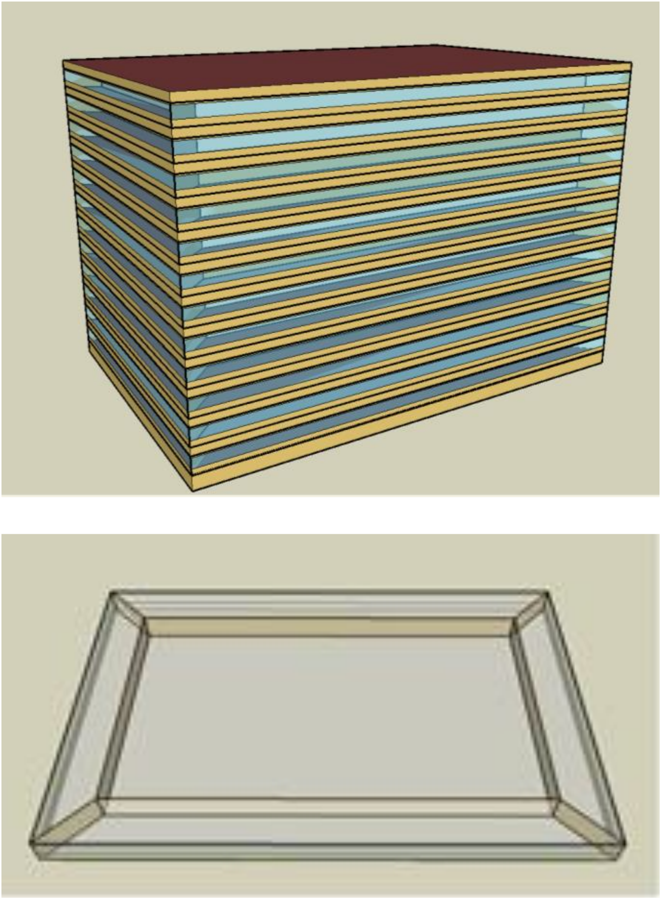


Figure 4.1 DOE benchmark commercial building,
Source: (DOE, 2008)

were chosen as representatives of all 16 U.S. climate zones. For each climate zone the following cities were selected as follows:

- Miami, FL:1A, very hot-humid
- Phoenix, AZ: 2B, hot-dry
- San Francisco, CA: 3C, warm-marine
- Albuquerque, NM: 4B, mixed-dry
- Chicago, IL: 5A, cool-humid
- Minneapolis, MN: 6A, cool-marine
- Duluth, MN: 7, cold-dry
- Fairbanks, AK: 8, very col

4.2.1 Base case model

Table 4.1 shows the architectural and mechanical specifications of the base case model. These specifications were determined in accordance with the DOE benchmark models for commercial buildings, default occupancy schedules and activity, and the International Energy Conservation Code, where the latter two were set by

Table 4.1 The specifications of the base case model

Building dimension (ft)	100 x 50
Height (ft)	140
Window-to-wall ratio (%)	30
Occupancy density (people/ft^2)	0.010311
Occupancy schedule	7 am-7 pm
Wall U-value (BTU/h °F ft^2)	0.726
Window U-value (BTU/h °F ft^2)	1.078
Floor U-value (BTU/h °F ft^2)	0.623
Roof U-value (BTU/h °F ft^2)	0.829
Window type	Single pane 0.24 in
Window dimensions (ft)	Continuous horizontal
Heating set point (^{o}F)	72
Cooling set point (^{o}F)	75
Heating set back (^{o}F)	53
Cooling set back (^{o}F)	82
Heating-supply air temperature (^{o}F)	95
Cooling-supply air temperature (^{o}F)	53
Mechanical ventilation set point (^{o}F)	50
HVAC schedule	7 am-7 pm
HVAC systems	VAV with terminal reheat
Lighting target (fc)	37
Office equipment (W/ft^2)	1.09

the Design Builder and Energy Plus program.

To assess the impact of thermal mass, five different external concrete wall thicknesses, i.e. 4 in, 8 in, and 12, 16 in and 20 in were chosen. Selecting single-glazed windows over double-glazed ones allowed external concrete walls, not windows, to be the principal element of the building facade that delays heat transfer through the building envelope.

To investigate the impact of concrete thermal mass solely, and to avoid any additional effects on the building's thermal performance from insulation, the wall insulation was excluded from the building construction. The operation of HVAC systems follows the Compact

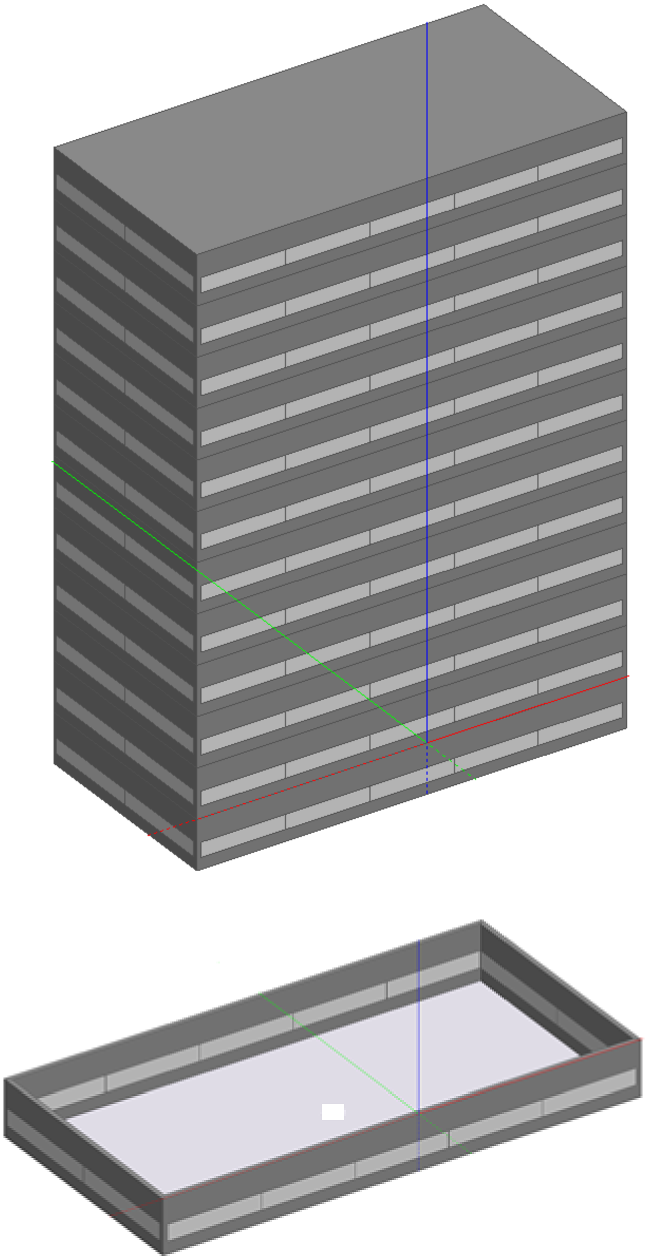


Figure 4.2. Basic case model, three dimensional image (top), open space and core thermal zones (bottom)

Schedule when such systems operate from 7 am until 7 pm. To explore the performance of thermal mass, the effect of increased wall thickness on the reduction of heating and cooling requirements as well as indoor temperatures is compared among different scenarios. In other words, the basic scenario is to have a 12-story concrete building with a wall and roof slab thickness of 4 in and a window-to-wall area ratio of 30%. In the following scenarios, the wall thickness is changed to 8 in, 12 in, 16 in and 20 in while other variables remain unchanged. Under each scenario, the heating and cooling requirements as well as thermal comfort parameters including air, radiant and operative temperatures are changed; therefore, by comparing these changes among the various cases, the effectiveness of concrete thermal mass can be determined given different external wall thicknesses.

4.3 Energy analysis

In terms of the energy consumption analysis, the annual heating and cooling energies as well as peak heating and cooling loads are the measurement indices used to compare the energy performance of the different models, albeit other design parameters such as thermal mass area or slab thickness are kept constant in accordance with the base case model (i.e. thermal mass area: 70% of the façade and slab thickness: 4 in). Annual heating and cooling energies are the total amount of energy (in kWh) consumed to provide heating and cooling for the building. Peak heating and cooling loads are the hourly maximum amount of heating or cooling power (in kWh/hr.), which are used to size and design the heating and cooling HVAC equipment, i.e., boilers and chillers, respectively.

4.3.1 Heating energy analysis

Figure 4.3 and Table 4.2 show the heating energy performance for different wall thicknesses in eight locations studied in this research.

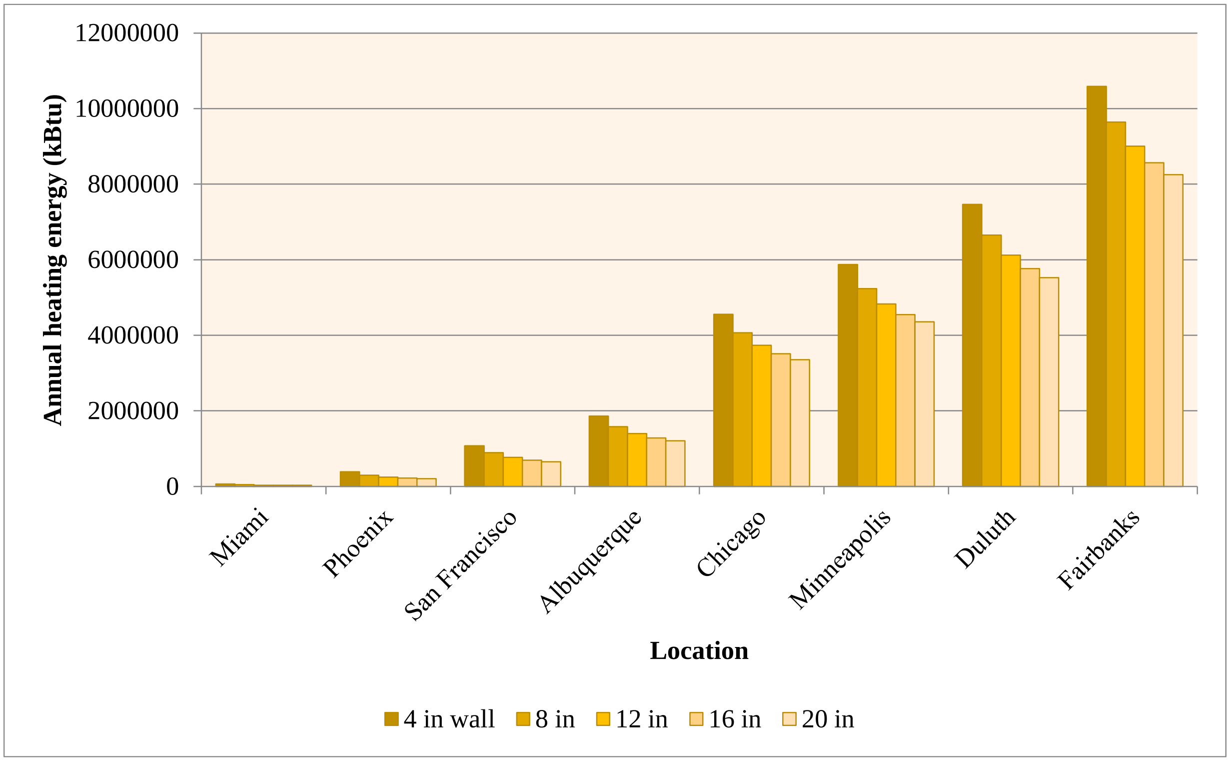


Figure 4.3 Heating energy use comparison

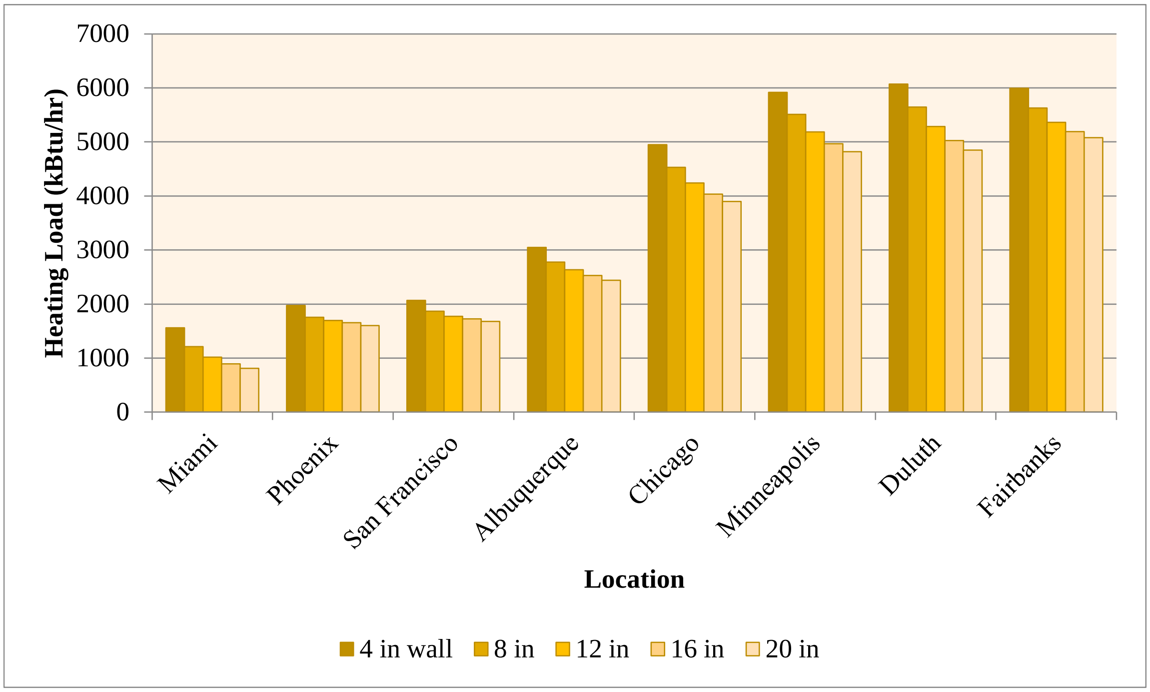


Figure 4.4 Heating load comparison

Table 4.2 Heating energy reductions

WT* / Location	Percent reduction (increase) of heating energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	34.9	22.7	12.6	6.3
Phoenix	22.9	16.2	10.7	6.8
San Francisco	17.0	13.6	9.5	6.3
Albuquerque	15.2	11.5	8.4	5.9
Chicago	10.8	8.0	6.1	4.4
Minneapolis	10.8	7.8	5.9	4.2
Duluth	10.9	7.9	5.9	4.2
Fairbanks	8.9	6.6	5.0	3.6

Table 4.3 Heating load reductions

WT / Location	Percent reduction (increase) of heating load			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	22.5	15.8	12.3	9.0
Phoenix	11.0	3.4	2.7	3.1
San Francisco	9.5	5.0	2.9	2.5
Albuquerque	9.0	5.1	4.0	3.4
Chicago	8.6	6.3	4.8	3.4
Minneapolis	6.9	5.9	4.3	2.9
Duluth	7.0	6.4	5.0	3.5
Fairbanks	6.1	4.7	3.2	2.1

*. WT: Wall Thickness

As shown, the increase of wall thickness has led to the reduction of heating energies in all cases. Figure 4.4 and Table 4.3 demonstrate the impact of wall thickness increase on peak heating loads in different climate zones. Similar to the heating energy use, the peak heating loads are also shown to reduce as the result of thermal mass increase. It is shown that the effect of wall thickness increase on heating demands follows the principle of “diminishing returns”. In other words, as the wall thickness continues to increase, the energy reductions get smaller and smaller. For instance, in Minneapolis, when the wall thickness increases form 4 in to 8 in, the annual heating energy reduces by %11; however, when it increases from 16 in to 20 in, the heating energy reduction becomes 4%, which is almost one third of the original reduction.

The reduction of both heating energies seems to be relatively higher in hot locations such as Miami or Phoenix as compared to the cold climates. The same conclusion can also be drawn for heating loads although the heating load differences among various locations are not as great. This phenomenon was also observed in preliminary design phase, where the reduction of heating demands due to thermal mass is considerably higher in hot climates than it is in cold locations. It is known that temperature swings are considerably higher in hot climates as compared to cold locations. Furthermore, unlike the cold climate zones, all hot locations in this study are also very sunny locations; therefore, exposure to the sun can improve and enhance the effect of thermal mass. These reasons can explain the higher effects of thermal mass in hot locations

4.3.2 Cooling energy analysis

Figures 4.5 and 4.6 and Tables 4.4 and 4.5 show the effects of wall thickness increase on cooling energies and cooling loads. As shown for all locations, the increase of thermal mass from 4 in to 12 in has led to the reduction of cooling loads, however, the effects of wall thickness increase of annual cooling energies are showing mixed results of both increase and decrease in different locations.

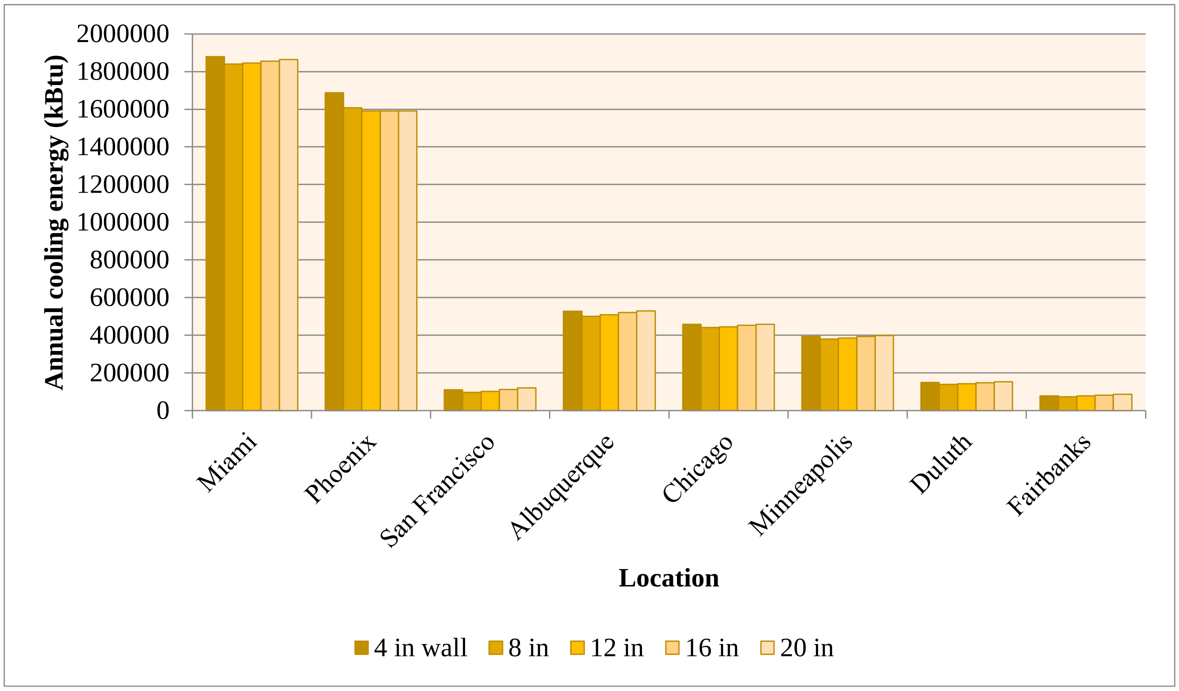


Figure 4.5 Cooling energy use comparison

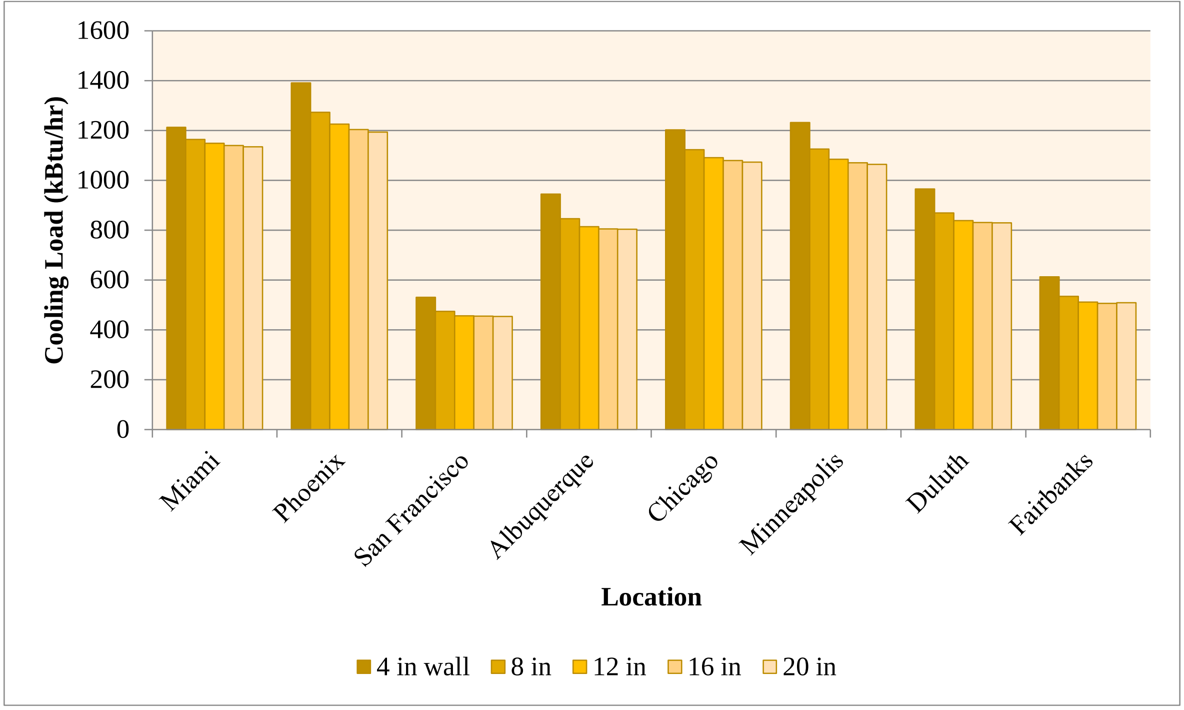


Figure 4.6 Cooling load comparison

Table 4.4 Cooling energy reductions

WT Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	2.1	(0.3)	(0.6)	(0.5)
Phoenix	4.8	1.0	0.1	(0.0)
San Francisco	12.3	(4.5)	(9.7)	(8.1)
Albuquerque	5.0	(1.6)	(2.3)	(1.8)
Chicago	3.6	(0.9)	(1.7)	(1.3)
Minneapolis	3.1	(1.3)	(1.9)	(1.4)
Duluth	6.4	(2.0)	(3.9)	(3.3)
Fairbanks	5.1	(5.2)	(6.4)	(4.7)

Table 4.5 Cooling load reductions

WT Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	3.9	1.4	0.8	0.4
Phoenix	8.5	3.7	1.7	0.9
San Francisco	10.7	3.7	0.2	0.4
Albuquerque	10.5	3.8	1.1	0.3
Chicago	6.6	2.9	1.1	0.6
Minneapolis	8.6	3.6	1.4	0.6
Duluth	9.9	3.6	1.0	0.1
Fairbanks	12.7	4.4	0.8	(0.4)

Similar to heating loads, the reduction of cooling loads due to the increase of wall thickness is higher when the wall thickness increases from 4 in to 8 in as compared to other cases. This can greatly help reduce the size of HVAC systems and therefore initial cost of mechanical systems.

The annual cooling energies decrease when the wall thickness increases from 4 in to 8 in; however, for other cases and almost for all locations, an increase of cooling energies due to the increase of wall thickness is observed, which is neither expected nor desirable. Therefore, one may consider further investigation to determine the cause of such behavior. To further study the effect of wall thickness increase beyond 8 in, two prominent locations, i.e. Miami and Fairbanks, are chosen to represent both hot and cold climates. Then, a series of simulations with different setups in terms of building type, HVAC schedule and so forth are conducted to determine what other parameters than wall thickness increase may have led to the increase of cooling energies.

4.3.2.1 Influence of building occupancy on cooling energy

Office buildings have inherently high internal gains due to occupants, equipment, and lighting. This generated heat can be stored in building mass, i.e. walls, slabs, which in turn, can increase building cooling demands. Therefore, one potential explanation for the increase of cooling energies as a result of wall thickness increase can be greater heat storage in building mass to the extent that not only it overcomes potential thermal mass benefits, but also the stored heat requires more cooling energies to dissipate. This can perfectly lead to the increase of cooling energies as a result of wall thickness increase. One way to test this explanation is to change the building type to, for instance, a residential building, where such high internal loads generally do not exist. In this study, the building type was changed to a residential building for both Miami and Fairbanks to further study the effects of wall thickness increases on building cooling performance.

Table 4.6 Office versus residential specification comparison

Specs Occupancy	Base case specification comparison		
	Density (people/ft^2)	Illuminance (fc)	Office equipment (W/ft^2)
Office	0.010311	37	1.09
Residential	0.001742	14	0.3623

For the residential buildings, the base case model specifications with respect to internal gains are significantly different than office buildings (Table 4.6), which are set by ASHRAE Standard 90.1 and International Energy Conservation Code. The people density in the residential model is less than 83% of that in the office models. The lighting level and equipment gain are also about 62% and 67% 1of those in office buildings, respectively. This clearly shows the much greater level of internal gains for office buildings.

Figure 4.7 and Table 4.7 show the effects of wall thickness increase in residential buildings in Miami and Fairbanks.

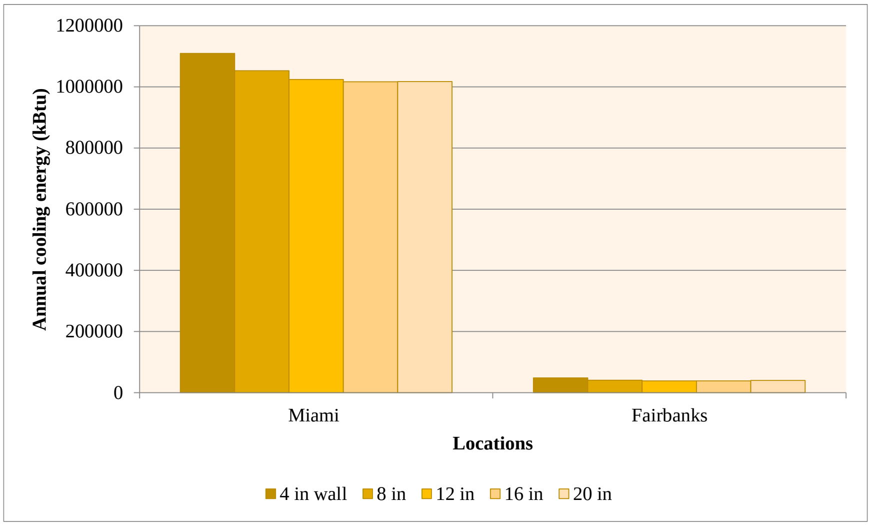


Figure 4.7 Residential cooling energies

Table 4.7 Residential cooling energy reduction

WT / Location	**Percent reduction (increase) of cooling energy**			
	4 in - 8 in	8 in - 12 in	2 in - 16 i	16 in - 20 in
Miami	5.1	2.7	0.8	(0.1)
Fairbanks	16.0	5.1	(0.6)	(2.4)

As it is shown, the change of building occupancy has been generally effective in reversing the pattern of cooling energy increase observed before. In both Miami and Fairbanks, the increase of cooling energies as a result of wall thickness increase, has changed to a reduction although 16 in and 20 in wall thicknesses still increase the energy use.

To further study such phenomenon, the cooling and ventilation schedules were changed to full time operation (as opposed to previously-set 7AM to 7 PM schedule) for 16 in and 20 in wall thickness cases. The goal was to further dissipate the stored heat from the thermal mass wall by increasing the amount of cooling and fan operated-mechanical ventilation.

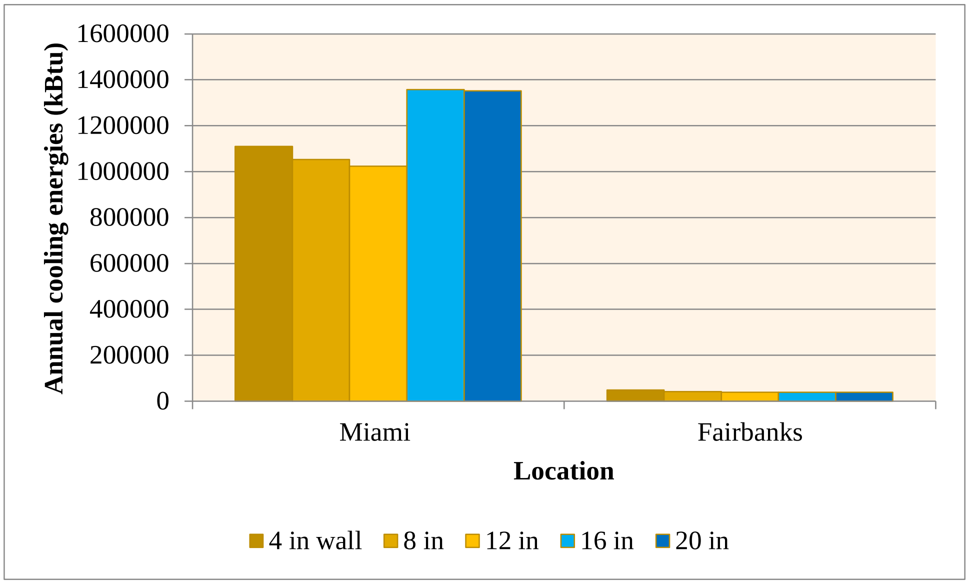


Figure 4.8 Residential cooling energies with full time cooling and ventilation

Table 4.8 Residential cooling energy reduction with full time cooling and ventilation

WT / Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	5.1	2.7	(32.6)	0.4
Fairbanks	16.0	5.1	1.6	(1.8)

Figure 4.8 and Table 4.8 show the effect of full time cooling and ventilation operation on building cooling performance. The strategy seems to have been relatively successful in Fairbanks in reducing the cooling demands or containing its increase; however, in Miami, this technique has led to a spike in energy consumption, which is not desirable.

A full time outside mechanical ventilation (cooling operates as scheduled) to dissipate the stored heat from the thermal mass walls was a further step to study this behavior.

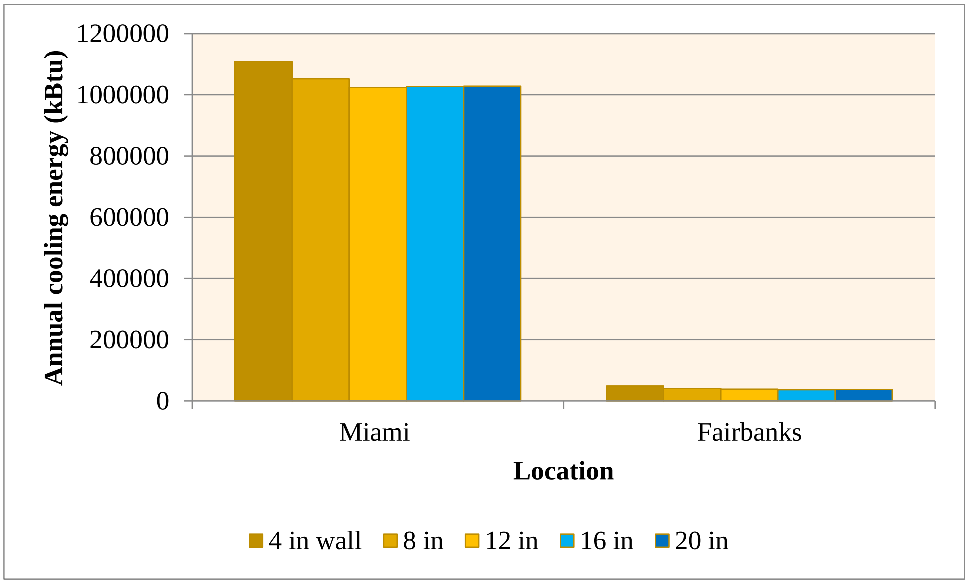


Figure 4.9 Residential cooling energies with full time ventilation

Table 4.9 Residential cooling energy reduction with full time ventilation

WT / Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	5.1	2.7	(0.3)	(0.03)
Fairbanks	16.0	5.1	5.8	(1.8)

Figure 4.9 and Table 4.9 show the effect of full time fan ventilation on cooling performance of residential buildings. As compared to both cooling and ventilation, ventilation alone seems to be more effective in improving building cooling performance and either reduce the cooling demands or considerably limit its increases.

4.3.2.2 Change of HVAC schedule

As discussed in previous section, the change of HVAC schedule, i.e. full time cooling or fan ventilation or both, can also affect the building energy performance. In Section 4.3.2.1, such effects were studied for residential buildings. In this section, they are considered for office buildings, which is in line with the scope of this research.

According to Table 4.9, fan ventilation only has shown to be more effective in improving building cooling performance. Therefore, in this section, the HVAC schedule for office models in both Miami and Fairbanks are changed to full time operation to remove the excessive stored heat in walls. These changes were applied only to 12 in, 16 in and 20 in wall thickness cases that had shown an increase of cooling energy while 4 in and 8 in wall thickness cases remained with the original HVAC schedule. Figure 4.10 and Table 4.10 show the result of full time mechanical ventilation on office models' cooling performance.

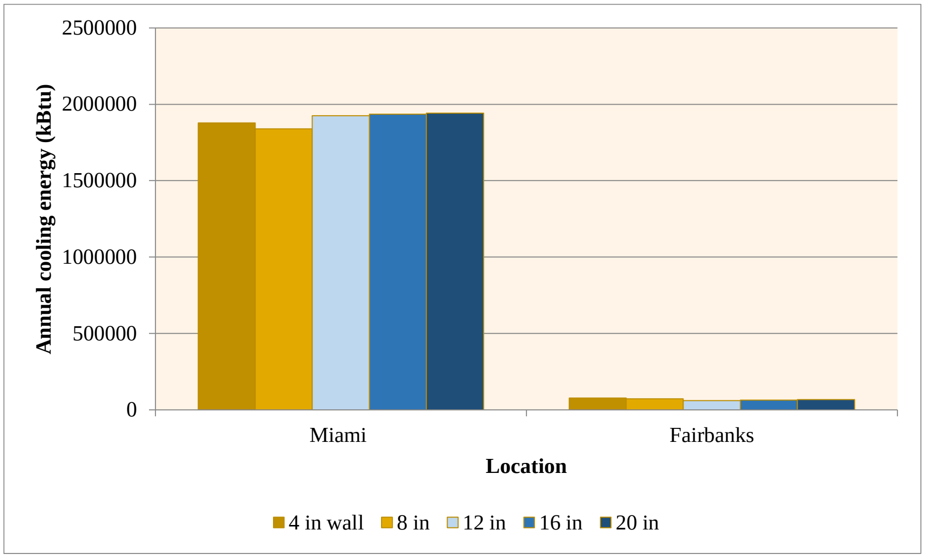


Figure 4.10 Cooling energies with full time ventilation

Table 4.10 Cooling energy reduction with full time ventilation

WT / Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	2.1	(4.7)	(0.5)	(0.4)
Fairbanks	5.1	16.0	(4.8)	(3.8)

It is shown that in Miami, change of HVAC schedule seems not to have led to the reduction of cooling energies. In Fairbanks, on the other hand, 12 in wall thickness case is showing 16% of energy reduction as compared to 8 in wall thickness case and even following increases cannot completely erase the benefits gained in this case.

Contrary to the cooling benefits observed here, one may want to evaluate the effect of full time fan operation on heating energies because it is known that greater operation of mechanical ventilation can usually lead to an increase of heating energies. Therefore, the effects of full time fan operation on heating energies for both Miami and Fairbanks for 12 in - 20 in wall thickness cases were evaluated and results are shown in Figure 4.11 and Table 4.11.

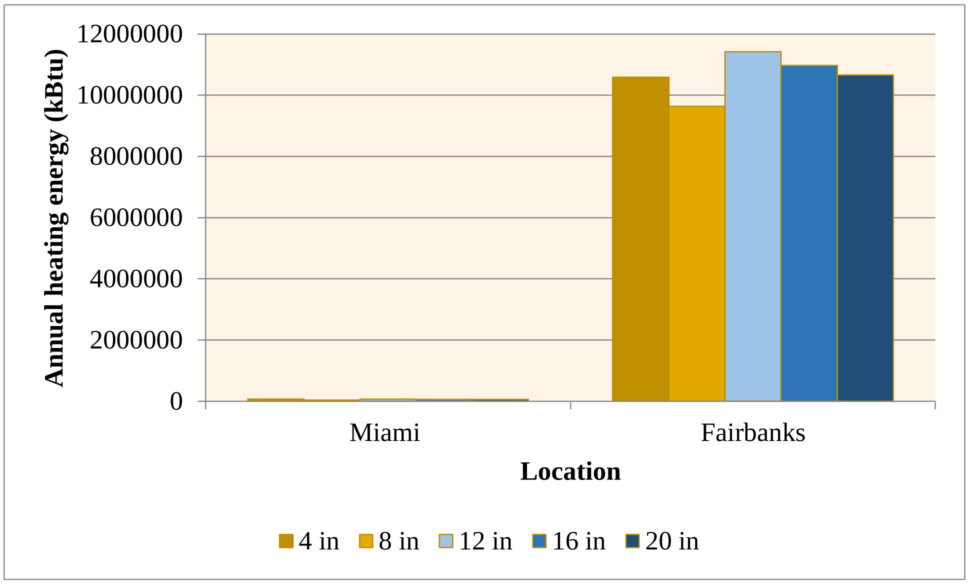


Figure 4.11 Heating energies with full time ventilation

Table 4.11 Heating energy reduction with full time ventilation

WT Location	Percent reduction (increase) of cooling energy			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	34.9	(59.2)	9.0	4.9
Fairbanks	8.9	(18.5)	3.9	2.8

Both Miami and Fairbanks have shown a spike in heating energy demands for 12 in wall thickness and even following energy savings for 16 in and 20 in cases could not compensate for the significant heating energy reductions. Although, given both cooling and heating energies, it seems full-time fan operation cannot lead to a great energy performance; it is still a viable solution to counter cooling demands increase as a result of wall thickness increase.

4.3.3 Total energy analysis

As mentioned in the previous sections, the heating energies seem to increase and the cooling energies seem to decrease as the result of thermal mass area increase; therefore, the total energies can be expected to show various behaviors of increase or reduction given the different locations. However, the large benefits of heating energy reductions seem to have countered any potential losses due to cooling demand increases. As a result, total energy consumption seem to decrease in almost all cases.

Figure 4.12 and Table 4.12 show the effect of increase in wall thickness on a building's total energy performance. As shown, except for Miami, where the cooling demands dominate the energy design and the total energy use is shown to have increases beyond 12 in thickness, for all other locations, an increase of wall thickness has resulted in the reduction of building's energy use.

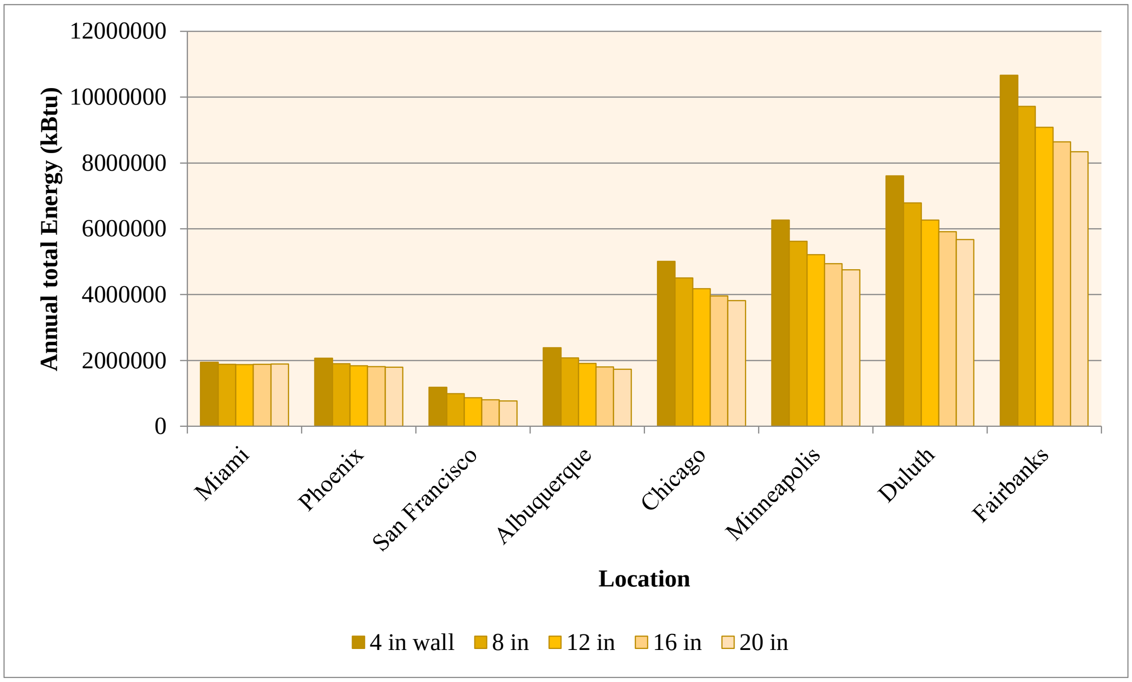


Figure 4.12 Total energy use comparison

Table 4.12 Total energy reductions

WT Location	**Percent reduction (increase) of total energy**			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	3.2	0.3	(0.4)	(0.3)
Phoenix	8.2	3.3	1.5	0.8
San Francisco	16.5	11.9	7.3	4.3
Albuquerque	12.9	8.3	5.5	3.7
Chicago	10.2	7.1	5.2	3.7
Minneapolis	10.3	7.2	5.3	3.8
Duluth	10.8	7.7	5.6	4.0
Fairbanks	8.9	6.5	4.9	3.5

Mild and cold climates are shown to have generally resulted in benefit more from the wall thickness increase as compared to hot locations, and the energy reduction from 4 in to 8 in wall thickness is significantly greater than other cases, regardless of location.

4.4 Thermal comfort

To study the effects of varied thermal mass thickness (a physical thermal property of material) on thermal comfort (a sociocultural and functional quality), the air, radiant and operative temperatures are measured as the comfort indices. To differentiate between seasonal effects on building thermal comfort performance, the first day of the summer and winter—June 21st and December 20th—are chosen to represent the summer and winter conditions. December 20th is taken in lieu of December 21st (actual first winter day) because December 21st is a Saturday (in 2013), when occupants are not present in the building. Furthermore, based on the occupancy schedule, the thermal comfort indices are measured in two categories: 1) occupied hours between 7 AM and 7 PM, and 2) unoccupied hours: before 7 AM and after 7 PM

4.4.1 Air temperature

Figures 4.13 and 4.14, and Tables 4.13 and 4.14 show the change in air temperature as a result of increase in wall thickness in summer during occupied and unoccupied hours.

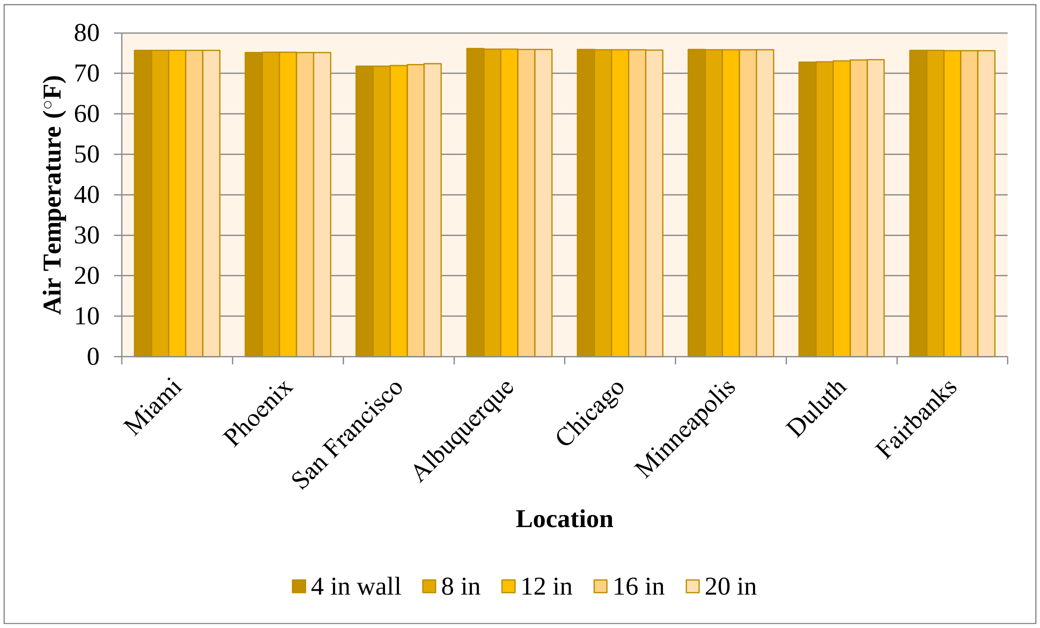


Figure 4.13 Air temperature, summer: occupied hours

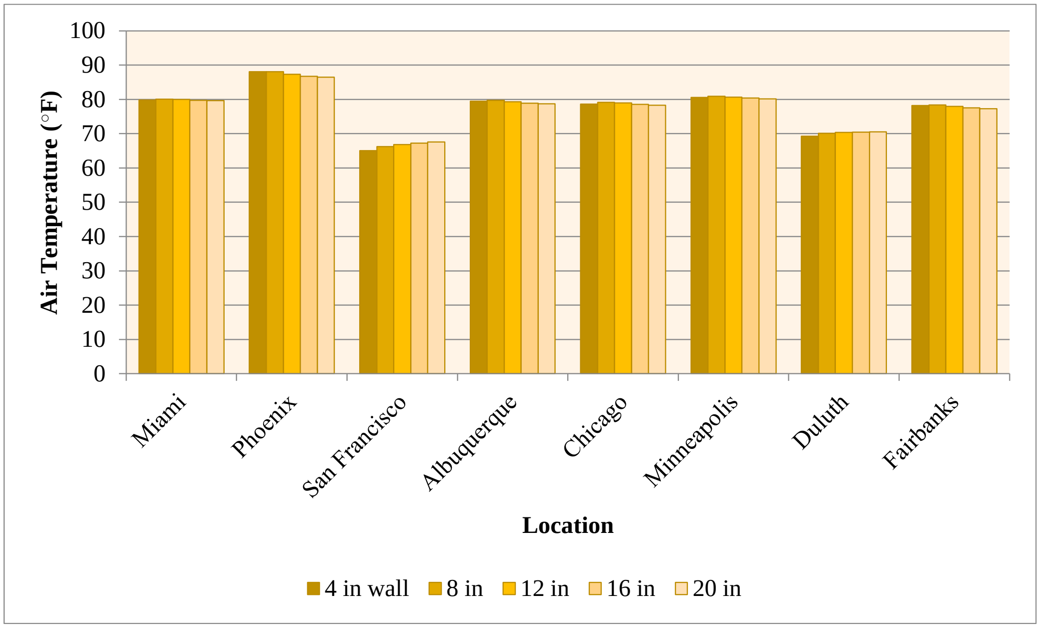


Figure 4.14 Air temperature, summer: unoccupied hours

Table 4.13 Reduction of air temperature, summer occupied hours

WT / Location	**Percent reduction (increase) of air temperature**			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.002)	0.03	0.02	0.01
Phoenix	(0.015)	0.005	0.002	0.003
San Francisco	(0.02)	(0.17)	(0.36)	(0.32)
Albuquerque	0.12	0.08	0.04	0.01
Chicago	0.04	0.05	0.03	0.02
Minneapolis	0.07	0.04	0.01	0.00
Duluth	(0.15)	(0.36)	(0.27)	(0.13)
Fairbanks	0.06	0.04	0.02	0.02

Table 4.14 Reduction of air temperature, summer unoccupied hours

WT / Location	**Percent reduction (increase) of air temperature**			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.4)	0.2	0.3	0.2
Phoenix	0.0	0.9	0.6	0.3
San Francisco	(1.8)	(0.9)	(0.7)	(0.5)
Albuquerque	(0.3)	0.6	0.5	0.2
Chicago	(0.7)	0.3	0.5	0.4
Minneapolis	(0.3)	0.3	0.3	0.3
Duluth	(1.2)	(0.3)	(0.1)	(0.1)
Fairbanks	(0.1)	0.5	0.5	0.3

Although it would be difficult to draw a consistent pattern of temperature increase or decrease, most locations show a slight decrease of air temperature as a result of wall thickness increase. The same reduction pattern is observed for the unoccupied hours; however, the magnitude of reduction is relatively greater during the unoccupied hours as compared to the occupied hours. Such behavior can be explained by the fact that the HVAC schedule closely follows the occupancy schedule. In other words, during unoccupied hours, the building's air temperature is generally controlled by the building envelope and materials as compared to daytime when the temperature is mainly modulated by the HVAC system, which results in less temperature fluctuations.

Figures 4.15 and 4.16 and Tables 4.15 and 4.16 show the air temperature change in winter during both occupied and unoccupied hours. Compared to the summer time, a considerably less change of air temperature is shown when the occupants are present in the building. In fact, except for hot climates, the air temperature relatively remains unchanged in all thermal mass thickness cases. For winter unoccupied hours, in almost all locations, an increase of air temperature is observed as a result of wall thickness increase, which is desirable because it would require less heating demands in the following day.

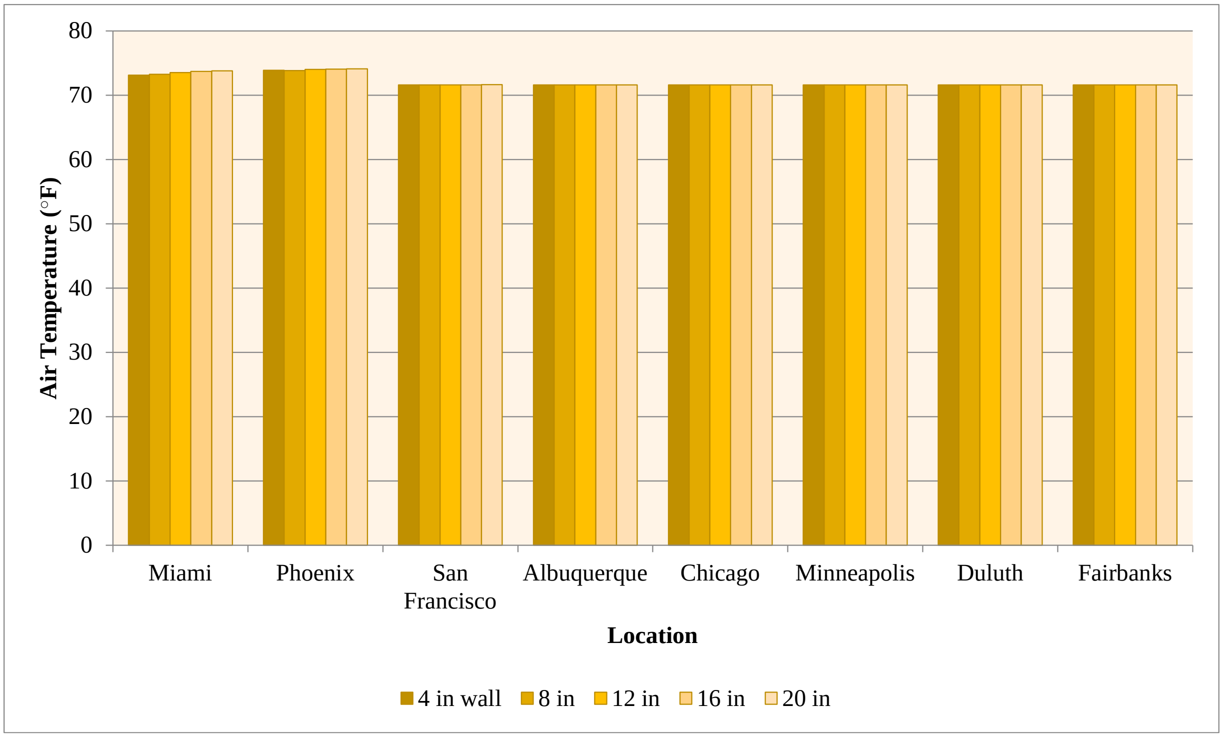


Figure 4.15 Air temperature, winter: occupied hours

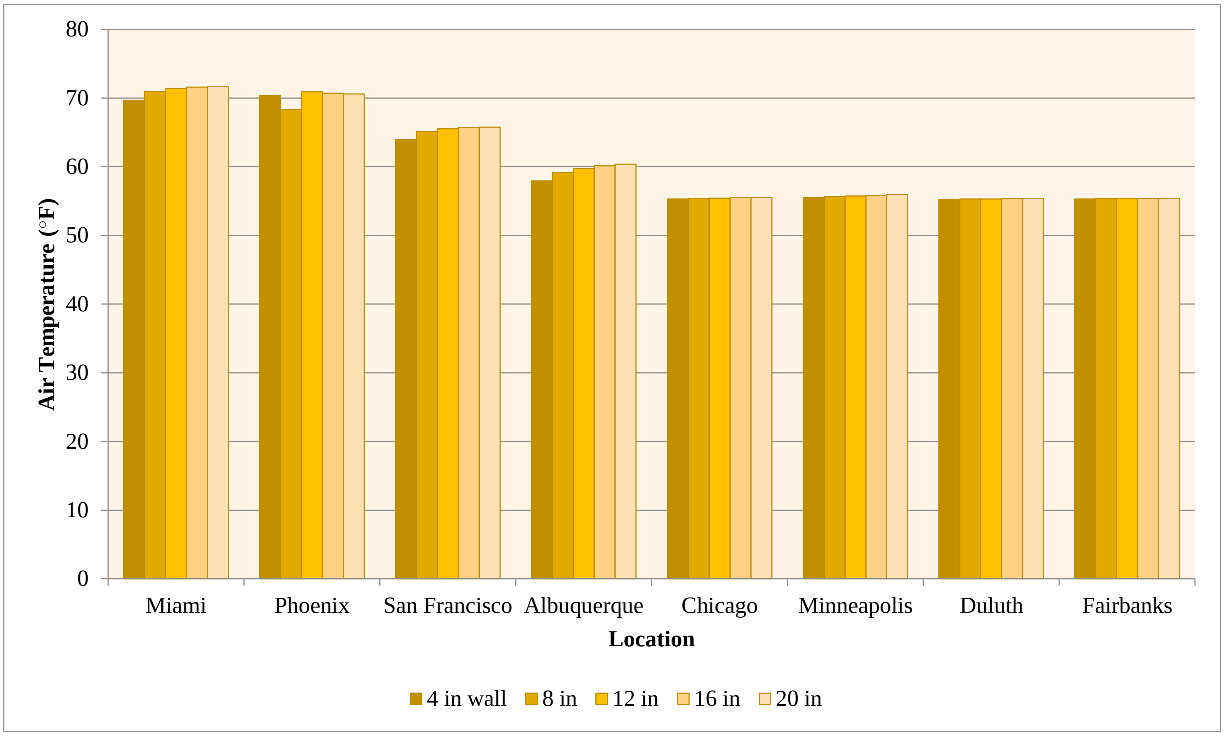


Figure 4.16 Air temperature, winter: unoccupied hours

Table 4.15 Reduction of air temperature, winter occupied hours

WT Location	Percent reduction (increase) of air temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.2)	(0.4)	(0.2)	(0.1)
Phoenix	0.1	(0.2)	(0.1)	0
San Francisco	0	0	0	0
Albuquerque	0	0	0	0
Chicago	0	0	0	0
Minneapolis	0	0	0	0
Duluth	0	0	0	0
Fairbanks	0	0	0	0

Table 4.16 Reduction of air temperature, winter unoccupied hours

WT Location	Percent reduction (increase) of air temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(1.86)	(0.63)	(0.28)	(0.15)
Phoenix	2.88	(3.76)	0.30	0.16
San Francisco	(1.81)	(0.60)	(0.24)	(0.14)
Albuquerque	(2.09)	(1.00)	(0.63)	(0.38)
Chicago	(0.12)	(0.11)	(0.10)	(0.08)
Minneapolis	(0.29)	(0.18)	(0.17)	(0.15)
Duluth	(0.05)	(0.03)	(0.03)	(0.04)
Fairbanks	(0.05)	(0.05)	(0.04)	(0.03)

4.4.2 Radiant temperature

As stated in Chapters 1 and 2, surface temperature is an important factor in determining the level of thermal comfort in a room. The stored heat in a thermal mass material can generally result in an increase of surface temperature of the material, thereby affecting the thermal comfort of the surrounding environment. Figures 4.17 and 4.18 and Tables 4.17 and 4.18 show the change of radiant temperature as a result of thermal mass thickness increase in summer during both occupied and unoccupied hours.

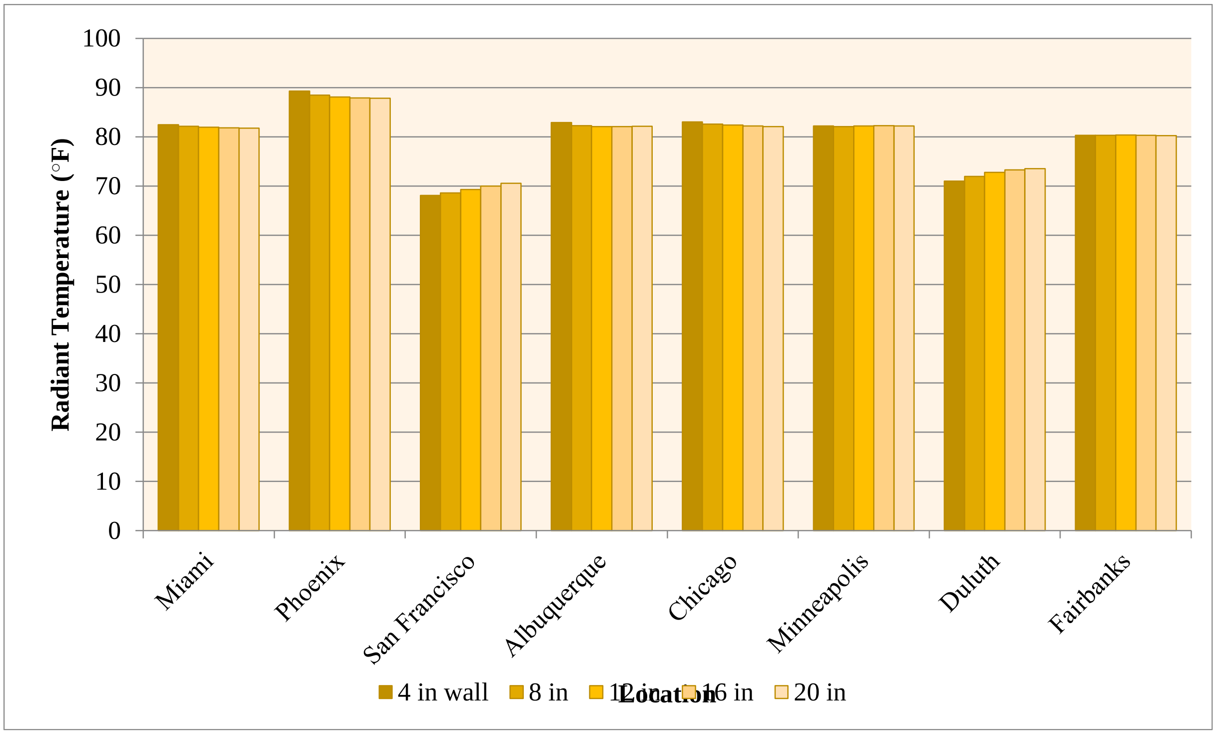


Figure 4.17 Radiant temperature, summer: occupied hours

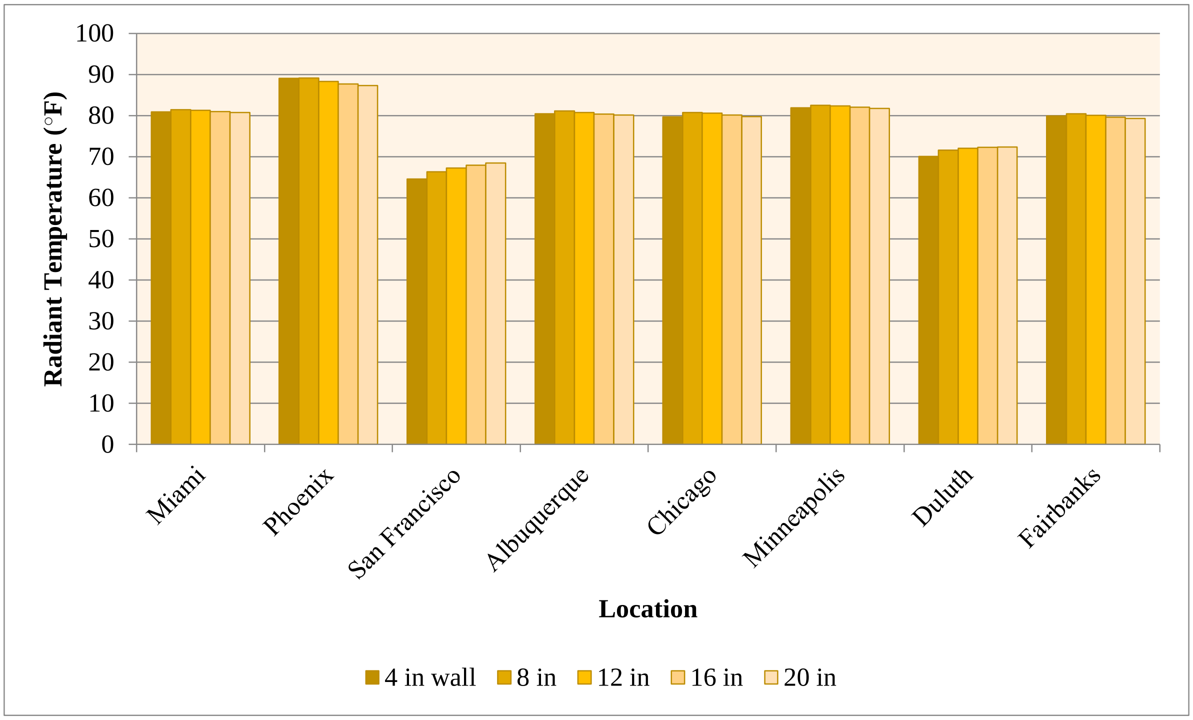


Figure 4.18 Radiant temperature, summer: unoccupied hours

Table 4.17 Reduction of radiant temperature, summer occupied hours

WT / Location	Percent reduction (increase) of radaint temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	0.4	0.2	0.2	0.1
Phoenix	0.9	0.4	0.2	0.1
San Francisco	(0.7)	(1.0)	(1.0)	(0.8)
Albuquerque	0.8	0.2	(0.0)	(0.1)
Chicago	0.5	0.2	0.2	0.2
Minneapolis	0.1	(0.1)	(0.0)	0.1
Duluth	(1.3)	(1.1)	(0.7)	(0.4)
Fairbanks	0.0	(0.1)	0.1	0.1

Table 4.18 Reduction of radiant temperature, summer unoccupied hours

WT / Location	Percent reduction (increase) of radaint temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.6)	0.2	0.3	0.2
Phoenix	(0.1)	0.9	0.7	0.4
San Francisco	(2.7)	(1.4)	(1.0)	(0.7)
Albuquerque	(0.9)	0.5	0.5	0.2
Chicago	(1.3)	0.2	0.6	0.5
Minneapolis	(0.8)	0.2	0.4	0.3
Duluth	(2.2)	(0.7)	(0.2)	(0.1)
Fairbanks	(0.7)	0.5	0.6	0.4

It is shown that the surface temperature generally decreases when the thermal mass thickness increases. Compared to the air temperature during summer, the radiant temperatures seem to show greater reductions as the result of thermal mass increase. This phenomenon can be explained by the fact that, unlike air temperature that is generally controlled by the thermostats, the radiant temperature is mainly affected by the heat generated from surrounding objects. Therefore, in office

buildings where a lot of heat is generated by internal sources, the surface temperature is expected to show more changes as compared to the air temperature. Furthermore, when the thermal mass thickness increases, the same amount of generated heat is absorbed by a larger mass, which consequently can result in lower radiant temperatures, which is observed in this analysis.
The same reduction pattern is observed for unoccupied hours; however, the magnitude of reductions is slightly greater during unoccupied hours as compared to occupied hours, which could be due to the fact that the lack of HVAC operation during unoccupied hours would let building mass solely take charge of maintaining temperature, which in turn, could result in a slightly higher surface temperature reduction.

Figures 4.19 and 4.20, and Tables 4.19 and 4.20 show the radiant temperature change in winter during both occupied and unoccupied hours. In comparison with the summer time, a considerably more change of radiant temperature is observed when the occupants are present in the building and when they are not. For both occupied and unoccupied hours, the increase of wall thickness has led to an increase of radiant temperature. In fact, such increase is closely correlated with the heating demands reduction discussed in section 4.3.1, which such reduction can relatively be attributed to the increase of radiant temperature. It was also observed that the heating reduction was greater when the wall thickness increased from 4 in to 8 in as compared to other cases. Interestingly, such pattern is also shown for the radiant temperature, where the increase of temperature is higher for 4 in-8 in thickness increase case compared to other thickness increases.

In cold climates, the radiant temperatures show a greater increase as a result of an increase in thermal mass thickness than that in hot locations. This can be explained by the effect of greater HVAC operation in cold climates during the day in winter. Although the radiant temperature is mainly affected by the surrounding objects, the impact of heat convection due to the HVAC operation cannot be neglected. Since the production of hot air is greater in cold climates during the day in winter, greater amount of heat can be stored in the thermal mass. The more thermal mass, the more heat is absorbed by the thermal mass, and therefore, the surface temperature increases when the thermal mass areas increase.

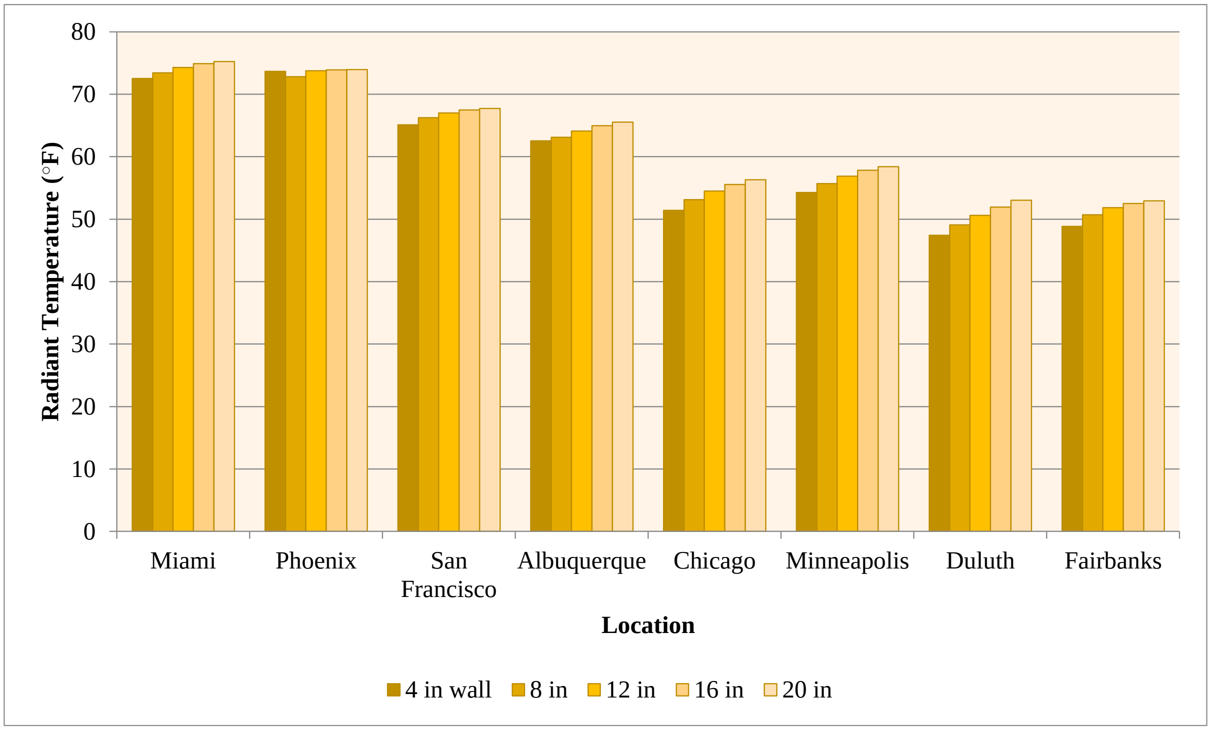


Figure 4.19 Radiant temperature, winter: occupied hours

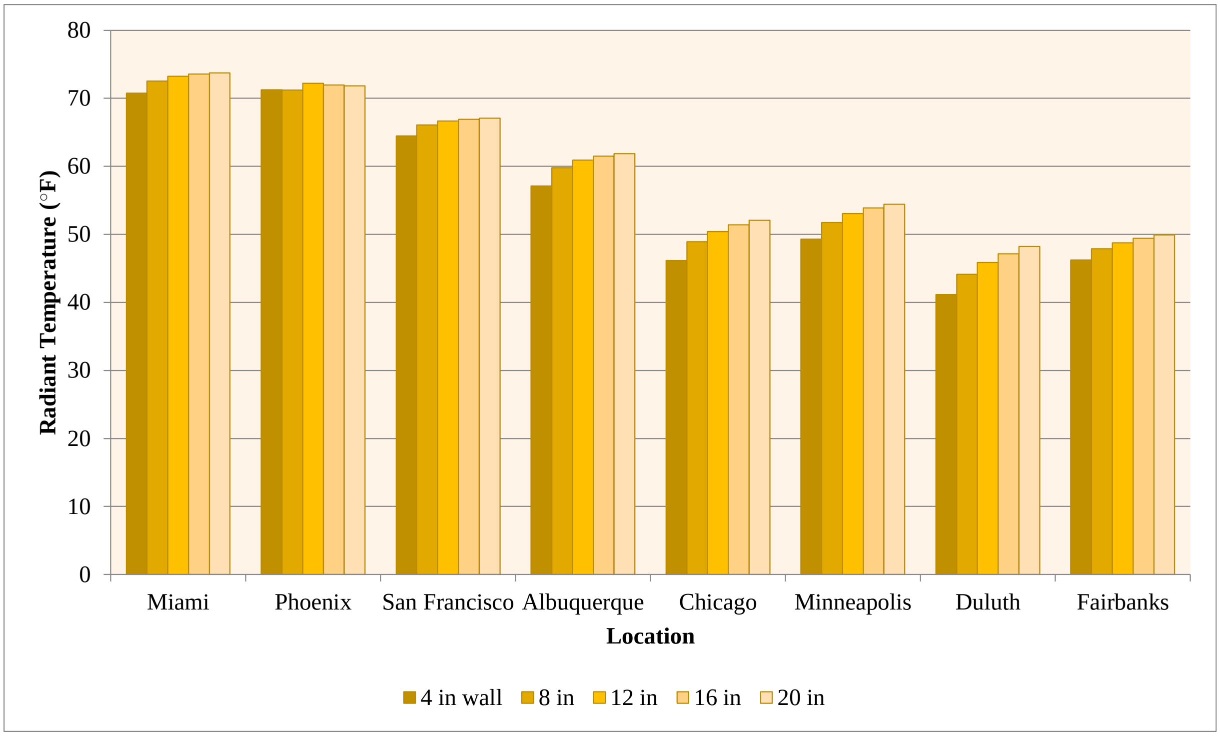


Figure 4.20 Radiant temperature, winter: unoccupied hours

Table 4.19 Reduction of radiant temperature, winter occupied hours

WT Location	Percent reduction (increase) of radaint temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(1.3)	(1.2)	(0.8)	(0.4)
Phoenix	1.2	(1.3)	(0.2)	(0.1)
San Francisco	(1.7)	(1.2)	(0.7)	(0.4)
Albuquerque	(0.9)	(1.6)	(1.3)	(0.9)
Chicago	(3.3)	(2.6)	(1.9)	(1.3)
Minneapolis	(2.6)	(2.2)	(1.6)	(1.0)
Duluth	(3.6)	(3.1)	(2.6)	(2.0)
Fairbanks	(3.8)	(2.2)	(1.3)	(0.8)

Table 4.20 Reduction of radiant temperature, winter unoccupied hours

WT Location	Percent reduction (increase) of radaint temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(2.5)	(1.0)	(0.4)	(0.2)
Phoenix	0.1	(1.4)	0.3	0.2
San Francisco	(2.5)	(0.9)	(0.4)	(0.2)
Albuquerque	(4.7)	(1.9)	(1.0)	(0.6)
Chicago	(5.9)	(3.1)	(2.0)	(1.4)
Minneapolis	(4.9)	(2.6)	(1.6)	(1.0)
Duluth	(7.2)	(3.9)	(2.9)	(2.2)
Fairbanks	(3.5)	(1.8)	(1.3)	(1.0)

4.4.3 Operative temperature

As indicted in Chapters 1 and 2, the operative temperature is an average of both air and surface radiant temperatures, both of which are affected by the thermal mass property of concrete. Therefore, operative temperature is a proper indicator of overall thermal level of a room with respect to temperature. Figures 4.21 and 4.22 and Tables 4.21 and 4.22 show the change of operative temperature as a result of wall thickness increase in summer during occupied and unoccupied hours.

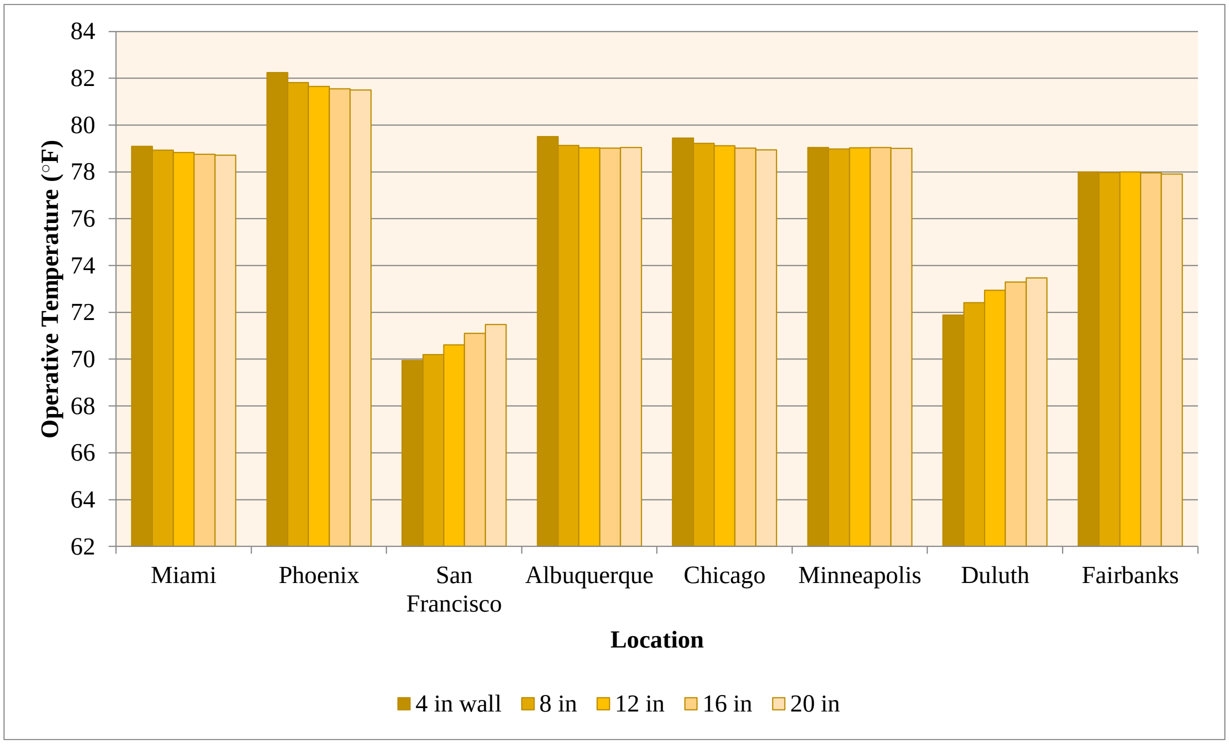


Figure 4.21 Operative temperature, summer: occupied hours

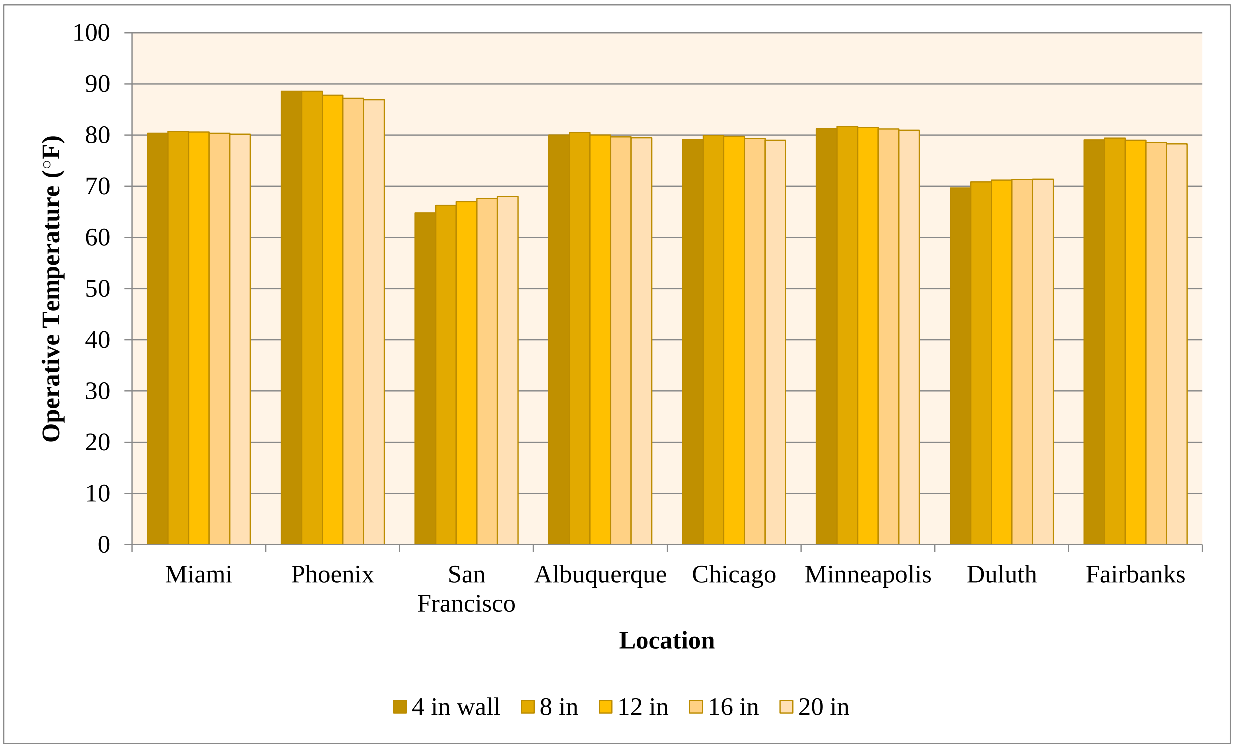


Figure 4.22 Operative temperature, summer: unoccupied hours

Table 4.21 Reduction of operative temperature, summer occupied hours

WT / Location	Percent reduction (increase) of operative temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	0.2	0.1	0.1	0.1
Phoenix	0.5	0.2	0.1	0.1
San Francisco	(0.4)	(0.6)	(0.7)	(0.5)
Albuqurque	0.5	0.1	0.0	0.0
Chicago	0.3	0.1	0.1	0.1
Minneapolis	0.1	(0.1)	0	0
Duluth	(0.7)	(0.7)	(0.5)	(0.3)
Fairbanks	0	0	0	0.1

Table 4.22 Reduction of operative temperature, summer unoccupied hours

WT / Location	Percent reduction (increase) of operative temperature			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.5)	0.2	0.3	0.2
Phoenix	(0.0)	0.9	0.7	0.4
San Francisco	(2.2)	(1.2)	(0.8)	(0.6)
Albuqurque	(0.6)	0.6	0.5	0.2
Chicago	(1.0)	0.2	0.5	0.4
Minneapolis	(0.5)	0.2	0.4	0.3
Duluth	(1.7)	(0.5)	(0.2)	(0.1)
Fairbanks	(0.4)	0.5	0.5	0.3

It is shown that the operative temperature generally decreases when the thermal mass thickness increases except for Duluth and San Francisco. The pattern of operative temperature reduction is more similar to the reduction pattern observed for the radiant temperature than the air temperature, which highlights the importance of surface temperature effects on thermal comfort.

Figures 4.23 and 4.24 and Tables 4.23 and 4.24 show the operative temperature changes in winter during both occupied and unoccupied hours. Compared to summer time, a considerably more change of operative temperature is observed when the occupants are present in the building than when they are not. In cold climates, the operative temperature shows a greater increase as a result of an increase in thermal mass thickness, especially during occupied hours, than that in hot locations. This can be explained by the effect of greater HVAC operation in cold climates during the day in winter. In other words, although the radiant temperature is mainly affected by the surrounding objects, the impact of heat convection due to the HVAC operation cannot be neglected. Since the production of hot air is greater in cold climates during the day in winter compared to hot locations simply because of colder ambient conditions, greater amount of heat can be stored in the thermal mass. The more thermal mass, the more heat is absorbed by the thermal mass, and therefore, the surface temperature increases when the thermal mass areas increase.

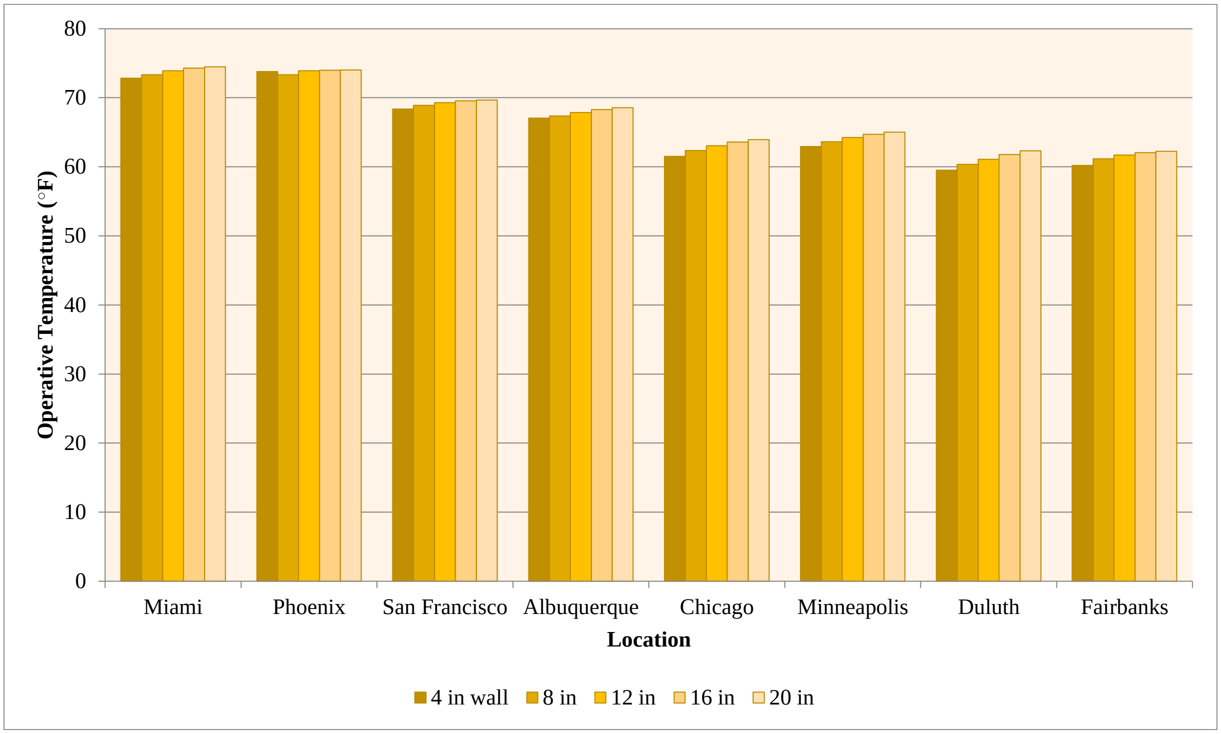


Figure 4.23 Operative temperature, winter: occupied hours

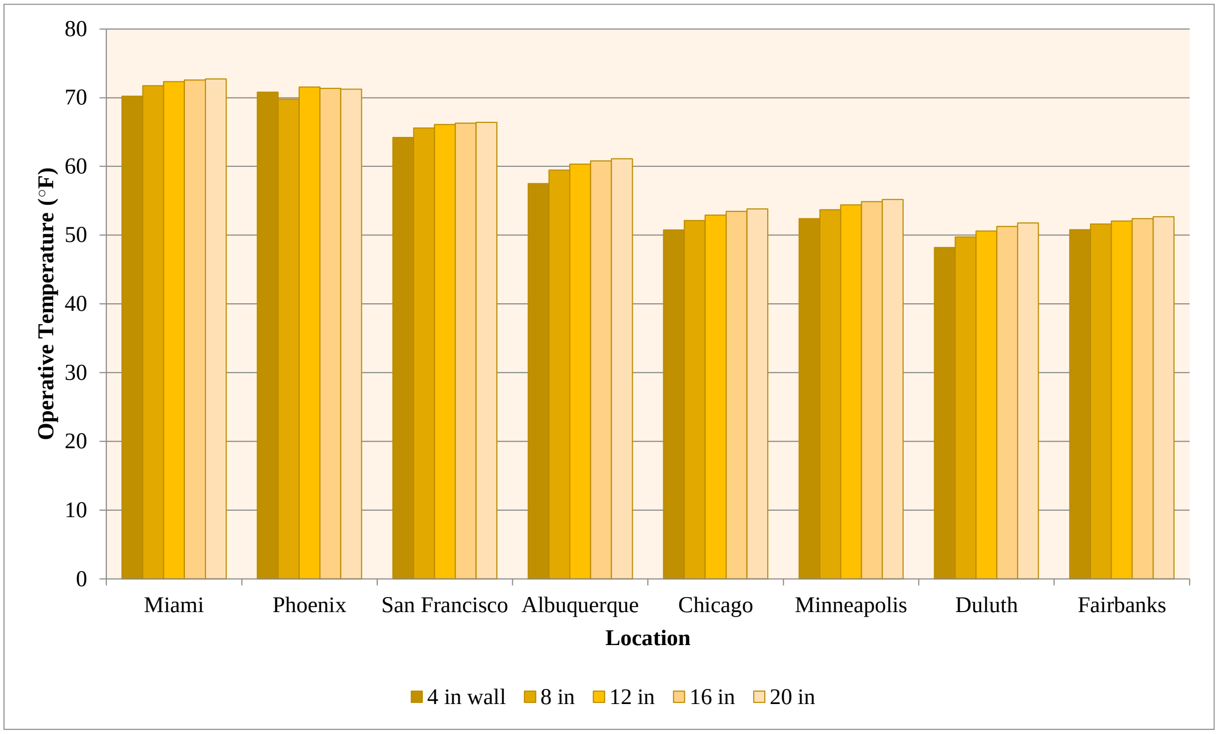


Figure 4.24 Operative temperature, winter: unoccupied hours

Table 4.23 Reduction of operative temperature, winter occupied hours

WT Location	**Percent reduction (increase) of operative temperature**			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(0.7)	(0.8)	(0.5)	(0.3)
Phoenix	0.6	(0.8)	(0.1)	(0.1)
San Francisco	(0.8)	(0.6)	(0.3)	(0.2)
Albuquerque	(0.4)	(0.8)	(0.6)	(0.4)
Chicago	(1.4)	(1.1)	(0.8)	(0.6)
Minneapolis	(1.1)	(1.0)	(0.7)	(0.5)
Duluth	(1.4)	(1.3)	(1.1)	(0.9)
Fairbanks	(1.6)	(0.9)	(0.6)	(0.3)

Table 4.24 Reduction of operative temperature, winter unoccupied hours

WT Location	**Percent reduction (increase) of operative temperature**			
	4 in - 8 in	8 in - 12 in	12 in - 16 in	16 in - 20 in
Miami	(2.2)	(0.8)	(0.4)	(0.2)
Phoenix	1.5	(2.6)	0.3	0.2
San Francisco	(2.2)	(0.8)	(0.3)	(0.2)
Albuquerque	(3.4)	(1.4)	(0.8)	(0.5)
Chicago	(2.8)	(1.5)	(1.0)	(0.7)
Minneapolis	(2)	0	(1)	(1)
Duluth	(3.1)	0	0	(1.04)
Fairbanks	(1.6)	(0.9)	(0.7)	(0.5)

4.5 Final remarks

In this chapter the increase of wall thickness—from 4 in to 20 in—on building energy use and thermal comfort has been studied. The results have shown that incremental thermal mass area can be very effective in changing the building's energy and thermal comfort performance.

In terms of building energy use, the increase of thermal mass area is noted to consistently reduce the heating energy use for all cases, regardless of location. The heating loads are also shown to decrease as a result of wall thickness increase, which is beneficial in downsizing the HVAC heating equipment such as boilers. The cooling energies, on the other hand, seem to generally increase when the thermal mass thickness increases with an exception for the increase of wall thickness from 4 in to 8 in where the cooling energies decreases ranging from 2% in Miami to 12% in San Francisco. Change of building occupancy from office to residential, and consequently having lower internal gains, seems to have been relatively beneficial to reverse the pattern of cooling increase. Furthermore, in residential occupancy, the changes of HVAC cooling and fan schedule for full time, do not help with the cooling energy increase; however, the use of full time mechanical ventilation, i.e. fan operation alone, can help reduce the building cooling demands. Even for the original office case models, while the full time fan operation cannot completely result in cooling energy reductions, the heating energy use increases due to further fan operation. The cooling loads, on the other hand, seem to reduce as a result of thermal mass increase, which helps reduce the size of HVAC cooling equipment, e.g., chillers. The total energy use of the building is found to generally decrease as a result of wall thickness increase, which is a beneficial quality of thermal mass.

Regarding thermal comfort parameters, the summer air temperature seems to have shown a mixed pattern of increase and decrease in different locations. In the winter, the air temperature has shown a consistent pattern of increase, which is beneficial with respect to heating energies. Similarly, the summer radiant and operative temperatures have not shown a consistent pattern of either increase or decrease; however, when the wall thickness is increased from 4 in to 8 in, especially during unoccupied hours, the both radiant and operative temperatures have consistently increased in all locations. During winter, the radiant and operative temperatures are noted to have increased as a result of wall thickness increase to which the reduction of heating energies could be attributed as a cause.

The next chapter focuses on the effectiveness of thermal mass area of the perimeter wall thickness on building energy and thermal comfort performance.

4.6 Summary

This chapter reviews the effect of the variation in thickness of perimeter wall on building energy and thermal comfort performance. The increase of wall thickness leads to a general reduction of the heating energies and heating loads, regardless of location. The thermal mass increases show an effective reduction of the cooling loads in all cases; however, the same conclusion cannot be made for annual cooling energy use. The higher internal loads in office buildings and potentially excessive stored heat in the thicker walls has been investigated as a possible cause of such increase of cooling demands. The results have shown that lessening the effects of internal gains through providing more cooling or ventilation or even change of building occupancy to residential can have limited effects in reversing the pattern of cooling energy increase. Summer time air, radiant, and operative temperatures have shown a mixed pattern of increase and decrease as a result of wall thickness increase. During winter, the increase of wall thickness is shown to have increased all air, surface and operative temperatures, which is beneficial in reducing the building's heating demands.

Chapter 5

PERIMETER WALL SURFACE AREA and BUILDING PERFORMANCE

As indicated in Chapter 1, primary thermal mass elements are the ones that are directly exposed to sun light and solar heat gain, mainly located on the perimeter of the building, as opposed to interior secondary thermal mass elements. In Chapter 4, the thickness of the perimeter thermal mass and its impact on building energy and thermal comfort indices were discussed. In this chapter, the other aspect of primary thermal mass—the distribution of thermal mass on the building façade, or the area of exterior thermal mass—is explained.

In this study, the area of thermal mass distribution varies from 20% to 40%, 55%, 70% (base case model), and 80%. The energy simulation for each case is conducted and the energy use and thermal comfort results are compared among different cases.

5.1 Energy analysis

In terms of the energy consumption analysis, the annual heating and cooling energies as well as peak heating and cooling loads are the measurement indices used to compare the energy performance of the different models, albeit keeping other design parameters such as wall or slab thickness constant conforming with the base case model.

5.1.1 Heating energy analysis

Figure 5.1 and Table 5.1 show the heating energy performance for different thermal mass area percentages with respect to the wall area in eight locations studied in this research. It should be noted that TMA stands for Thermal Mass Area in all tables.

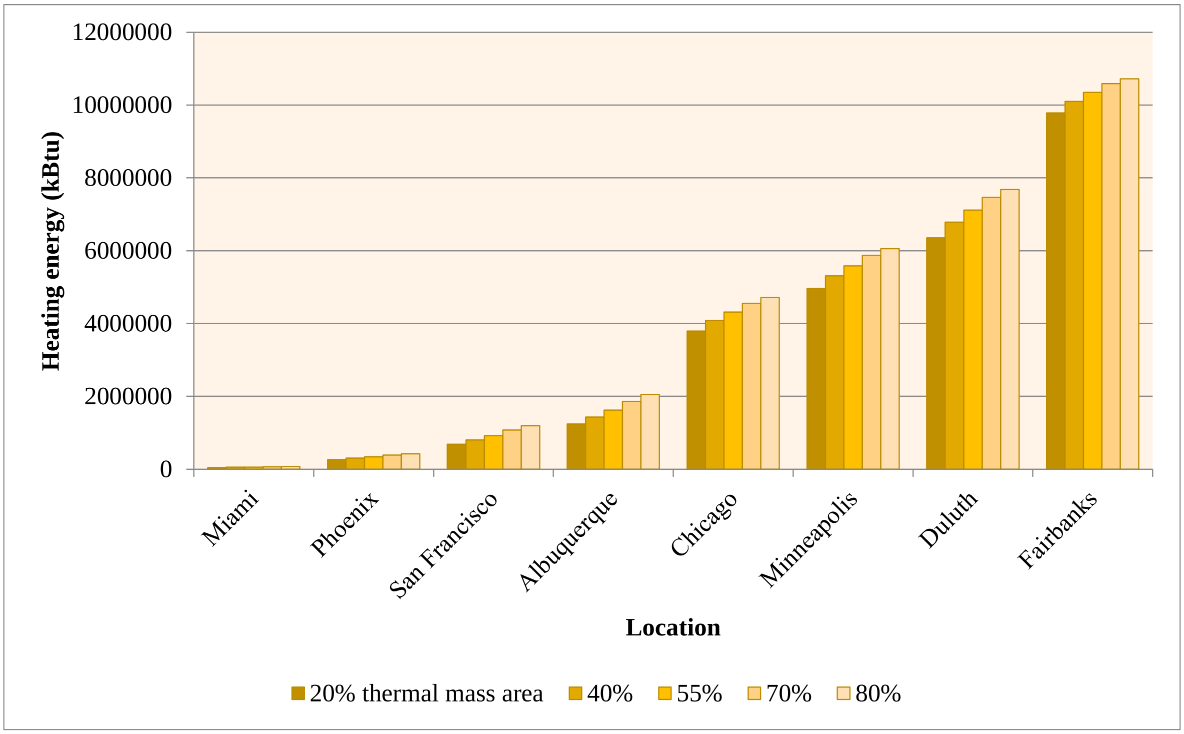


Figure 5.1 Heating energy use comparison

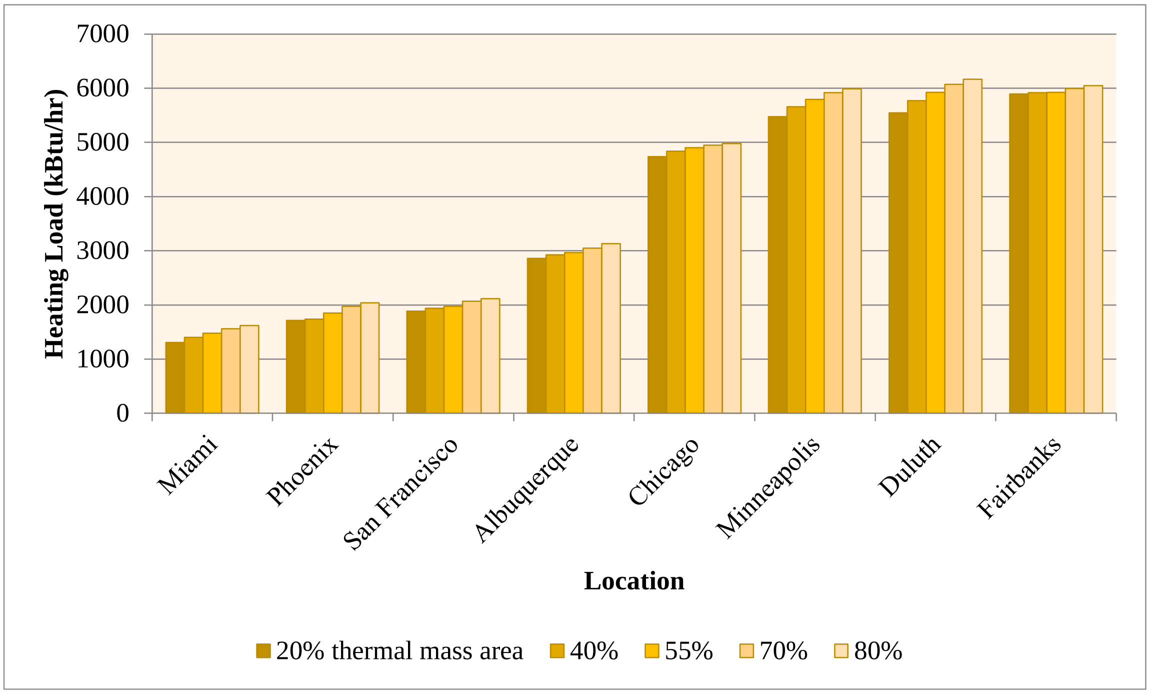


Figure 5.2 Heating load comparison

Table 5.1 Heating energy reductions (increase)

% TMA*	Percent reduction (increase) of heating energy			
Location	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	(12.1)	(11.2)	(14.0)	(10.4)
Phoenix	(13.3)	(11.9)	(13.9)	(10.0)
San Francisco	(17.3)	(14.6)	(16.6)	(11.2)
Albuquerque	(15.7)	(13.3)	(14.7)	(10.0)
Chicago	(7.6)	(5.7)	(5.7)	(3.4)
Minneapolis	(7.0)	(5.2)	(5.1)	(3.1)
Duluth	(6.7)	(4.9)	(4.9)	(2.9)
Fairbanks	(3.3)	(2.4)	(2.3)	(1.3)

Table 5.2 Heating load reductions (increase)

% TMA	Percent reduction (increase) of heating load			
Location	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	(7.0)	(5.5)	(5.7)	(3.6)
Phoenix	(1.4)	(6.3)	(6.8)	(3.2)
San Francisco	(2.6)	(1.8)	(4.8)	(2.3)
Albuquerque	(2.2)	(1.4)	(2.8)	(2.8)
Chicago	(2.1)	(1.3)	(1.0)	(0.5)
Minneapolis	(3.4)	(2.3)	(2.2)	(1.2)
Duluth	(4.0)	(2.7)	(2.5)	(1.5)
Fairbanks	(0.4)	(0.1)	(1.1)	(0.9)

*. TMA = Thermal Mass Area

As shown, the increase of thermal mass distribution on building façade has led to an increase of heating energies in all cases. Figure 5.2 and Table 5.2 demonstrate the impact of exterior thermal mass on peak heating loads in different climate zones. Similar to the heating energy use, the peak heating loads are also shown to increase as a result of thermal mass increase. The reduction of both heating energies seems to be relatively higher in mild climates such as San Francisco or Albuquerque, or hot locations such as Miami as compared to the cold climates. The same conclusion can also be drawn for heating loads although the heating load differences among various locations are not as great.

One explanation for the increase of heating demands as the result of wall area increase would be the fact that, as the area of thermal mass increases, the area of fenestrations decreases. In other words, the area of exterior openings—the main components of building envelope to absorb solar heat—decreases when the area of opaque thermal mass increases. It seems even a greater thermal mass distribution on the façade could not compensate for the reduced solar heat gain due to the less fenestration areas. This highlights the importance of solar heat gain in heating design.

Although the reduction of solar heat gain due to the increase of thermal mass is a plausible explanation for the observed thermal mass performance, the effect of thermal mass is generally expected to reduce the building energy use, not increase it. Therefore, a further investigation was carried out to study this phenomenon. Section 5.1.4 will later explain the behavior of thermal mass to determine to what extent the distribution of thermal mass can affect the building heating performance.

5.1.2 Cooling energy analysis

Figures 5.3 and 5.4 and Tables 5.3 and 5.4 show the effects of thermal mass area increase on cooling energies and cooling loads. As shown for all locations, the increase of thermal mass from 20% to 80% has led to the reduction of cooling demands.

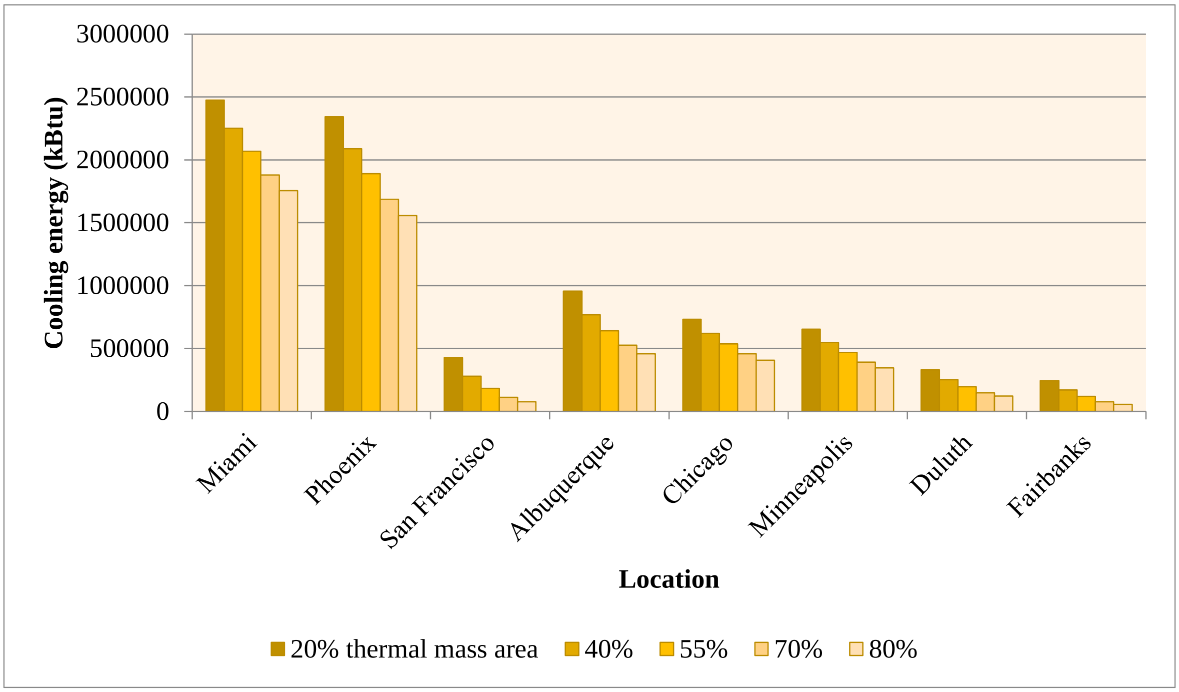


Figure 5.3 Cooling energy use comparison

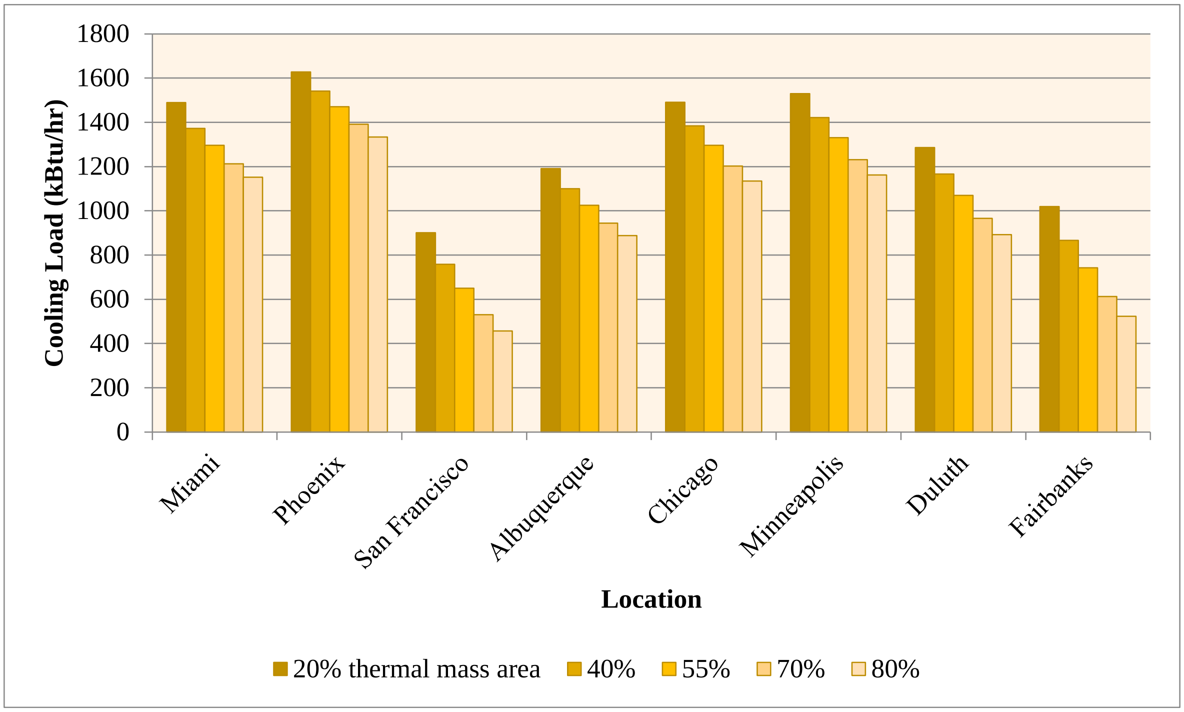


Figure 5.4 Cooling load comparison

Table 5.3 Cooling energy reductions

% TMA / Location	Percent reduction (increase) of cooling energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	9.1	8.1	9.2	6.6
Phoenix	10.9	9.5	10.6	7.8
San Francisco	34.6	34.0	39.7	31.5
Albuquerque	19.6	16.6	17.9	13.0
Chicago	15.3	13.3	15.0	11.1
Minneapolis	16.4	14.4	16.1	11.9
Duluth	24.0	21.8	24.4	18.1
Fairbanks	30.8	29.4	35.2	28.1

Table 5.4 Cooling load reductions

% TMA / Location	Percent reduction (increase) of cooling energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	7.9	5.6	6.5	5.0
Phoenix	5.3	4.6	5.4	4.1
San Francisco	15.9	14.1	18.5	13.7
Albuquerque	7.7	6.8	7.8	6.0
Chicago	7.1	6.3	7.3	5.6
Minneapolis	7.0	6.4	7.4	5.6
Duluth	9.3	8.3	9.7	7.5
Fairbanks	14.9	14.3	17.6	14.6

To explain such behavior, one may want to consider both the effect of concrete thermal mass to store heat and delay the heat transfer through the building envelope, and the reduced area of fenestrations due to the increase thermal mass area. As indicated in Chapter 2, one of the main advantages of thermal mass is to preserve heat, which in turn, can lead to delaying the heat transfer through the material. It also reduces the magnitude of the heat passing through the building envelope, which in turn, moderates the indoor temperature variations. All these advantages from thermal mass can lead to reducing the cooling energies and cooling loads inside the building.

As discussed before, when the thermal mass area increases, the heating energies increase as well because there will be less fenestrations and therefore less solar heat gain. The same reason could explain the reduction of cooling demands due to the increase of thermal mass area. The fewer openings could result in less solar heat gain, which in turn, can result in less demands for the cooling systems; therefore, the cooling energies decrease when the thermal mass area increases.

5.1.3 Total energy analysis

As mentioned in the previous sections, the heating energies seem to increase and the cooling energies seem to decrease as the result of thermal mass area increase; therefore, the total energies can be expected to show various behaviors of increase or reduction given the different locations.

Figure 5.5 and Table 5.5 show the effect of increase in thermal mass area on a building’s total energy performance. As shown, in the location s such as Miami or Phoenix, where the cooling demands dominate the energy design, an increase of thermal mass area has resulted in the reduction of building’s energy use. However, in cold climate, where the heating demands govern the energy design, the pattern of total energy change resulting from thermal mass increase is similar to that of the heating energies. In other words, as the distribution of thermal mass on the building façade increases, the total energy use increases as well.

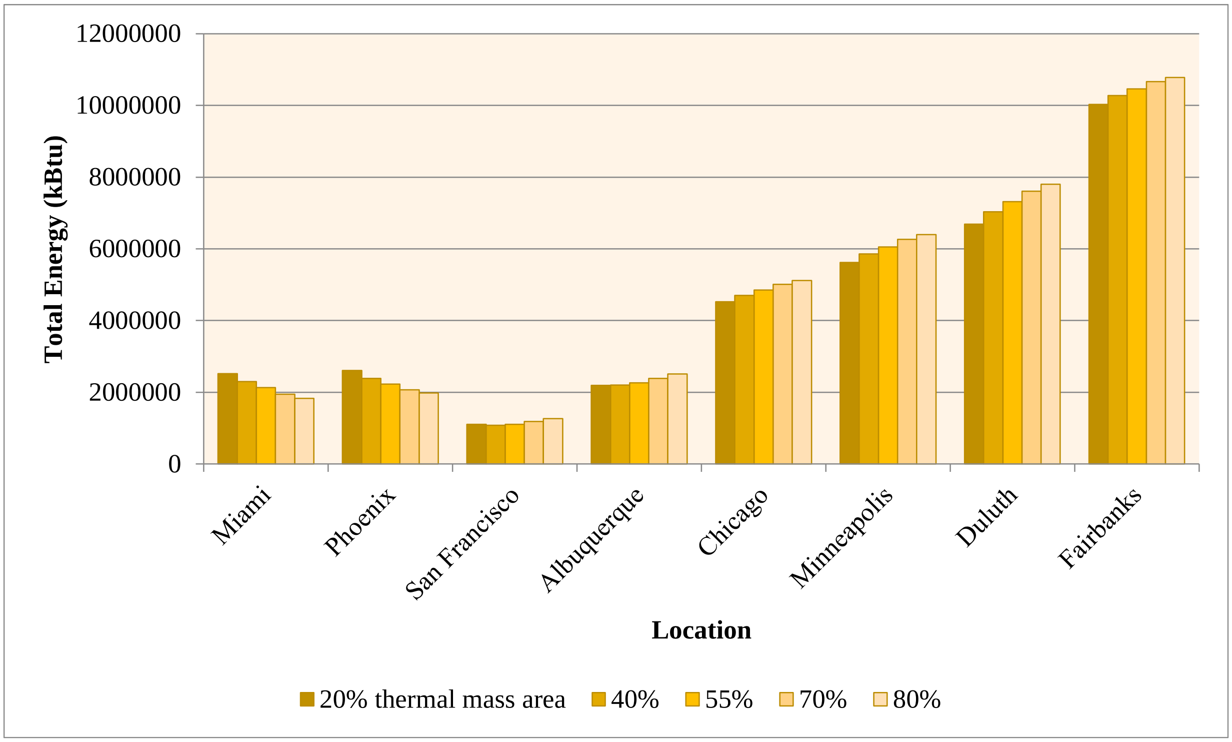


Figure 5.5 Total energy use comparison

Table 5.5 Total energy reductions

% TMA Location	Percent reduction (increase) of total energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	8.7	7.6	8.5	6.0
Phoenix	8.4	6.8	6.9	4.4
San Francisco	2.6	(2.1)	(7.2)	(7.2)
Albuquerque	(0.3)	(2.8)	(5.5)	(5.0)
Chicago	(3.9)	(3.2)	(3.4)	(2.1)
Minneapolis	(4.3)	(3.4)	(3.4)	(2.2)
Duluth	(5.2)	(4.0)	(4.1)	(2.5)
Fairbanks	(2.5)	(1.9)	(1.9)	(1.1)

5.1.4 Thermal mass area and different wall thicknesses

In Chapter 4, five wall thickness cases including 4 in, 8 in, 12 in, 16 in, and 20 in wall thicknesses were selected to study the effect of thermal mass thickness of the perimeter wall on building energy and comfort performance, where the base case model—with 70% primary thermal mass has a thickness of 4 in. As described in Section 5.1.1, the increase of thermal mass area can lead to an increase of heating energies, which is not desirable. To further explore the effect of exterior thermal mass distribution on building energy use, different thermal mass area cases with different perimeter wall thicknesses were studied for Chicago, and the effects of different areas and thicknesses on building energy performance were analyzed.

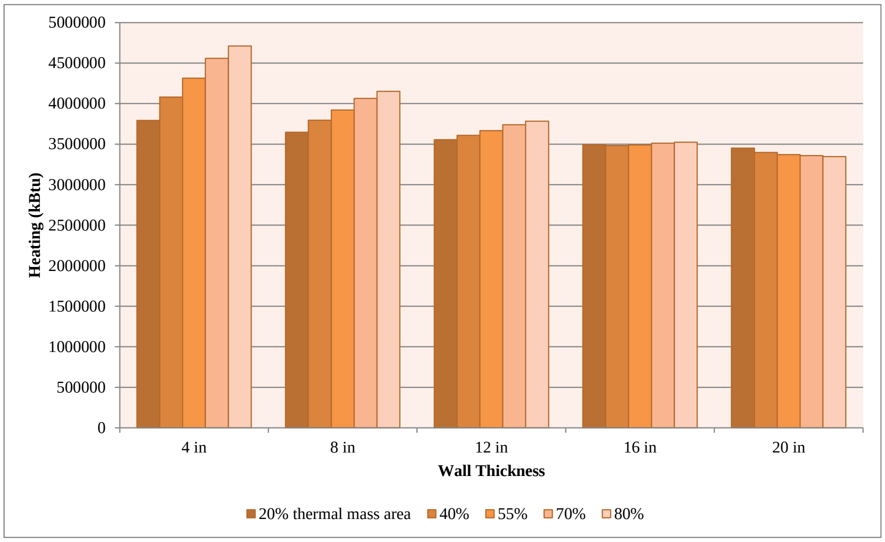


Figure 5.6 Heating energy use comparison

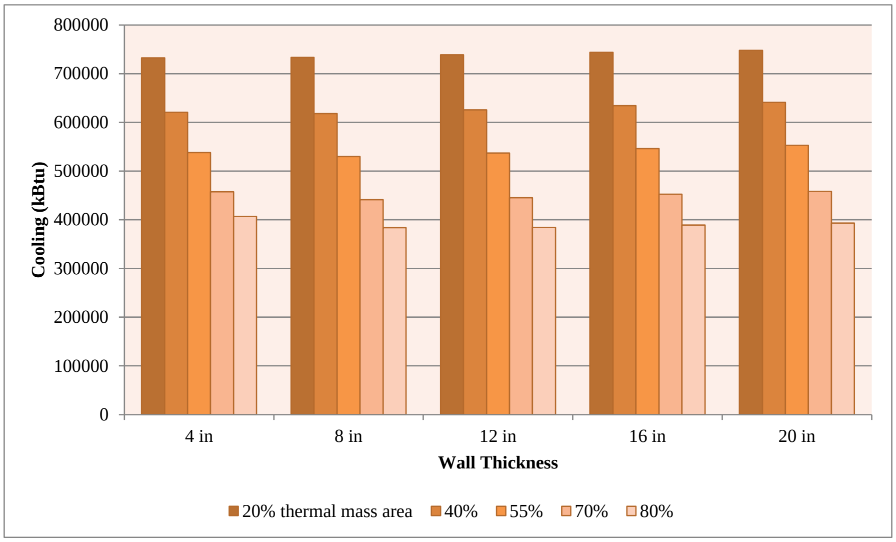


Figure 5.7 Cooling energy use comparison

Table 5.6 Heating energy reductions

% TMA / Location	Percent reduction (increase) of heating energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
4 in wall	(7.6)	(5.7)	(5.7)	(3.4)
8 in wall	(4.0)	(3.3)	(3.6)	(2.2)
12 in wall	(1.5)	(1.6)	(2.0)	(1.2)
16 in wall	0.3	(0.2)	(0.7)	(0.3)
20 in wall	1.6	0.8	0.3	0.3

Table 5.7 Cooling energy reductions

% TMA / Location	Percent reduction (increase) of cooling energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
4 in wall	15.3	13.3	15.0	11.1
8 in wall	15.7	14.3	16.7	13.0
12 in wall	15.3	14.2	17.1	13.6
16 in wall	14.7	13.9	17.1	14.0
20 in wall	14.3	13.7	17.1	14.2

As shown in Figures 5.6-5.8 and Tables 5.6-5.8, thermal mass thicknesses from 4 in (base case) to 16 in have led to an increase of heating energies while exterior thermal mass area increased. The first change of pattern—reduction of heating energies—is observed for the 16 in wall, when the thermal mass area increases from 20% to 40%. The effect of thermal mass area increase on building heating energies is shown to totally change for the 20 in-wall. Unlike other scenarios, the 20 in-thermal mass thickness is shown to reduce the heating use for all thermal mass area scenarios. This indicates that the reduced solar heat gain due to less fenestration areas can be compensated for as long as the exterior wall is increased to 20 in. In terms of the cooling energies, it is shown that as the thermal mass area increases, the cooling demands decrease as well, which is desirable.

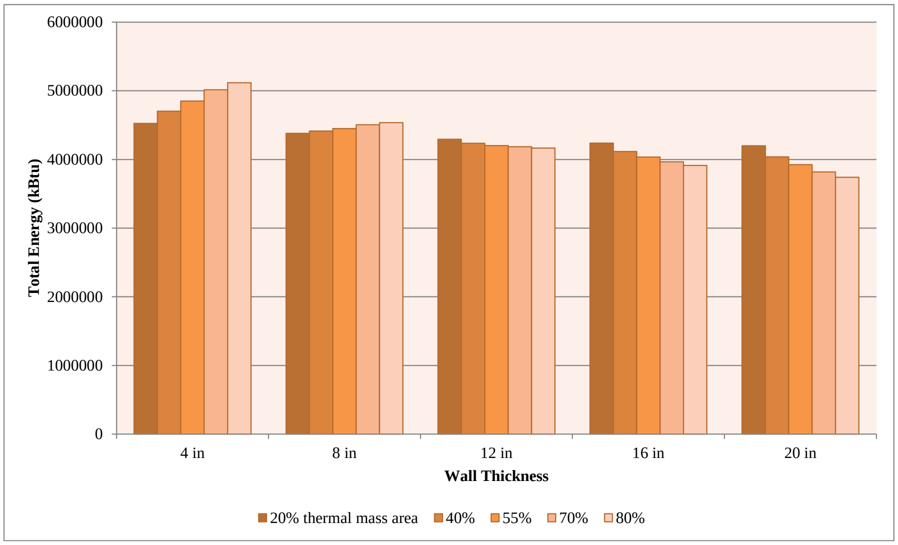


Figure 5.8 Total energy use comparison

Table 5.8 Total energy reductions

% TMA / Location	Percent reduction (increase) of total energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
4 in wall	(3.9)	(3.2)	(3.4)	(2.1)
8 in wall	(0.7)	(0.9)	(1.2)	(0.7)
12 in wall	1.4	0.8	0.5	0.4
16 in wall	2.8	2.0	1.8	1.3
20 in wall	3.8	2.8	2.7	2.0

However, the total energy demands seem to show different patterns in different climate zones. The 4 in and 8 in wall thicknesses are noted to increase the total energy consumption as the thermal mass area increases. However, this pattern starts to reverse beyond the 8-in thickness. As a matter of fact, 12 in, 16 in and 20 in walls are shown to reduce the energy use as the thermal mass distribution on the façade expands. This highlights the effects of exterior wall thickness with respect to the exterior wall areas to reduce total building energy consumptions.

5.2 Thermal comfort

To study the effects of varying thermal mass areas on thermal comfort, the air, radiant and operative temperatures are measured as the comfort indices. To differentiate between seasonal effects on building thermal comfort performance, the first day of the summer and winter—June 21st and December 20th—are chosen to represent the summer and winter conditions. December 20th is taken in lieu of December 21st (actual first winter day) because December 21st is a Saturday (in 2013), when occupants are not present in the building. Furthermore, based on the occupancy schedule, the thermal comfort indices are measured in two categories: 1) occupied hours between 7 AM and 7 PM, and 2) unoccupied hours: between 7 PM and 7 AM.

5.2.1 Air temperature

Figures 5.9 and 5.10, and Tables 5.9 and 5.10 show the change in indoor air temperature as a result of increase in thermal mass area in summer during occupied and unoccupied hours.

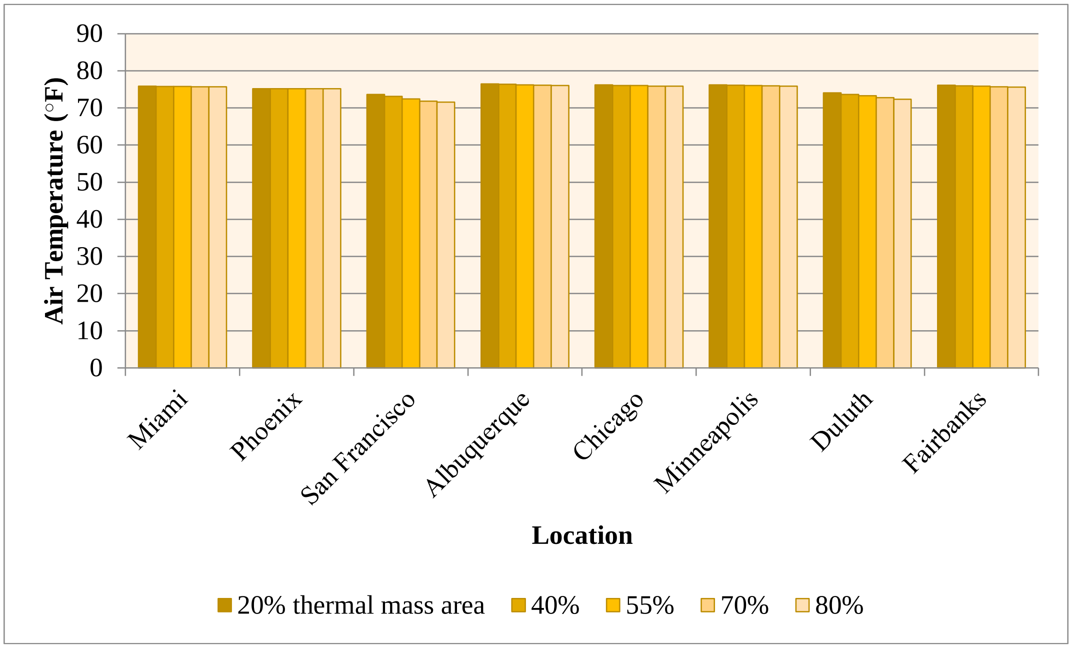


Figure 5.9 Air temperature, summer: occupied hours

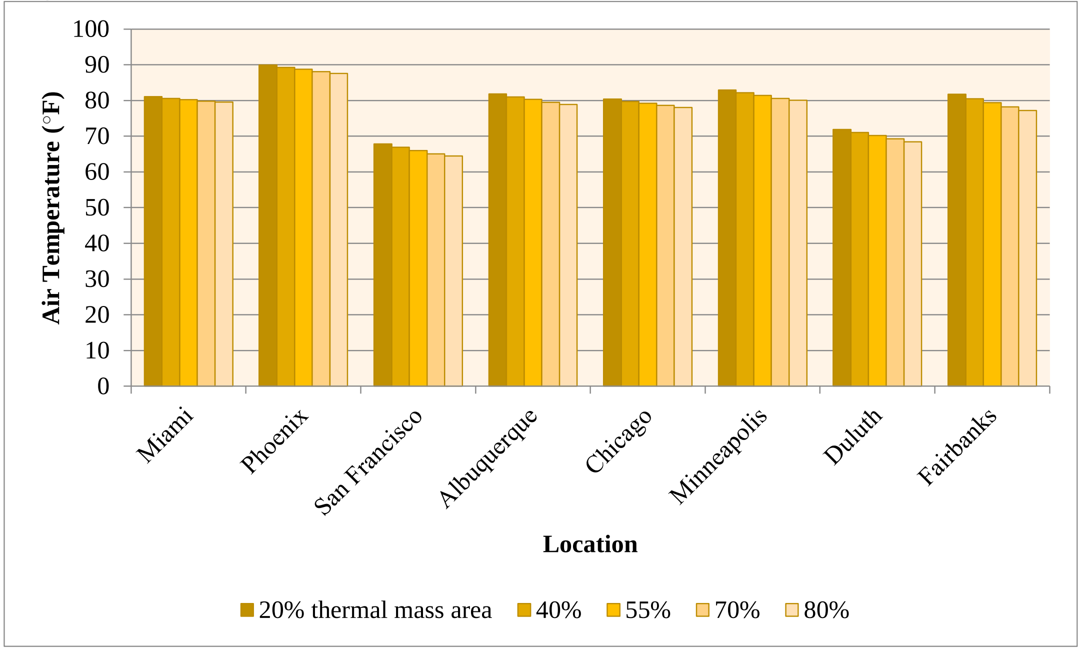


Figure 5.10 Air temperature, summer: unoccupied hours

Table 5.9 Reduction of air temperature, summer occupied hours

% TMA Location	Percent reduction (increase) of air temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.07	0.04	0.05	0.03
Phoenix	0.004	0.002	0.003	0.003
San Francisco	0.70	0.96	0.89	0.33
Albuquerque	0.16	0.14	0.16	0.12
Chicago	0.14	0.10	0.11	0.09
Minneapolis	0.11	0.10	0.12	0.09
Duluth	0.52	0.50	0.72	0.62
Fairbanks	0.20	0.15	0.18	0.17

Table 5.10 Reduction of air temperature, summer unoccupied hours

% TMA Location	Percent reduction (increase) of air temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.6	0.5	0.5	0.4
Phoenix	0.8	0.6	0.7	0.5
San Francisco	1.4	1.3	1.4	0.9
Albuquerque	1.0	0.9	1.0	0.8
Chicago	0.8	0.6	0.8	0.6
Minneapolis	1.0	0.9	1.0	0.7
Duluth	1.2	1.1	1.4	1.1
Fairbanks	1.6	1.3	1.5	1.4

It is shown that the air temperature generally decreases when the thermal mass area on the façade increases regardless of the locations. The same reduction pattern is observed for the unoccupied hours; however, the magnitude of reduction is relatively greater during the unoccupied hours as compared to the occupied hours. Such behavior can be explained by the fact that the HVAC schedule closely follows the occupancy schedule. In other words, during unoccupied hours, the building's air temperature is generally controlled by the building envelope and materials as compared to daytime when the temperature is mainly modulated by the HVAC system, which results in less temperature fluctuations.

Figures 5.11 and 5.12 and Tables 5.11 and 5.12 show the air temperature change in winter during both occupied and unoccupied hours. Compared to the summer time, a considerably less change of air temperature is shown when the occupants are present in the building and when they are not. In fact, except for hot climates, the air temperature relatively remains unchanged in all thermal mass area cases. It is also shown that, for Miami and Phoenix, where greater changes of air temperatures are observed, more reduction of air temperatures due to the increase in thermal mass area generally occurs during occupied hours rather than unoccupied hours.

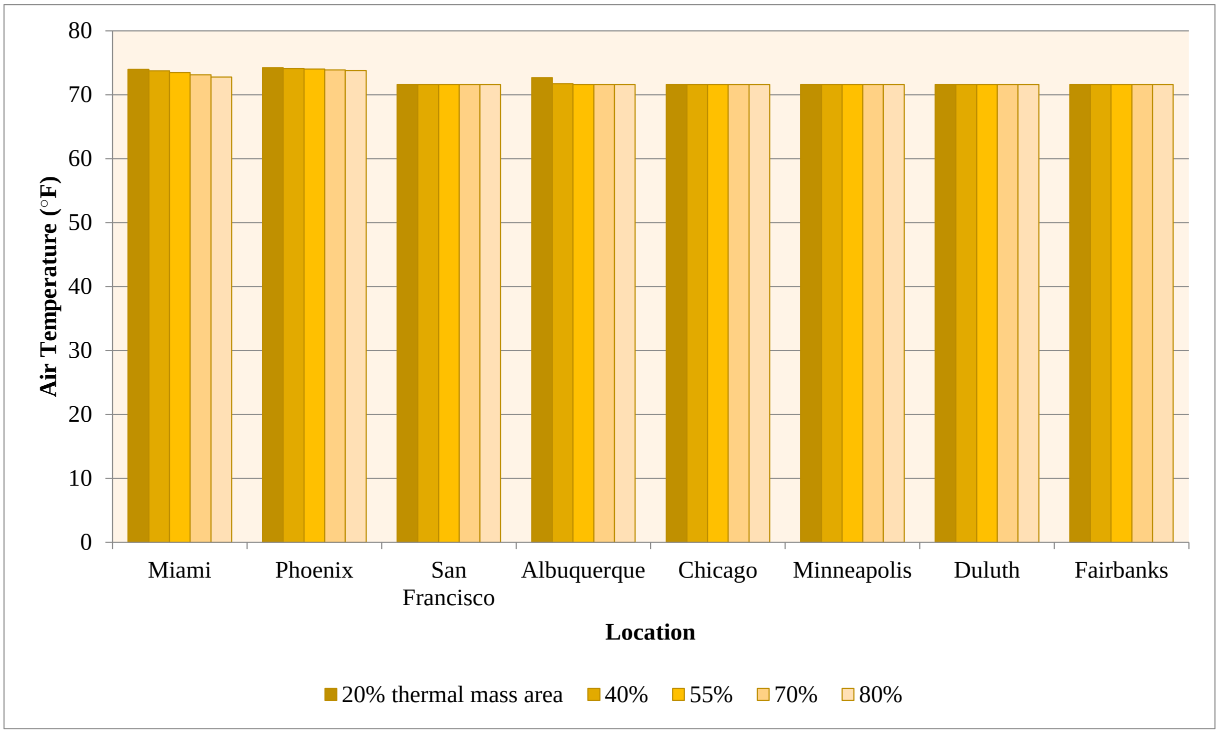


Figure 5.11 Air temperature, winter: occupied hours

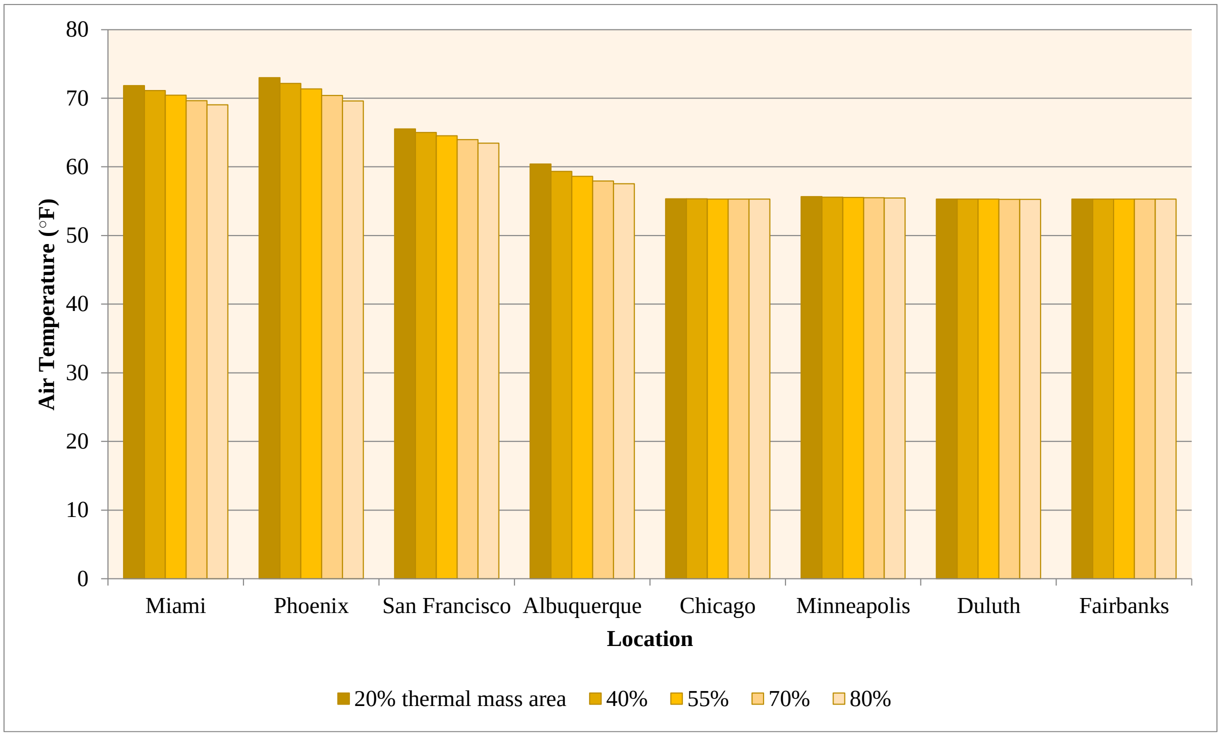


Figure 5.12 Air temperature, winter: unoccupied hours

Table 5.11 Reduction of air temperature, winter occupied hours

% TMA Location	**Percent reduction (increase) of air temperature**			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.3	0.3	0.5	0.5
Phoenix	0.2	0.1	0.1	0.1
San Francisco	0	0	0	0
Albuquerque	1.3	0	0	0
Chicago	0	0	0	0
Minneapolis	0	0	0	0
Duluth	0	0	0	0
Fairbanks	0	0	0	0

Table 5.12 Reduction of air temperature, winter unoccupied hours

% TMA Location	**Percent reduction (increase) of air temperature**			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	1.0	0.9	1.1	0.9
Phoenix	1.2	1.1	1.4	1.1
San Francisco	0.8	0.7	0.9	0.8
Albuquerque	1.8	1.2	1.2	0.7
Chicago	0	0	0	0
Minneapolis	0	0	0	0
Duluth	0	0	0	0
Fairbanks	0	0	0	0

5.2.2 Radiant temperature

As stated in Chapters 1 and 2, surface temperature is an important factor in determining the level of thermal comfort in a room. The stored heat in a thermal mass material can generally result in an increase of surface temperature of the material, thus affects the thermal comfort of the surrounding environment through releasing heat due to radiation. Figures 5.13 and 5.14 and Tables 5.13 and 5.14 show the change of radiant temperature as the result of thermal mass area increase in summer during both occupied and unoccupied hours.

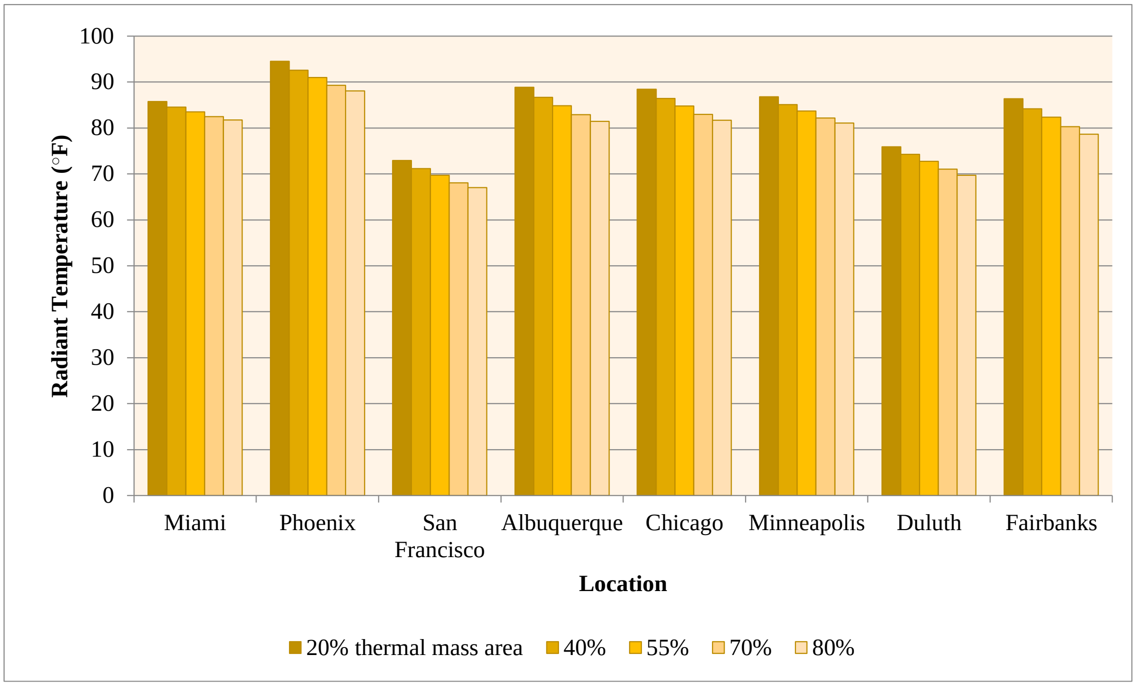


Figure 5.13 Radiant temperature, summer: occupied hours

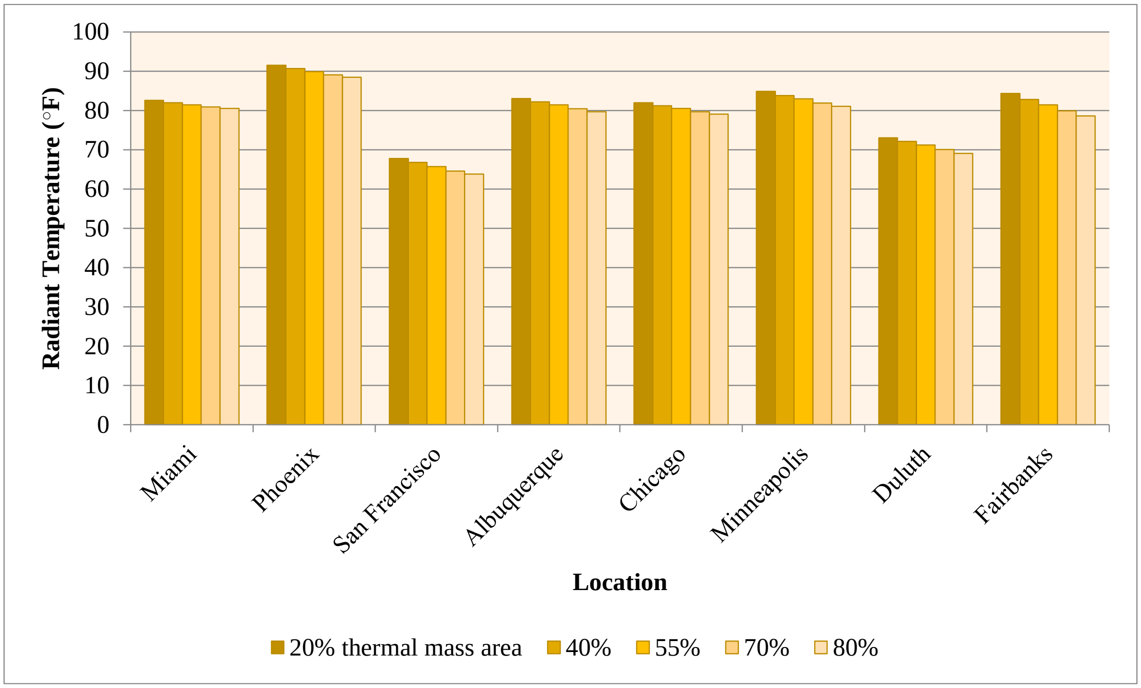


Figure 5.14 Radiant temperature, summer: unoccupied hours

Table 5.13 Reduction of radiant temperature, summer occupied hours

% TMA / Location	Percent reduction (increase) of radaint temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	1.4	1.2	1.3	0.9
Phoenix	2.1	1.7	1.9	1.3
San Francisco	2.4	2.1	2.3	1.5
Albuquerque	2.5	2.1	2.3	1.7
Chicago	2.3	1.9	2.1	1.6
Minneapolis	2.0	1.6	1.8	1.3
Duluth	2.2	2.0	2.4	1.8
Fairbanks	2.5	2.2	2.5	2.0

Table 5.14 Reduction of radiant temperature, summer unoccupied hours

% TMA / Location	Percent reduction (increase) of radaint temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.7	0.6	0.7	0.5
Phoenix	0.9	0.8	0.9	0.7
San Francisco	1.5	1.5	1.8	1.2
Albuquerque	1.0	1.0	1.2	0.9
Chicago	0.9	0.9	1.0	0.8
Minneapolis	1.2	1.1	1.3	1.0
Duluth	1.2	1.2	1.7	1.4
Fairbanks	1.8	1.6	2.0	1.6

It is shown that the surface temperature generally decreases when the thermal mass area on the façade increases regardless of the location. Compared to the air temperature during summer, the radiant temperatures seem to show significantly greater reductions as the result of thermal mass area increase. This phenomenon can be explained by the fact that, unlike air temperature that is generally controlled by the thermostats, the radiant temperature is mainly affected by the heat generated from surrounding objects. Therefore, in office buildings where a lot of heat is generated by internal sources, the surface temperature is expected to show more changes as compared to the air temperature. Furthermore, when the thermal mass area increases, the same amount of generated heat is absorbed by a larger area, which consequently can result in lower radiant temperatures, which is observed in this analysis.

The same reduction pattern is observed for unoccupied hours; however, the magnitude of reductions is relatively smaller during unoccupied hours as compared to occupied hours. Such behavior can be explained by the fact that, the less internal heat is generated during unoccupied hours; therefore, the effect of greater thermal mass area on surface temperature reduction is lessened when compared to that during occupied hours.

Figures 5.15 and 5.16, and Tables 5.15 and 5.16 show the radiant temperature change in winter during both occupied and unoccupied hours. In comparison with summer time, a considerably less change of radiant temperature is observed when the occupants are present in the building and when they are not. In cold climates the radiant temperatures during unoccupied hours remain unchanged or slightly increase as a result of an increase in thermal mass area. This can be explained by the effect of greater HVAC operation in cold climates during the day in winter. Although the radiant temperature is mainly affected by the surrounding objects, the impact of heat convection due to the HVAC operation cannot be neglected. Since the production of hot air is greater in cold climates during the day in winter, greater amount of heat can be stored in the thermal mass. The more the thermal mass area, the more heat is absorbed by it, and therefore, the higher surface temperature when the thermal mass areas increase.

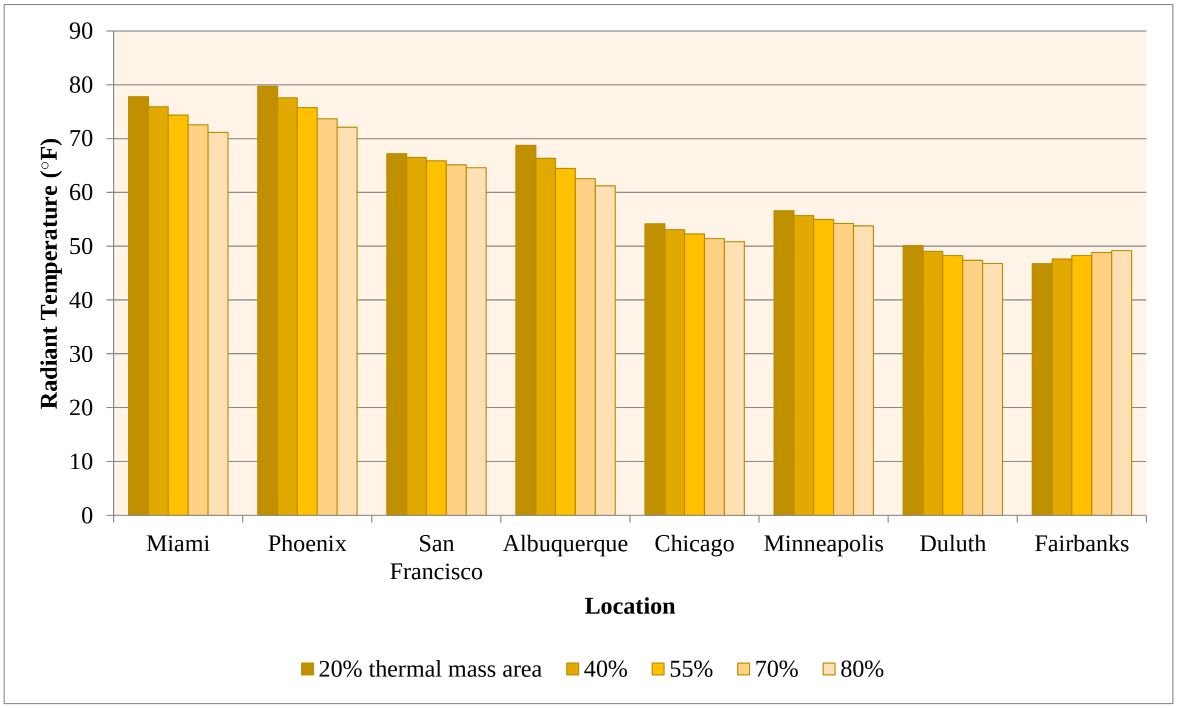


Figure 5.15 Radiant temperature, winter: occupied hours

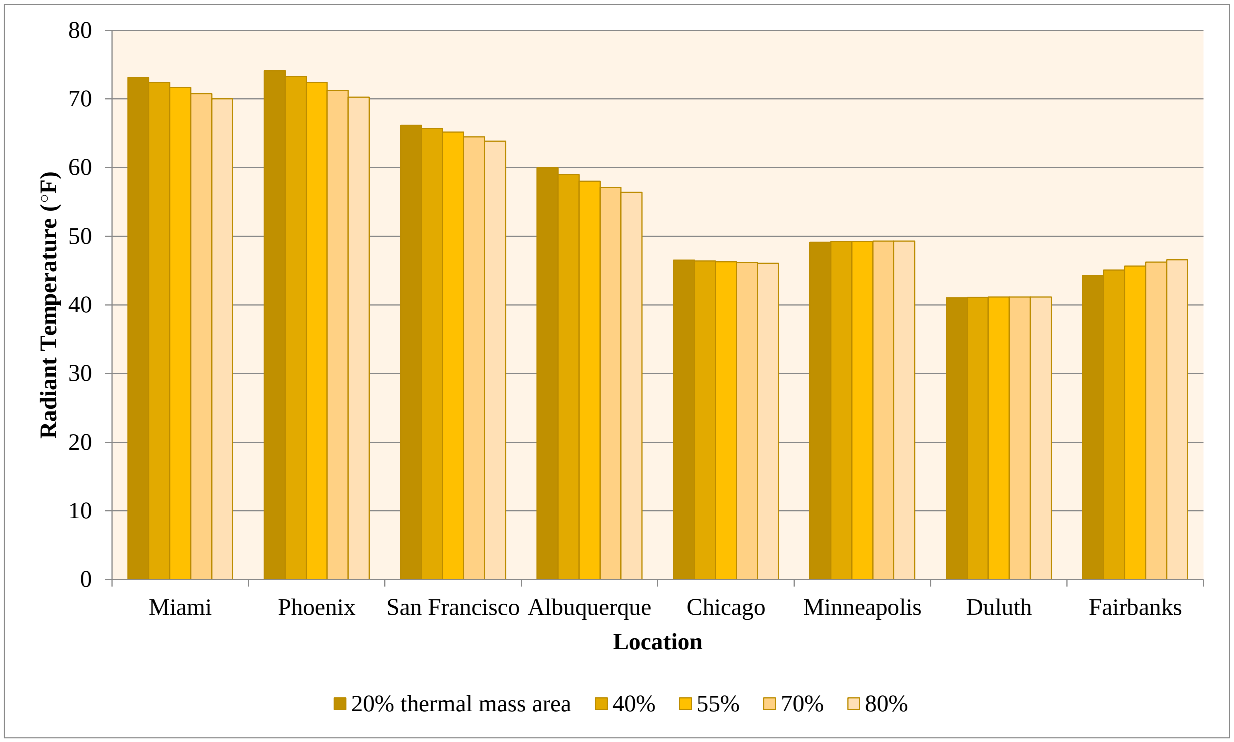


Figure 5.16 Radiant temperature, winter: unoccupied hours

Table 5.15 Reduction of radiant temperature, winter occupied hours

% TMA Location	Percent reduction (increase) of radaint temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	2.4	2.1	2.4	1.9
Phoenix	2.7	2.4	2.8	2.1
San Francisco	1.1	1.0	1.1	0.8
Albuqurque	3.5	2.8	3.0	2.1
Chicago	2.0	1.5	1.6	1.1
Minneapolis	1.6	1.2	1.3	0.9
Duluth	2.1	1.7	1.8	1.3
Fairbanks	(1.9)	(1.3)	(1.2)	(0.7)

Table 5.16 Reduction of radiant temperature, winter unoccupied hours

% TMA Location	Percent reduction (increase) of radaint temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	1.0	1.0	1.3	1.1
Phoenix	1.1	1.2	1.6	1.4
San Francisco	0.7	0.8	1.1	1.0
Albuqurque	1.7	1.6	1.6	1.2
Chicago	0.3	0.2	0.3	0.2
Minneapolis	(0.1)	(0.1)	(0.1)	(0.0)
Duluth	(0.2)	(0.1)	(0.0)	0.1
Fairbanks	(1.9)	(1.3)	(1.2)	(0.7)

5.2.3 Operative temperature

As discussed Chapters 1 and 2, the operative temperature is an average of both air and surface radiant temperatures, both of which are affected by the thermal mass property of concrete. Therefore, operative temperature is a proper indicator of overall thermal level of a room. Figures 5.17 and 5.18 and Tables 5.17 and 5.18 show the change of operative temperature as a result of thermal mass area increase in summer during occupied and unoccupied hours.

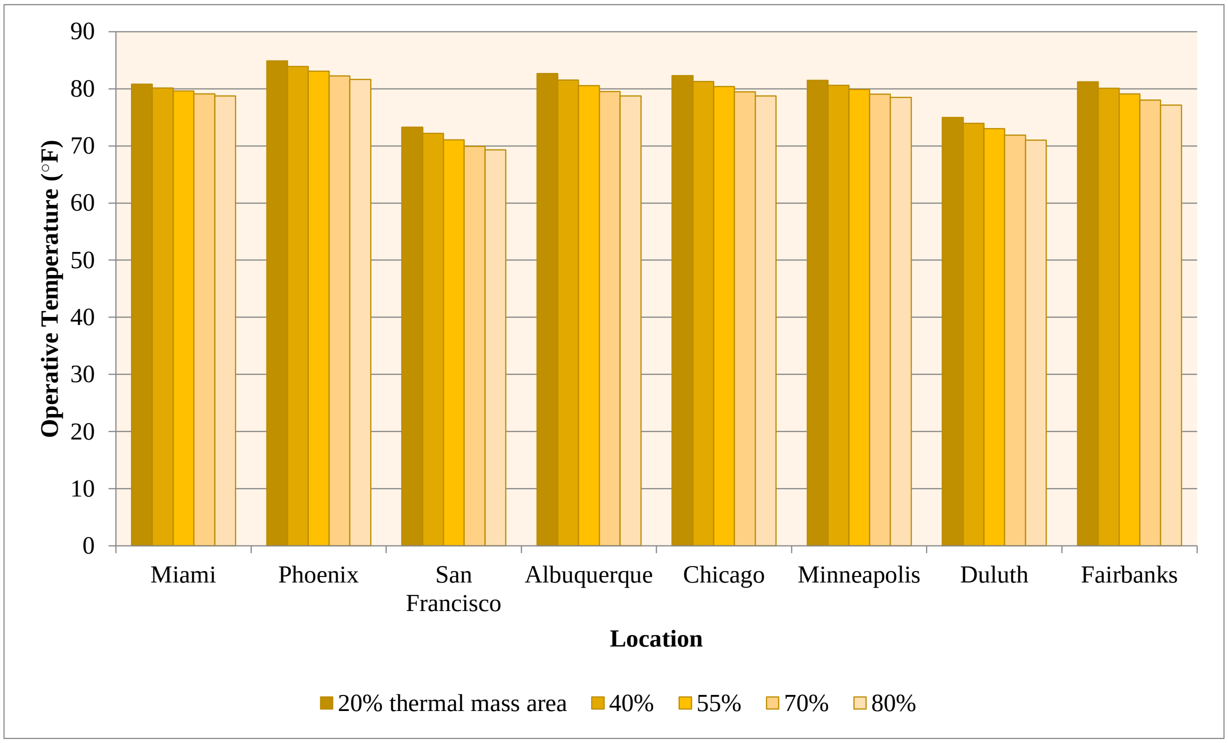


Figure 5.17 Operative temperature, summer: occupied hours

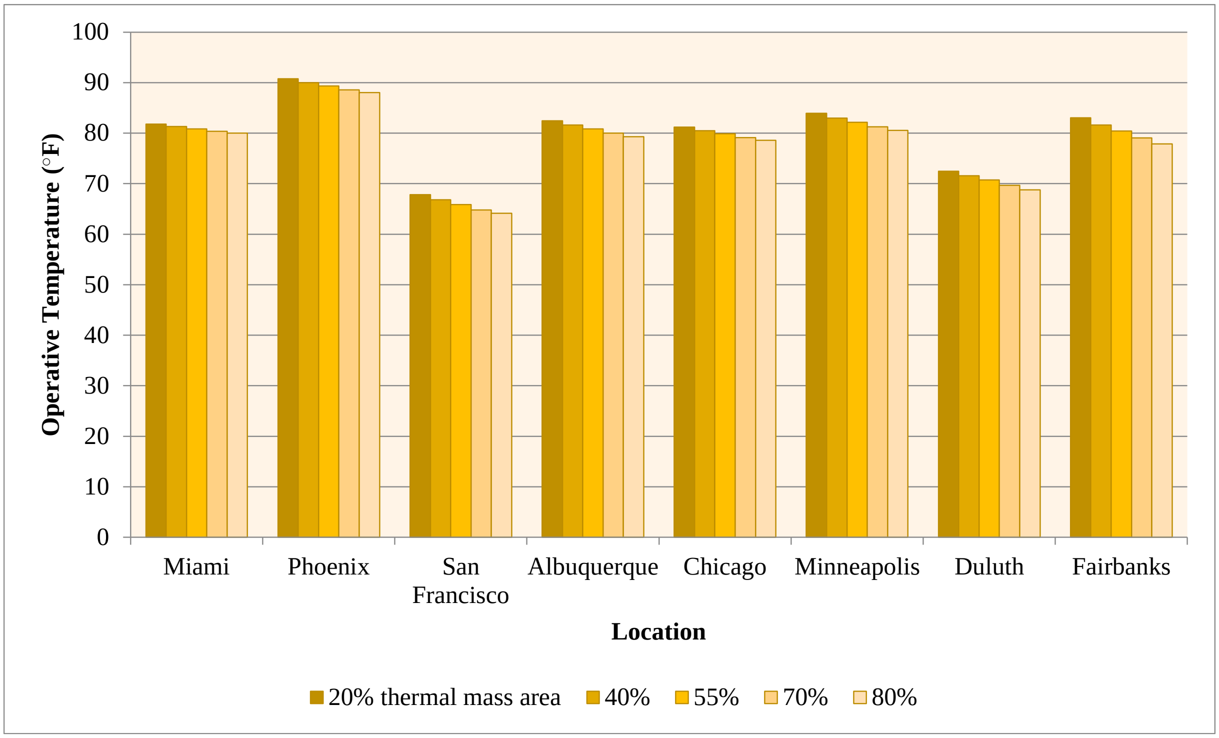


Figure 5.18 Operative temperature, summer: unoccupied hours

Table 5.17 Reduction of operative temperature, summer occupied hour

% TMA Location	Percent reduction (increase) of operative temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.8	0.6	0.7	0.5
Phoenix	1.2	0.9	1.0	0.7
San Francisco	1.5	1.5	1.6	0.9
Albuquerque	1.4	1.2	1.3	1.0
Chicago	1.3	1.1	1.2	0.9
Minneapolis	1.1	0.9	1.0	0.7
Duluth	1.4	1.3	1.6	1.2
Fairbanks	1.4	1.2	1.4	1.1

Table 5.18 Reduction of operative temperature, summer unoccupied hours

% TMA Location	Percent reduction (increase) of operative temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	0.6	0.5	0.6	0.4
Phoenix	0.8	0.7	0.8	0.6
San Francisco	1.4	1.4	1.6	1.1
Albuquerque	1.0	0.9	1.1	0.9
Chicago	0.9	0.7	0.9	0.7
Minneapolis	1.1	1.0	1.1	0.8
Duluth	1.2	1.2	1.5	1.3
Fairbanks	1.7	1.5	1.7	1.5

It is shown that the operative temperature generally decreases when the thermal mass area on the façade increases regardless of the locations. The pattern of operative temperature reduction is more similar to the reduction pattern observed for the radiant temperature than the air temperature, which highlights the importance of surface temperature effects on thermal comfort.

Figures 5.19 and 5.20, and Tables 5.19 and 5.20 show the operative temperature changes in winter during both occupied and unoccupied hours. Compared to summer time, a considerably less change of operative temperature is observed when the occupants are present in the building than when they are not. In cold climates, the operative temperatures during unoccupied hours remain unchanged or even slightly increase as a result of an increase in thermal mass area, which as discussed before, could be attributed to the greater heating operation of HVAC systems in cold climates during the day in winter in an office building. Since the production of hot air is greater in cold climates during winter, greater amount of heat can be stored in the thermal mass. The more the thermal mass area, the more is the heat absorbed by the thermal mass, and therefore, the surface temperature increases as a result of an increase in thermal mass area

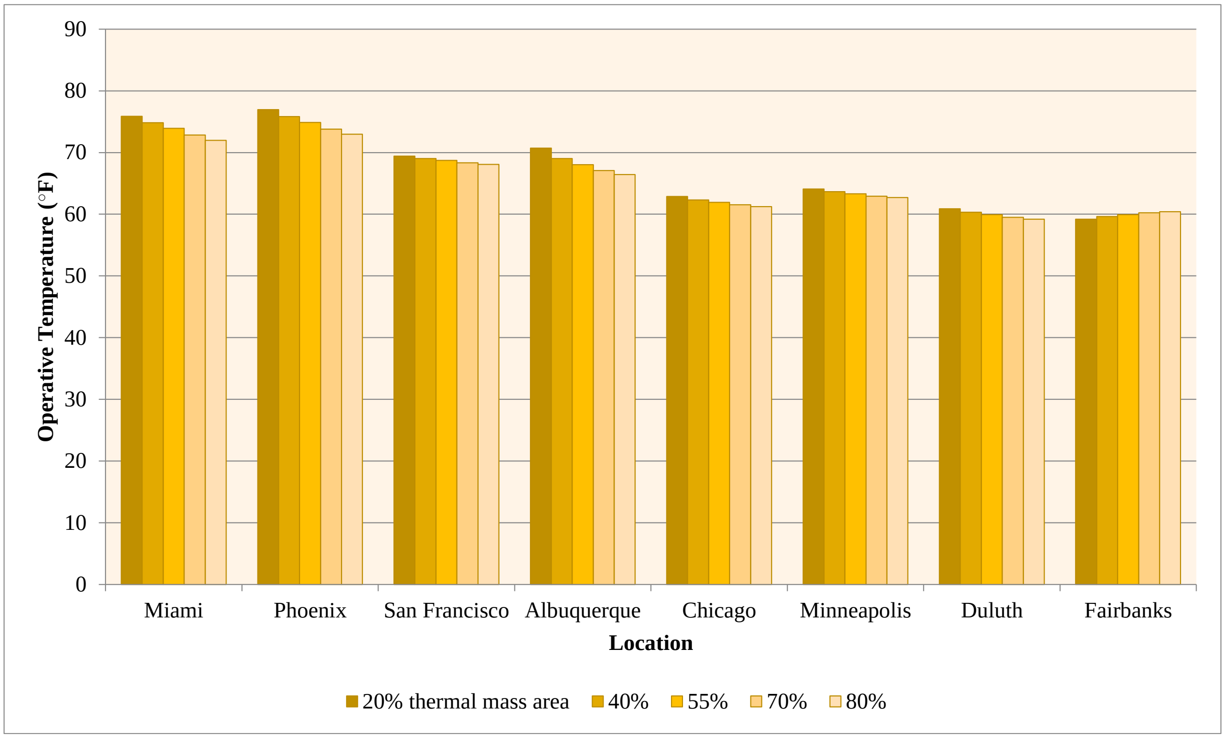


Figure 5.19 Operative temperature, winter: occupied hours

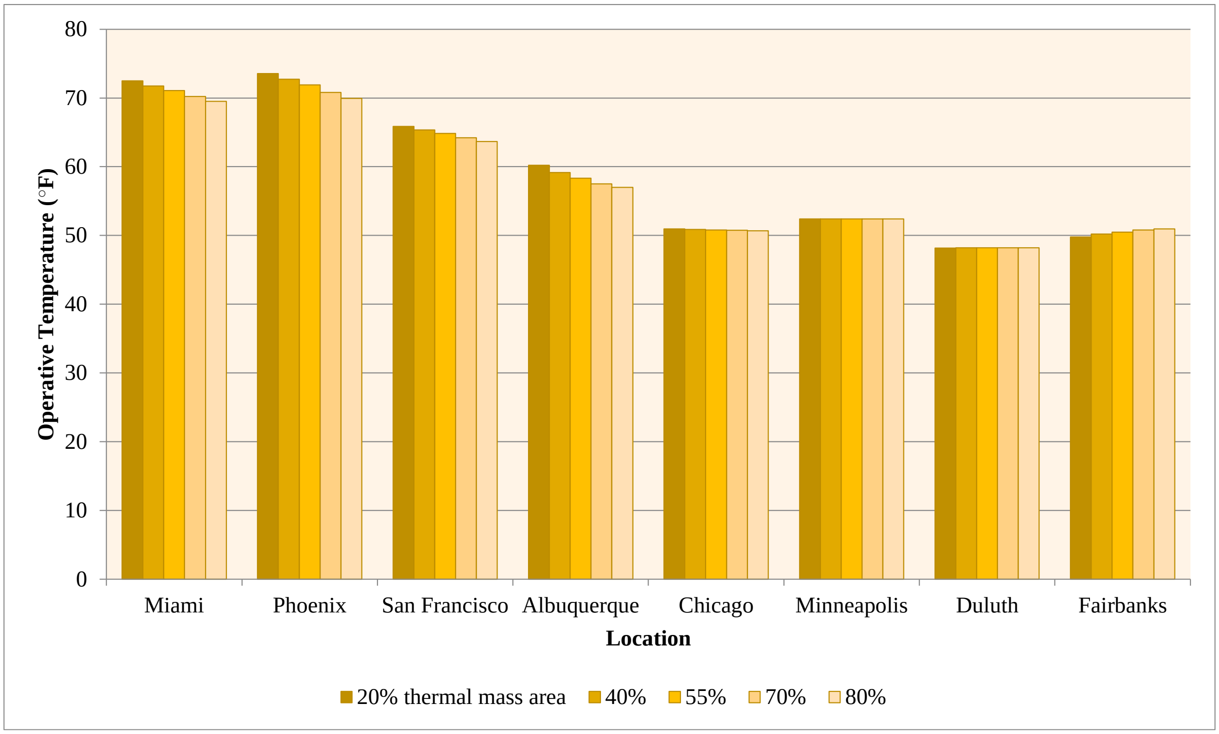


Figure 5.20 Operative temperature, winter: unoccupied hours

Table 5.19 Reduction of operative temperature, winter occupied hours

% TMA / Location	Percent reduction (increase) of operative temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	1.4	1.2	1.5	1.2
Phoenix	1.5	1.3	1.5	1.1
San Francisco	0.5	0.5	0.5	0.4
Albuquerque	2.4	1.4	1.4	1.0
Chicago	0.8	0.6	0.7	0.5
Minneapolis	0.7	0.5	0.6	0.4
Duluth	0.9	0.7	0.7	0.5
Fairbanks	(0.7)	(0.5)	(0.5)	(0.3)

Table 5.20 Reduction of operative temperature, winter unoccupied hours

% TMA / Location	Percent reduction (increase) of operative temperature			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Miami	1.0	1.0	1.2	1.0
Phoenix	1.1	1.1	1.5	1.2
San Francisco	0.8	0.8	1.0	0.9
Albuquerque	1.7	1.4	1.4	0.9
Chicago	0.2	0.1	0.1	0.1
Minneapolis	0	0	0	0
Duluth	(0.1)	0	0	0.03
Fairbanks	(0.8)	(0.6)	(0.6)	(0.3)

5.3 Final remarks

In this chapter the increase of thermal mass area—from 20% to 80% of building façade—on building energy use and thermal comfort has been studied. The results have shown that incremental thermal mass area can be very effective in changing the building's energy and thermal comfort performance.

In terms of building energy use, the increase of thermal mass area is noted to generally increase the heating energy use for the base case model with the wall thickness of 4 in. However, when the wall thickness is increased to 20 in, the increase of thermal mass distribution on the building envelope reduces the heating energy use, which highlights the importance of thermal mass thickness in reducing the energy consumption. The cooling energies, on the other hand, tend to decrease when the thermal mass area increases even with the wall thickness of 4 in. The total energy use of the building is found to follow the pattern of either heating or cooling energy changes based on what dominates the energy design. In the hot locations, the increase of thermal mass area is shown to have led to the reduction of total energies; however, in cold climates, the total energies are shown to increase as the thermal mass area on the façade increases.

Regarding thermal comfort parameters, the air temperature in all locations is found to decrease as a result of incremental thermal mass area during summer in almost all locations; however, the winter air temperatures do not represent a significant difference as a result of thermal mass increase. The radiant temperatures during both summer and winter demonstrate considerably greater reductions when the thermal mass area increases, when compared to air temperature, although the pattern of temperature change is reversed (i.e., temperature increases) in winter time in cold climates. The operative temperature is also shown to generally decrease as a result of thermal mass area increase except for unoccupied winter hours in cold climates.

Taken together, the cumulative effect of air, radiant and operative temperatures in a concrete building due to its primary thermal mass in found to benefit the building for both energy efficiency and thermal comfort except for a few isolated cases where heating demands or temperature increased as a result of an increase of thermal mass area.

In the next chapter, the effect of secondary thermal mass including slab and interior portions, on building energy and thermal comfort performance is presented.

5.4. Summary

The increase of thermal mass area is noted to generally increase the heating energy use for the wall thickness of 4 in to 16 in. The increase of thermal mass distribution on the building envelope when the wall thickness is 20 in can reduce the heating energy use. The cooling energies decrease when the thermal mass area increases even with the wall thickness of 4 in. Given the wall thickness of 4 in, the change of total energy use due to incremental thermal mass area follows the pattern of either heating or cooling energy changes based on what dominates the energy design. Air temperature decreases as a result of incremental thermal mass area during summer, but not during winter when the changes are negligible. Radiant temperatures during both summer and winter reduce when the thermal mass area increases, with the exception of radiant temperature increases in winter time in cold climates. Operative temperature generally decreases as a result of thermal mass area increase except for unoccupied winter hours in cold climates.

5.5. Thermal mass façade

Although the role of thermal mass area in affecting building energy performance is certain, one may argue that since in this analysis, along with thermal mass area, the window-to-wall area ratio has also changed, some energy changes could be attributed to the change of solar heat gain instead of thermal mass area increase. To address such concern, a series of analyses in which the window-to-wall area ratio remained constant was conducted. Chicago was selected as the study location since it has both extreme hot and cold climate conditions.

The wall area was then divided into two segments, one of which represented a wall with nearly zero thermal mass property (less than 0.1 in. concrete wall and 1 in. gypsum board) and the other represented a high thermal mass property (an 8 in. concrete wall). It was ensured that the R-values of both wall assemblies were identical. Then, the area ratio between these two segments was changed from 20% thermal mass wall to 80% non-thermal mass wall, then 40%, 55%, 70% and 80% thermal mass areas to 60%, 45%, 30% and 20% non-thermal mass areas, respectively.

In terms of the energy consumption analysis, the annual heating and cooling energies were measurement indices used to compare the energy performance of the different models, albeit keeping other design parameters such as wall or slab thickness constant conforming to the base case model.

5.5.1 Energy analysis

Figure 5.21 and Table 5.21 show the heating, cooling and total energy performance for different thermal mass area percentages as opposed to non-thermal mass areas in eight locations studied in this research. It should be noted that TMA stands for Thermal Mass Area in all tables.

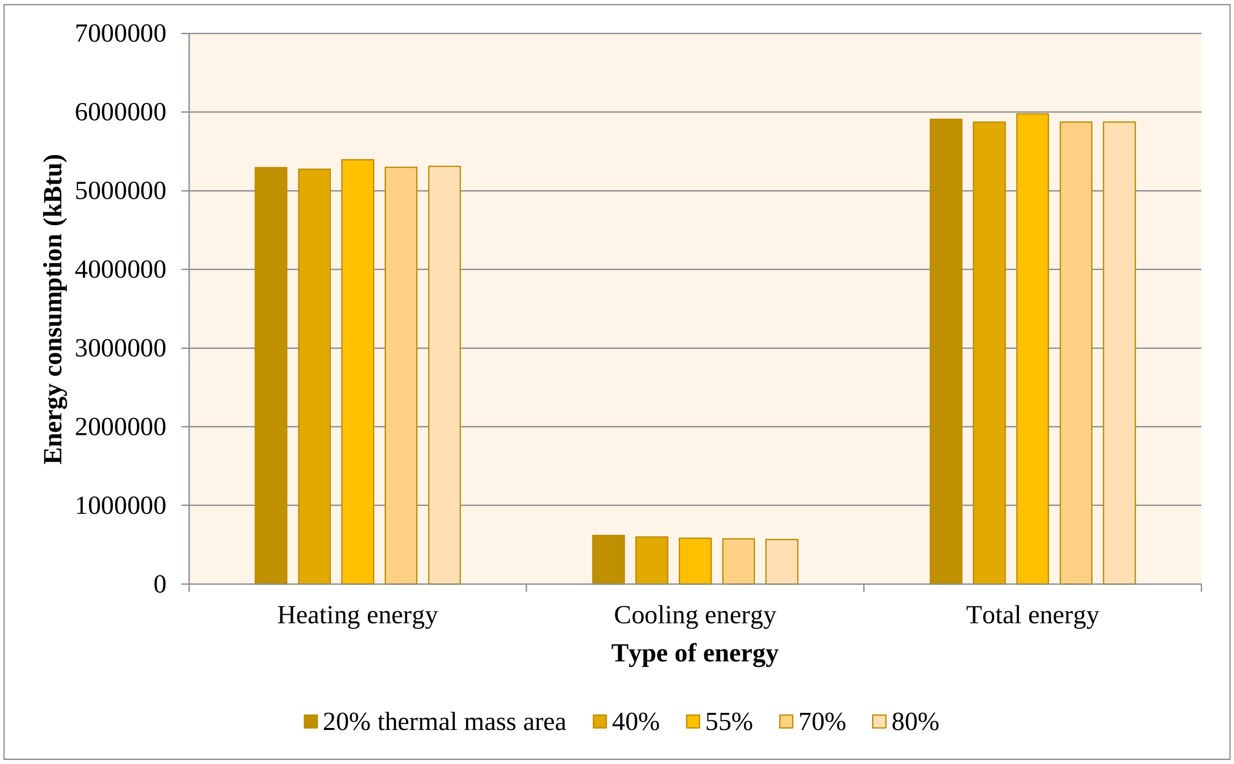


Figure 5.21 Heating energy use comparison

Table 5.21 Heating energy reductions

% TMA / Location	Percent reduction (increase) of energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Heating energy	0.3	(2.3)	1.8	(0.2)
Cooling energy	3.1	2.6	1.7	1.5
Total energy	0.6	(1.8)	1.8	0

As shown, the increase of thermal mass distribution on building façade has led to both increase and reductions of heating energies depending on the ratio of thermal mass wall to the non-thermal mass one. However, in terms of cooling performance, as shown for all cases, the increase of thermal mass from 20% to 80% has led to the reduction of cooling demands. The total energy generally shows a general reduction, although not very significant, as a result of increase of thermal mass area.

5.5.2 Alternative wall assembly

One still may argue that the thickness differences between thermal mass and non-thermal mass walls, rather than the effect of thermal mass itself, has been the main contributor to the reduction of energy consumption shown in Section 5.4. To address such concern, the thickness of non-thermal mass was increased to 8 in. to be identical to the thermal mass wall; however, the steel material was selected for the wall material since it has a significantly lower thermal mass property as compared to concrete.

Figure 5.22 and Table 5.22 show the effect of thermal mass area increase on building energy consumption in the presence of the steel wall as the non-thermal mass portion of façade.

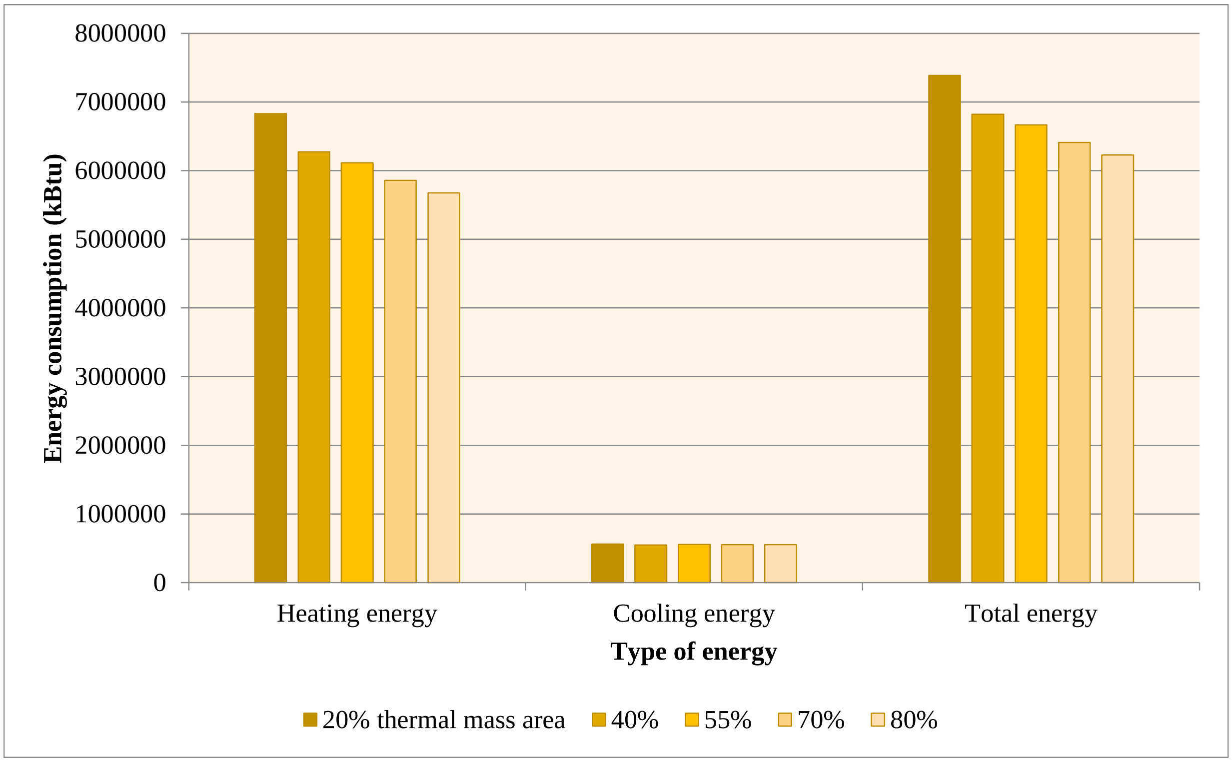


Figure 5.22 Energy use comparison in Chicago

Table 5.22 Energy reduction in Chicago

% TMA / Location	Percent reduction (increase) of energy			
	20% - 40%	40% - 55%	55% - 70%	70% - 80%
Heating energy	8.1	2.5	4.2	3.1
Cooling energy	2.0	(1.0)	0.2	0.2
Total energy	7.7	2.2	3.8	2.9

As shown, the increase of thermal mass area on the faced can effectively reduce both heating and cooling and consequently total energy consumption, which is desirable. Therefore, it can be concluded that the increase of thermal mass distribution on the building facade can reduce the building energy consumption regardless of location.

CHAPTER 6

EFFECTS of CONCRETE FLOOR SLAB on BUILDING PERFORMANCE

Chapter 4 and 5 discussed the primary thermal mass, perimeter wall thickness and thermal mass distribution on building façade, and how effectively they can affect building energy and thermal comfort performance. In this chapter, the discussion on secondary thermal mass, interior thermal mass elements, begins and continues in the following chapter. In this research, secondary or interior thermal mass includes interior concrete slabs and concrete walls. This chapter studies the effects of slab thickness increase on office buildings' energy use and thermal comfort. Chapter 7 will discuss to what extent different interior concrete wall layouts can affect building energy and thermal comfort performance.

In this study, the thickness of interior concrete slab was varied from 4 in (base case) to 6 in and 8 in. The energy simulation for each case is conducted and the energy use and thermal comfort results are compared among different cases

6.1 Energy analysis

In terms of the energy consumption, the annual heating and cooling energies as well as peak heating and cooling loads are the measurement indices used to compare the energy performance of the different models, albeit keeping other design parameters such as thermal mass area or wall thickness constant in accordance with the base case model (i.e. thermal mass area: 70% of the façade and wall thickness: 4in).

6.1.1 Heating energy analysis

Figure 6.1 and Table 6.1 show the heating energy performance for different slab thicknesses in eight locations studied in this research. In this chapter, ST stands for slab thickness.

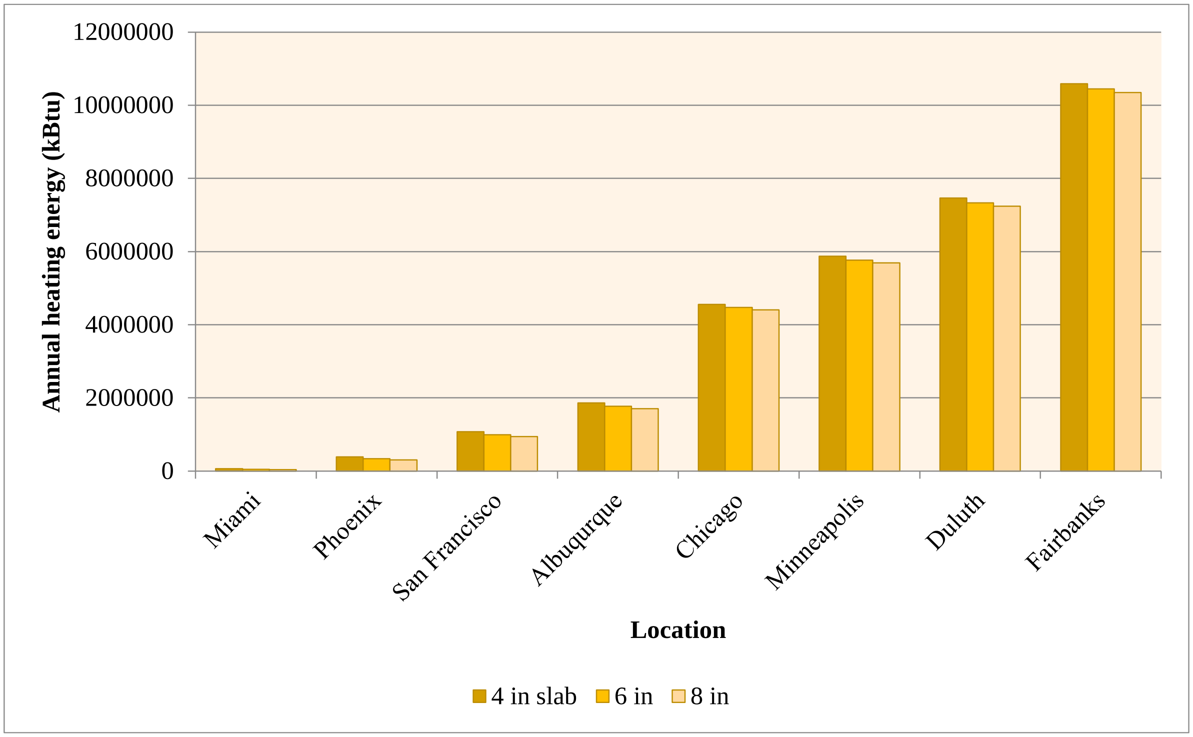


Figure 6.1 Heating energy use comparison

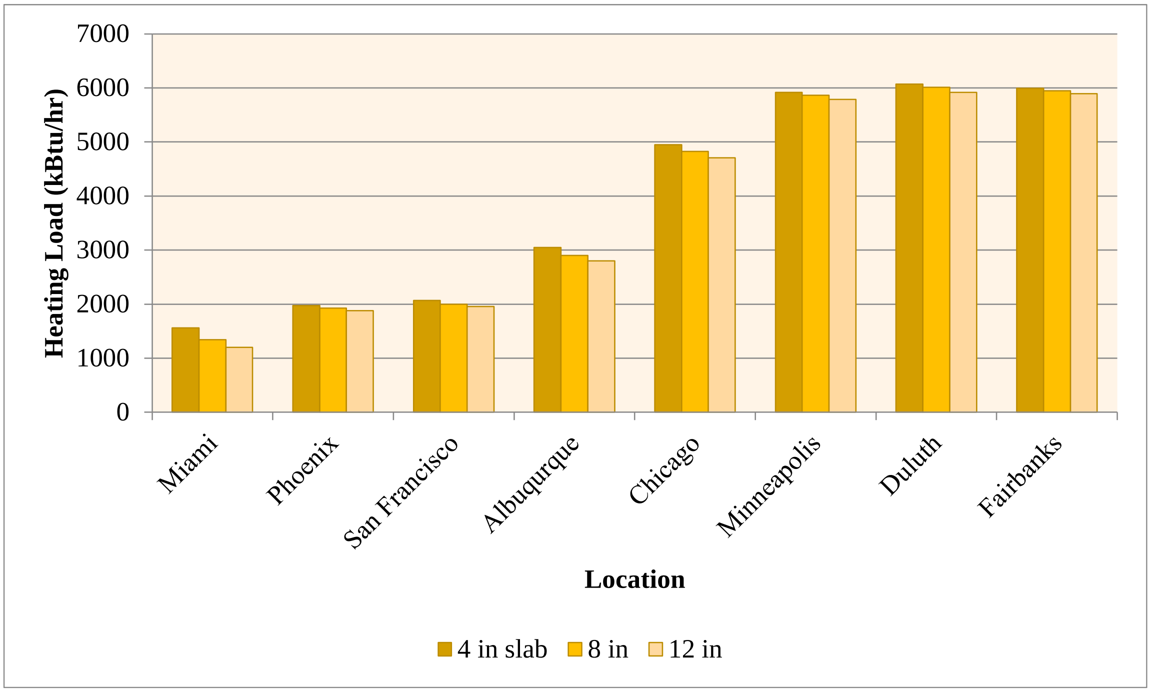


Figure 6.2 Heating load comparison

Table 6.1 Heating energy reductions (increases)

ST* / Location	Percent reduction (increase) of heating energy	
	4 in - 6 in	6 in - 8 in
Miami	27.8	21.6
Phoenix	13.0	9.5
San Francisco	7.3	5.2
Albuqurque	5.1	3.5
Chicago	1.9	1.4
Minneapolis	1.8	1.3
Duluth	1.7	1.3
Fairbanks	1.3	1.0

* ST: Slab Thickness

Table 6.2 Heating load reductions (increases)

ST / Location	Percent reduction (increase) of heating load	
	4 in - 6 in	6 in - 8 in
Miami	13.9	10.7
Phoenix	2.4	2.5
San Francisco	3.4	2.1
Albuqurque	4.8	3.6
Chicago	2.5	2.4
Minneapolis	0.9	1.3
Duluth	1.1	1.5
Fairbanks	0.8	0.9

As shown, the increase of slab thickness has led to the reduction of heating energies in all cases. Figure 6.2 and Table 6.2 demonstrate the impact of slab thickness increase on peak heating loads in different climate zones. Similar to the heating energy use, the peak heating loads are also noted to decrease as a result of thermal mass increase. It can be seen that the effect of slab thickness increase on heating demands is greater when the slab thickness increases from 4 in to 6 in than when it increases from 6 in to 8 in, regardless of locations. This could be an indication of the principle of “diminishing returns”. In other words, as the slab thickness continues to increase, the energy benefits keep diminishing. For instance, in San Francisco, when the slab thickness increases form 4 in to 6 in, the annual heating energy is reduced by 7.3%; however, when it increases from 6 in to 8 in, the heating energy reduction becomes 5.2%, which is almost 30% smaller than that when the slab thickness is increased from 4 in to 6 in.

The reduction of heating energies is observed to be relatively higher in hot climates such as in Miami or Phoenix as compared to cold climates. The same conclusion can also be drawn for heating loads although the heating load differences among various locations are not as great. This phenomenon was also observed in preliminary design phase, where the reduction of heating demands due to thermal mass is considerably higher in hot climates than it is in cold locations. It is known that temperature swings are in general considerably higher in hot climates as compared to cold locations. Furthermore, unlike the cold climate zones, all hot locations in this study are also very sunny locations; therefore, exposure to the sun can improve and enhance the effect of thermal mass. Furthermore, the building HVAC system—VAV with terminal reheats—can be another beneficiary from thermal mass. Since the building thermal mass stores heat for a longer period of time, the demand for re-heating the cool air to meet the cooling set-point temperature decreases. Therefore, there can be a lower demand for heating in the building, which in turn, can lead to a reduction in heating energies and heating loads.

6.1.2 Cooling energy analysis

Figures 6.3 and 6.4 and Tables 6.3 and 6.4 show the effects of slab thickness increase on cooling energies and cooling loads. As shown, these images, except for hot locations such as Miami or Phoenix, the increase of slab thickness has led to a reduction of both cooling energies and cooling loads.

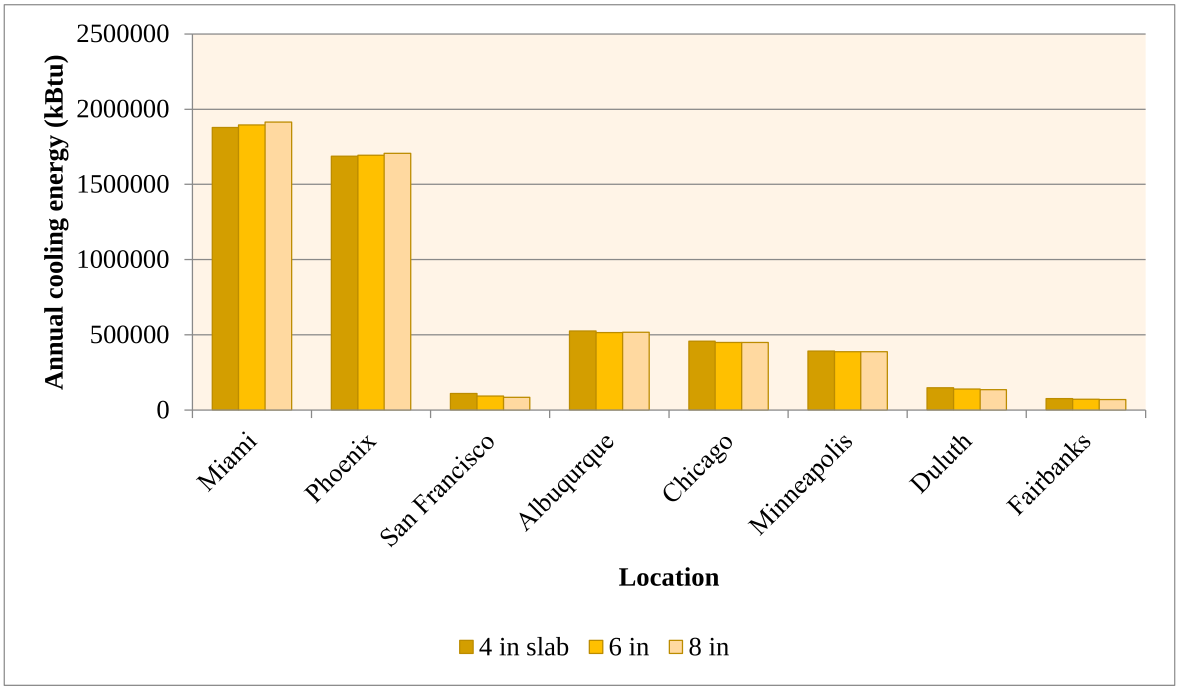


Figure 6.3 Cooling energy use comparison

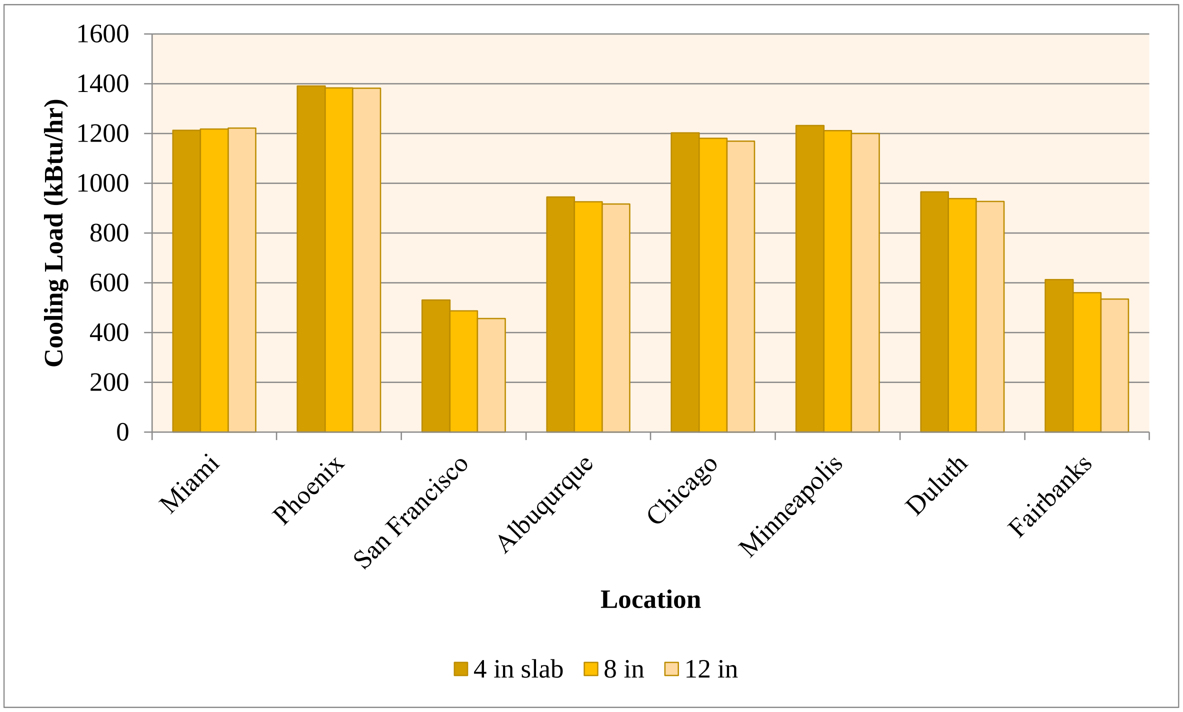


Figure 6.4 Cooling load comparison

Table 6.3 Cooling energy reductions (increases)

ST Location	Percent reduction (increase) of cooling energy	
	4 in - 6 in	6 in - 8 in
Miami	(0.9)	(1.0)
Phoenix	(0.4)	(0.8)
San Francisco	16.6	7.3
Albuquerque	2.0	(0.03)
Chicago	1.5	0.1
Minneapolis	1.3	(0.2)
Duluth	6.5	2.6
Fairbanks	7.3	2.6

Table 6.4 Cooling load reductions (increases)

ST Location	Percent reduction (increase) of cooling load	
	4 in - 6 in	6 in - 8 in
Miami	(0.5)	(0.3)
Phoenix	0.6	0
San Francisco	8.1	6.5
Albuquerque	2.1	0.9
Chicago	1.8	0.9
Minneapolis	1.7	0.9
Duluth	2.8	1.3
Fairbanks	8.5	4.8

Similar to heating loads, the reduction of cooling loads due to the increase of slab thickness is higher when the wall thickness increases from 4 in to 6 in as compared to the other case. Reduction of cooling loads can greatly help reduce the size of HVAC systems and therefore initial cost of mechanical systems.

The annual cooling energies are also seen to decrease when the slab thickness increases, except for hot climate zones, where the increase of slab thickness is shown to have led to a slight increase of cooling demands, which is neither expected nor desirable. Therefore, one may consider further investigation to determine the cause of such behaviors. To further study the effect of slab thickness increase on cooling demands in hot locations, Phoenix was chosen to run a series of simulations for with different setups in terms of building type, and HVAC schedule. The goal is to determine what parameters other than slab thickness increase may have led to the increase of cooling energies.

6.1.2.1 Change of HVAC schedule

Office buildings have inherently high internal gains due to occupants, office equipment, and indoor lighting. This generated heat can be stored in building mass, i.e., walls and slabs, which in turn, can increase building's cooling demands. Therefore, one explanation for the increase of cooling energies as a result of slab thickness increase is greater heat storage in building mass to the extent that not only it overcomes potential thermal mass benefits, but also the stored heat requires more cooling energies to dissipate. This can perfectly lead to the increase of cooling energies as a result of slab thickness increase. One way to validate this explanation is to expand the HVAC schedule, either cooling or ventilation or both, to help remove the potentially stored heat in the thermal mass. In this study, the HVAC cooling and ventilation schedules were changed to further study the effects of slab thickness increases on building energy performance.

Figures 6.5 and 6.6 and Tables 6.5 and 6.6 show the effect of slab thickness increase of building heating and cooling performance, where the cooling schedule had been extended to include nighttime hours (Figure 6.5) or to only full daytime operation (Figure 6.6) for 6 in and 8 in slab thickness cases.

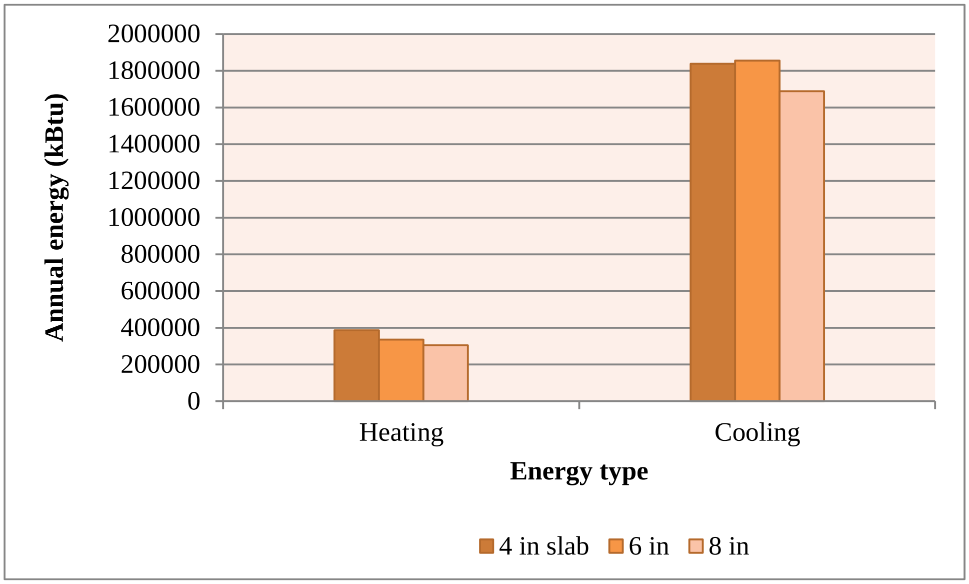


Figure 6.5 Energy use comparison with nighttime cooling

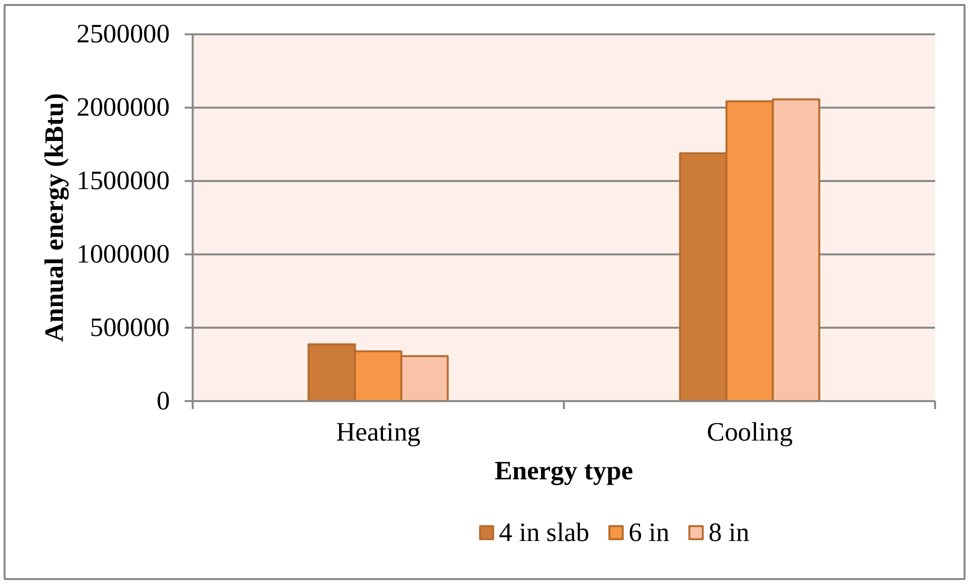


Figure 6.6 Energy use comparison with full daytime cooling

Table 6.5 Energy reduction with nighttime cooling

ST Energy type	Percent reduction (increase) of heating & cooling energy	
	4 in - 6 in	6 in - 8 in
Heating	13.0	9.5
Cooling	(0.9)	9.0

Table 6.6 Energy reductions with full daytime cooling

ST Energy type	Percent reduction (increase) of heating & cooling energy	
	4 in - 6 in	6 in - 8 in
Heating	12.4	9.6
Cooling	(21.1)	(0.6)

It can be seen that in both cases whether the nighttime cooling or full daytime cooling is implemented, the heating energies decrease, however, adding nighttime cooling to the HVAC operation to be more effective in reducing cooling demands than simply full daytime cooling operation. In fact, in both cases, there is an increase of cooling energies when the new cooling schedules are implemented for 6 in slab thickness as the base case of 4 in with the original cooling schedule. However, nighttime cooling leads to a reduction when the slab is further increased to 8 in while in the case of full daytime cooling, 8 in slab thickness is showing a higher cooling demands than 6 in slab, which is similar behavior observed with the original base case schedule in previous section. Despite some benefits gained from the nighttime cooling, the pattern of cooling energy increase as a result of slab thickness increase still remains relatively unchanged.

Figures 6.7 and 6.8 and Tables 6.7 and 6.8 demonstrate the effect of modified mechanical ventilation (fan operation only) schedules on building energy performance

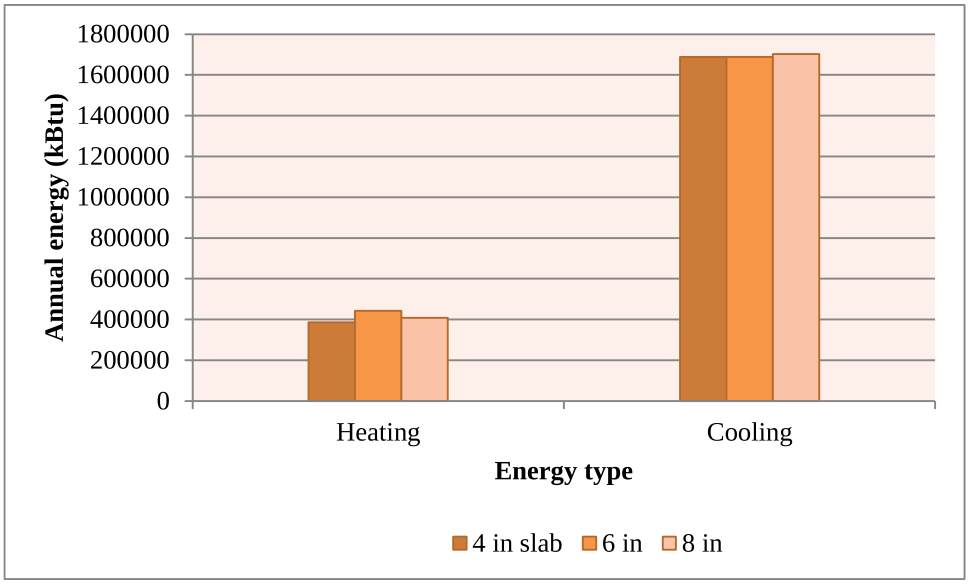


Figure 6.7 Energy use comparison with nighttime ventilation

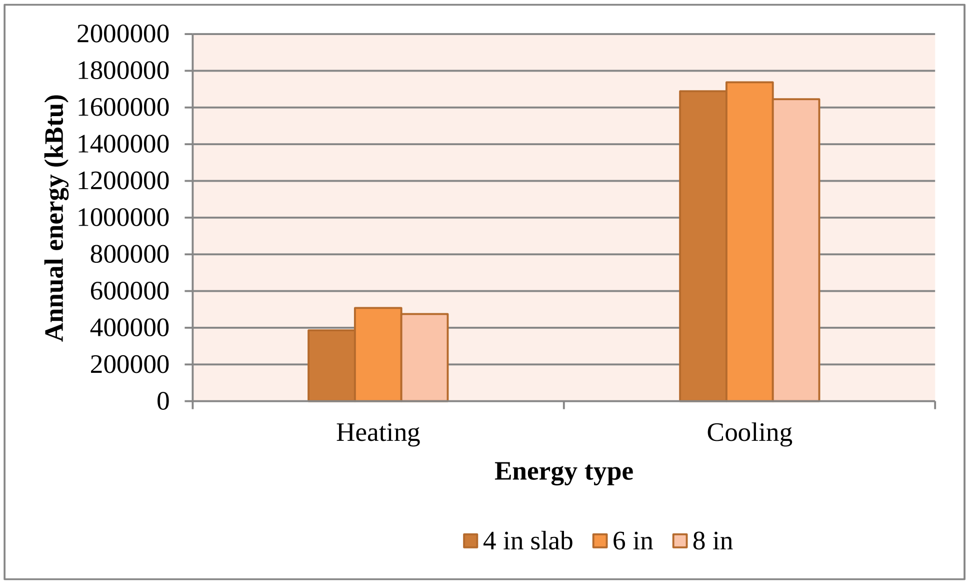


Figure 6.8 Energy use comparison with full daytime ventilation

Table 6.7 Energy reduction with nighttime ventilation

ST Energy type	**Percent reduction (increase) of heating & cooling energy**	
	4 in - 6 in	6 in - 8 in
Heating	(14.8)	7.7
Cooling	(0.1)	(0.8)

Table 6.8 Energy reduction with full time day ventilation

ST Energy type	**Percent reduction (increase) of heating & cooling energy**	
	4 in - 6 in	6 in - 8 in
Heating	(31.8)	6.7
Cooling	(2.9)	5.3

As can be seen, nighttime fan operation (Figure 6.7) and full daytime fan operation (Figure 6.8) have changed both heating and cooling performance. It should be noted that, unlike nighttime or fully daytime cooling, in these cases only fan operation schedule has been changed to include more hours during the day or night. In other words, more outside air (unconditioned) is being introduced to the building. As expected, extra fan operation has significantly increased the heating energy use, which is not desirable. Furthermore, these modified fan schedules are noted to have increased the cooling energies as well although full daytime fan operation significantly reduces the cooling energies when the slab thickness increases from 6 in to 8 in.

6.1.2.2 Change of building occupancy

As discussed in Chapter 4, the change of building occupancy, i.e., from office to residential buildings, can also affect the building energy performance since the level of internal gains changes from one building type to another. Therefore, the building occupancy was changed from office to residential to investigate the effect of reduced internal gains in residential buildings (Table 4.6) on building heating and cooling performance.

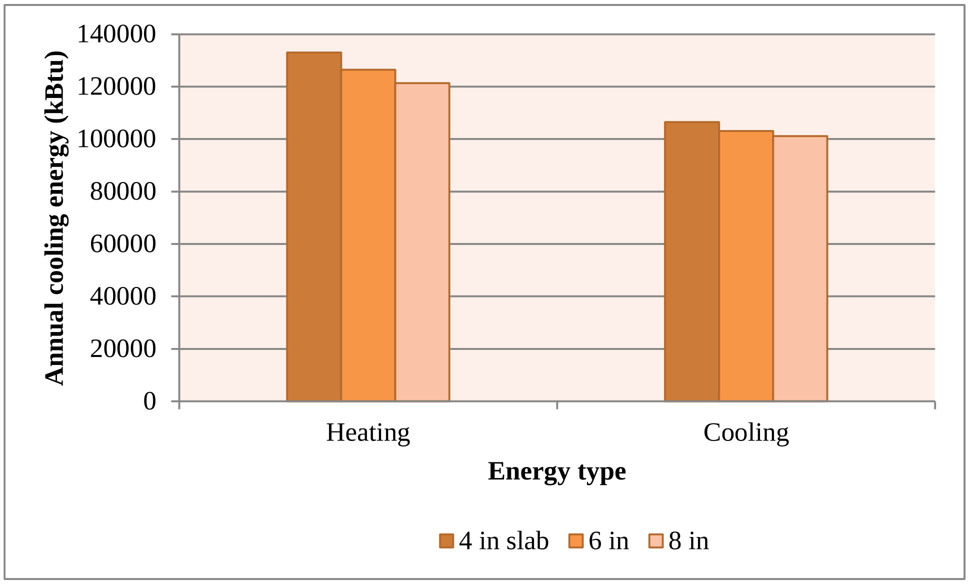


Figure 6.9 Residential energy use comparison

Table 6.9 Residential energy reduction

ST / Energy type	Percent reduction of heating & cooling energy	
	4 in - 6 in	6 in - 8 in
Heating	4.9	4.1
Cooling	3.2	1.9

Figure 6.9 and Table 6.9 show the effects of slab thickness increase in a residential building. It is shown that unlike office buildings, the increase of slab thickness in both cases—from 4 in to 6 in and from 6 in to 8 in—has led to a reduction of both heating and cooling energies, which is a strong indication of how effectively the presence of internal gains in office building and the lack of such internal loads in residential ones can change the building energy performance.

6.1.3 Total energy analysis

As mentioned in the previous sections, the cooling energies increase and the heating energies decrease as a result of slab thickness increase; therefore, the total energies can be expected to show various behaviors of increase or reduction given the different locations. However, the large benefits of heating energy reductions have countered any potential losses due to cooling demand increases. As a result, total energy consumption decreases in almost all cases.

Figure 6.10 and Table 6.10 show the effect of increase in slab thickness on a building's total energy performance. As shown, except for Miami, where the cooling demands dominate the energy design and the total energy use is seen to have increased beyond 8 in thickness, for all other locations, an increase of slab thickness has resulted in the reduction of building's energy use.

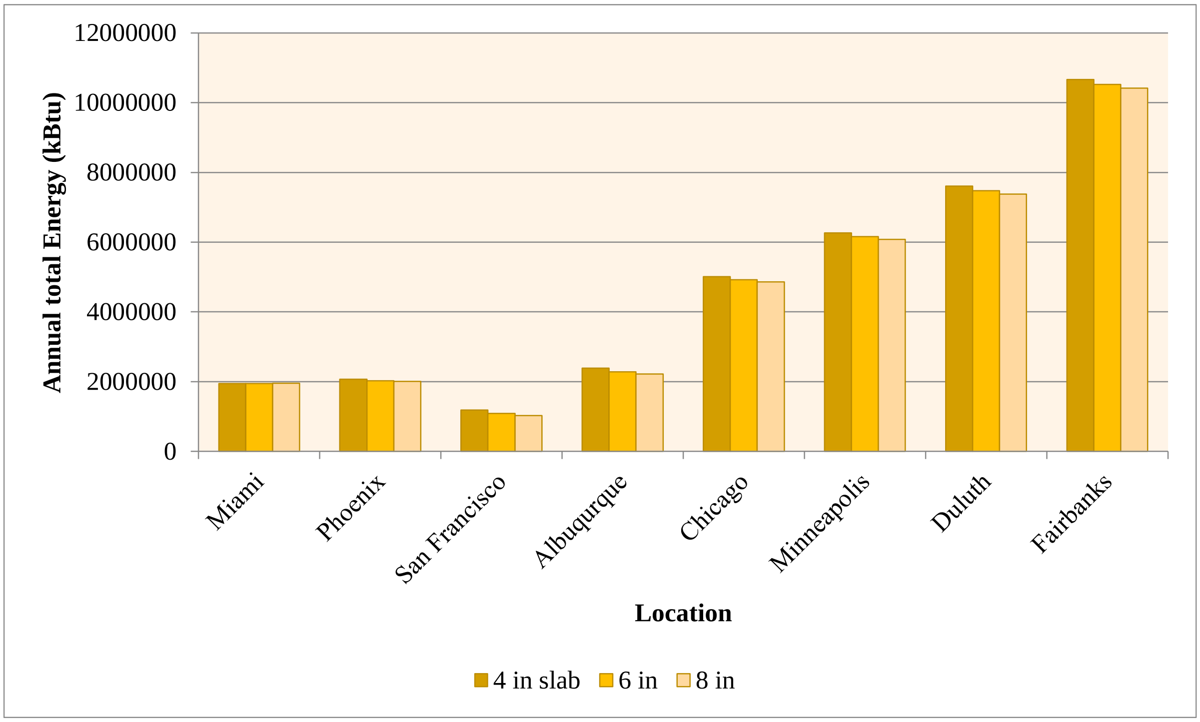


Figure 6.10.Total energy use comparison

Table 6.10 Total energy reductions

ST Location	Percent reduction (increase) of total energy	
	4 in - 6 in	6 in - 8 in
Miami	0.1	(0.4)
Phoenix	2.1	0.9
San Francisco	8.2	5.3
Albuqurque	4.4	2.7
Chicago	1.8	1.3
Minneapolis	1.7	1.2
Duluth	1.8	1.3
Fairbanks	1.3	1.0

6.2 Thermal comfort

To study the effects of variations in thermal mass thickness on thermal comfort, the air, radiant and operative temperatures are measured as the comfort indices. To differentiate between seasonal effects on a building's thermal comfort performance, the first day of the summer and winter—June 21st and December 20th—are chosen to represent the summer and winter conditions. December 20th was taken in lieu of December 21st (actual first winter day) because December 21st was a Saturday (in 2013), when occupants were not present in the building. Furthermore, based on the occupancy schedule, the thermal comfort indices are measured in two categories: 1) occupied daytime hours between 7 AM and 7 PM, and 2) unoccupied nighttime hours between 7 PM and 7 AM.

6.2.1 Air temperature

Figures 6.11 and 6.12, and Tables 6.11 and 6.12 show the change in air temperature as a result of increase in slab thickness in summer during occupied and unoccupied hours.

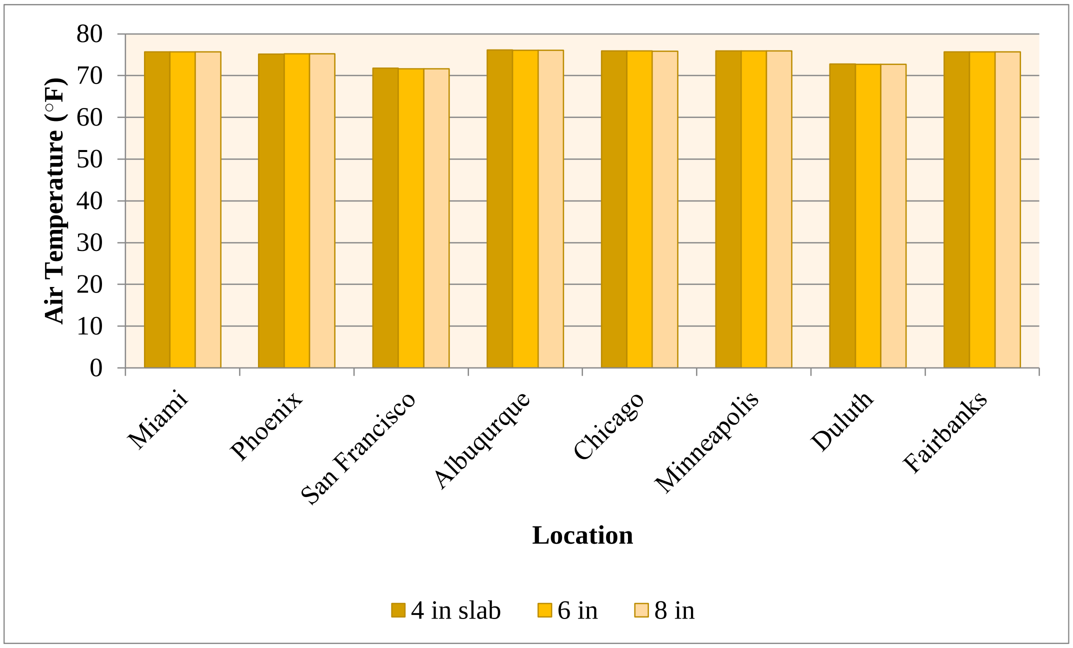


Figure 6.11 Air temperature, summer: occupied hours

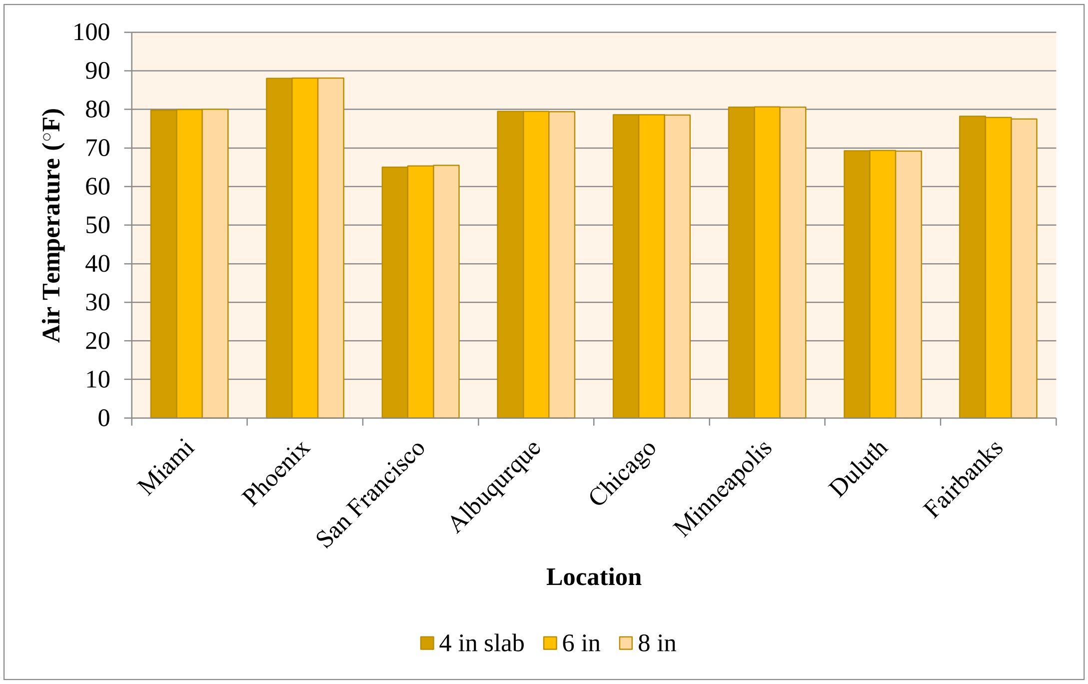


Figure 6.12 Air temperature, summer: unoccupied hours

Table 6.11 Reduction of air temperature, summer occupied hours

ST / Location	**Percent reduction (increase) of air temperature**	
	4 in - 6 in	6 in - 8 in
Miami	(0.01)	0.00
Phoenix	(0.013)	(0.003)
San Francisco	0.23	0.02
Albuqurque	0.02	0.02
Chicago	0.02	0.02
Minneapolis	0.01	0.00
Duluth	0.07	0.03
Fairbanks	(0.01)	0

Table 6.12 Reduction of air temperature, summer unoccupied hours

ST / Location	**Percent reduction (increase) of air temperature**	
	4 in - 6 in	6 in - 8 in
Miami	(0.2)	(0.0)
Phoenix	(0.1)	0.0
San Francisco	(0.5)	(0.2)
Albuqurque	0.0	0.1
Chicago	(0.1)	0.2
Minneapolis	(0.1)	0.1
Duluth	(0.1)	0.2
Fairbanks	0.4	0.5

During occupied hours in summer, it is shown that for Miami and Phoenix, the slab thickness increase has led to a slight air temperature increase, with which the observed cooling energy increase discussed in section 6.1.2 can be attributed. In all other locations, the increase of slab thickness is shown to have generally resulted in a slight reduction of air temperature.

During unoccupied hours in summer, on the other hand, the increase of slab thickness is not very effective in reducing building air temperature. In fact, in most cases, it has led to a slight increase of air temperature.

Figures 6.13 and 6.14 and Tables 6.13 and 6.14 show the air temperature change in winter during both occupied and unoccupied hours. Compared to the summer time, a considerably less change of air temperature takes place when the occupants are present in the building. In fact, except for hot climates, the air temperature relatively remains unchanged in all cases of thermal mass thickness. For unoccupied hours in winter, in almost all locations, a slight reduction of air temperature is observed as a result of wall thickness increase.

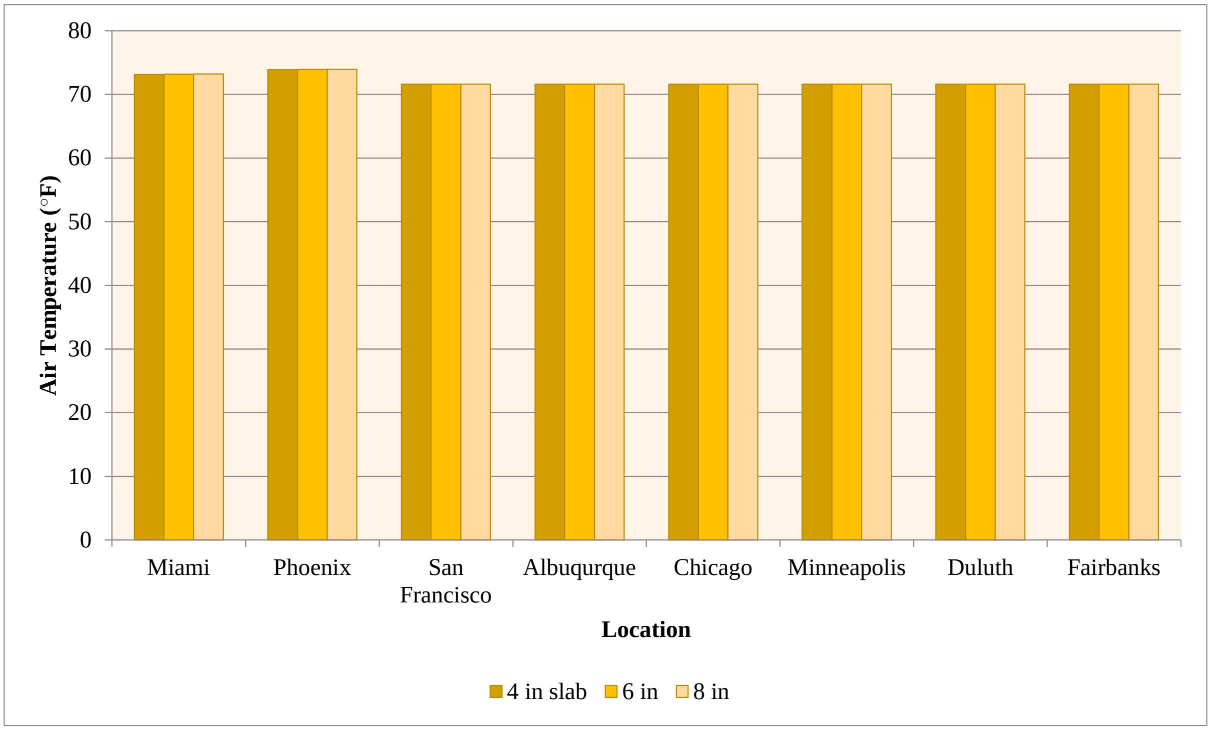


Figure 6.13 Air temperature, winter: occupied hours

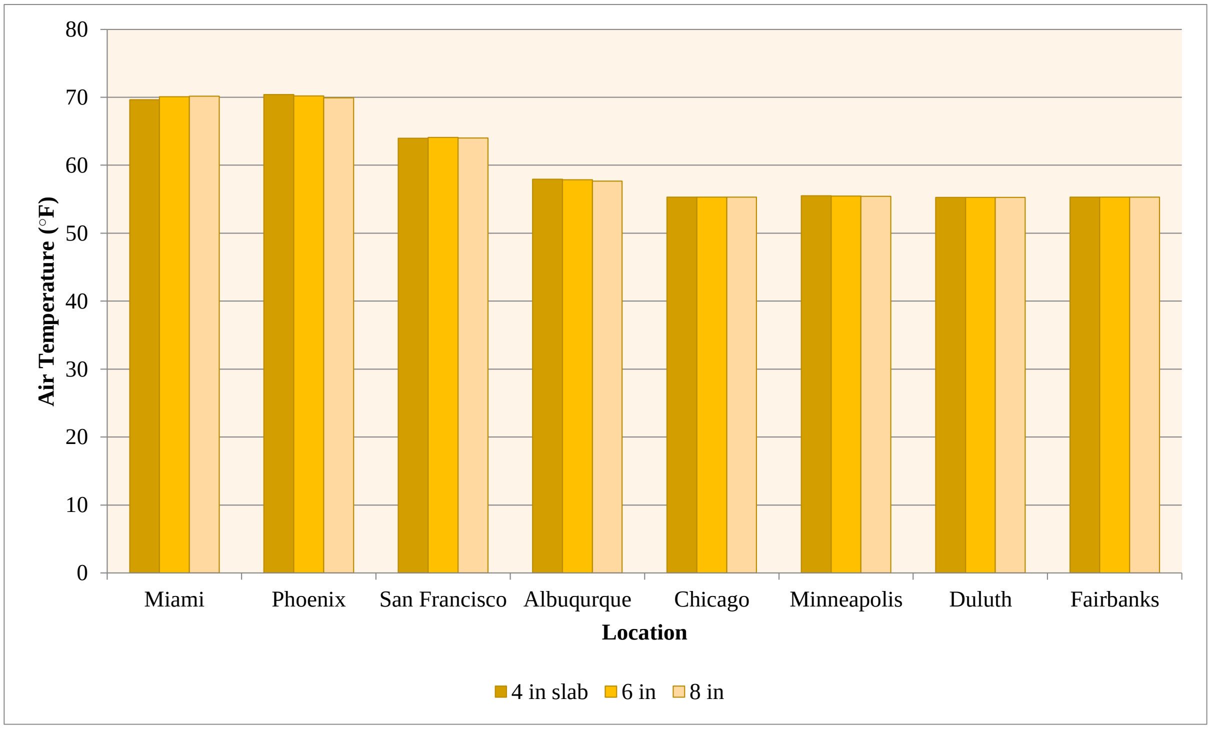


Figure 6.14 Air temperature, winter: unoccupied hours

Table 6.13 Reduction of air temperature, winter occupied hours

ST / Location	Percent reduction (increase) of air temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.04)	(0.08)
Phoenix	(0.03)	(0.01)
San Francisco	0	0
Albuqurque	0	0
Chicago	0	0
Minneapolis	0	0
Duluth	0	0
Fairbanks	0	0

Table 6.14 Reduction of air temperature, winter unoccupied hours

ST / Location	Percent reduction (increase) of air temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.64)	(0.09)
Phoenix	0.24	0.44
San Francisco	(0.22)	0.15
Albuqurque	0.16	0.30
Chicago	0.01	0.00
Minneapolis	0.06	0.04
Duluth	0.01	0.01
Fairbanks	0.01	0.01

6.2.2 Radiant temperature

As stated in Chapter 1 and 2, surface temperature is an important factor in determining the level of thermal comfort in a room. The stored heat in a thermal mass material can generally result in an increase of surface temperature of the material, thus affecting the thermal comfort of the surrounding environment. Figures 6.15 and 6.16 and Tables 6.15 and 6.16 show the change of radiant temperature as a result of thermal mass thickness increase in summer during occupied and unoccupied hours.

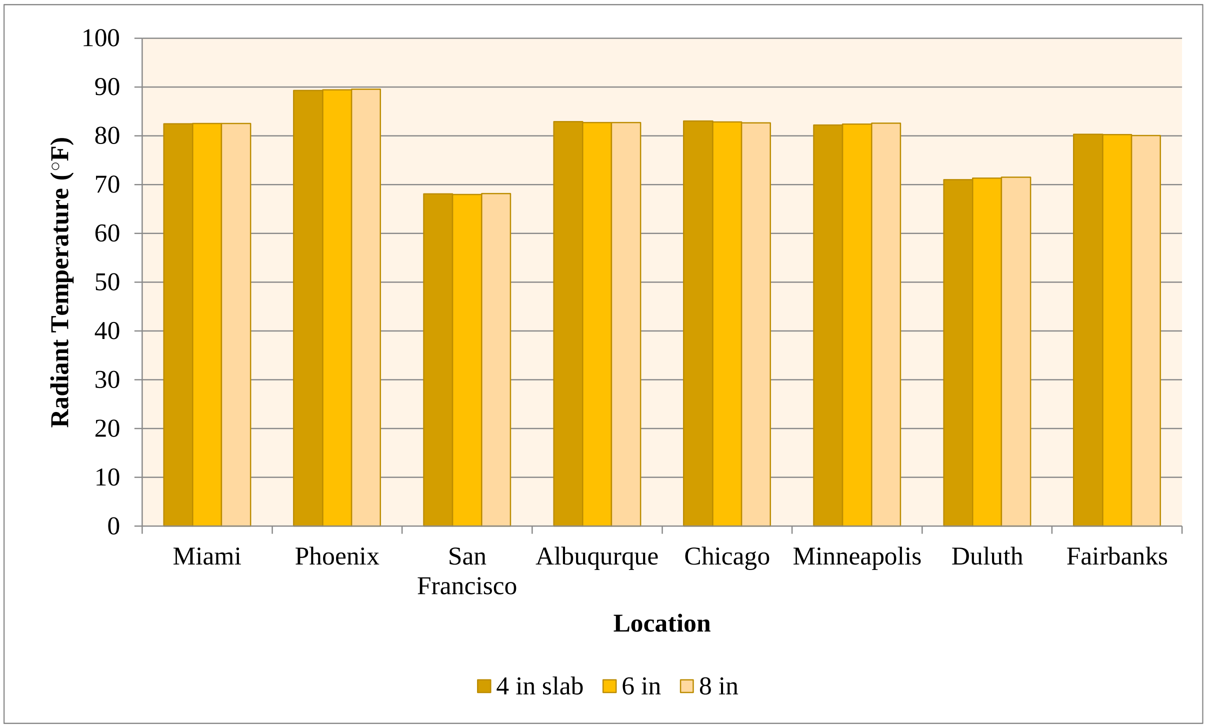


Figure 6.15 Radiant temperature, summer: occupied hours

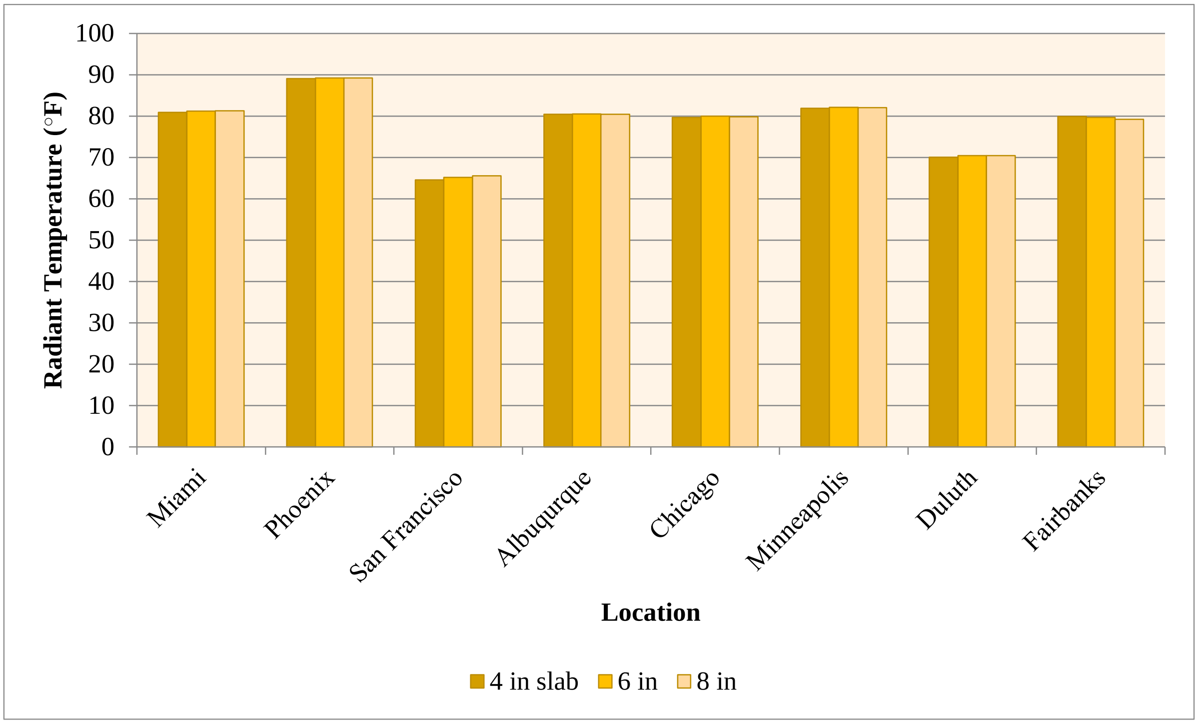


Figure 6.16 Radiant temperature, summer: unoccupied hours

Table 6.15 Reduction of radiant temperature, summer: occupied hours

ST Location	**Percent reduction (increase) of radaint temperature**	
	4 in - 6 in	6 in - 8 in
Miami	(0.0)	(0.0)
Phoenix	(0.1)	(0.2)
San Francisco	0.2	(0.2)
Albuqurque	0.2	0.0
Chicago	0.2	0.2
Minneapolis	(0.3)	(0.2)
Duluth	(0.4)	(0.2)
Fairbanks	0.1	0.2

Table 6.16 Reduction of radiant temperature, summer: unoccupied hours

ST Location	**Percent reduction (increase) of radaint temperature**	
	4 in - 6 in	6 in - 8 in
Miami	(0.3)	(0.1)
Phoenix	(0.1)	(0.1)
San Francisco	(1.0)	(0.5)
Albuqurque	(0.1)	0.1
Chicago	(0.3)	0.1
Minneapolis	(0.3)	0.0
Duluth	(0.6)	0.0
Fairbanks	0.2	0.5

It is shown that the surface temperature shows different patterns of increase and decrease in different locations. Compared to the air temperature during summer, the radiant temperatures show greater changes (whether increase or decrease) as a result of thermal mass increase. This phenomenon can be explained by the fact that unlike air temperature that is generally controlled by the thermostats, the radiant temperature is mainly affected by the heat generated from surrounding objects. Therefore, in office buildings where a lot of heat is generated by internal sources, the surface temperature is expected to show more changes as compared to the air temperature.

Contrary to occupied hours, the pattern of radiant temperature change during unoccupied hours is very similar to that of air temperature, which can be seen as a pattern of temperature increase as due to slab thickness increase. However, beyond 6 in slab thickness, the surface temperature generally tends to decrease.

Figures 6.17 and 6.18, and Tables 6.17 and 6.18 show the radiant temperature change in winter during both occupied and unoccupied hours. In comparison with the summer time, a relatively greater change of radiant temperature is observed when the occupants are present in the building than when they are not. For unoccupied hours, the increase of slab thickness has led to an increase of radiant temperature, which can be correlated with heating demand reduction discussed in section 6.1.1. However, during occupied hours, surface temperature tends to decrease in most locations except for the cases where the slab thickness increases beyond 6 in.

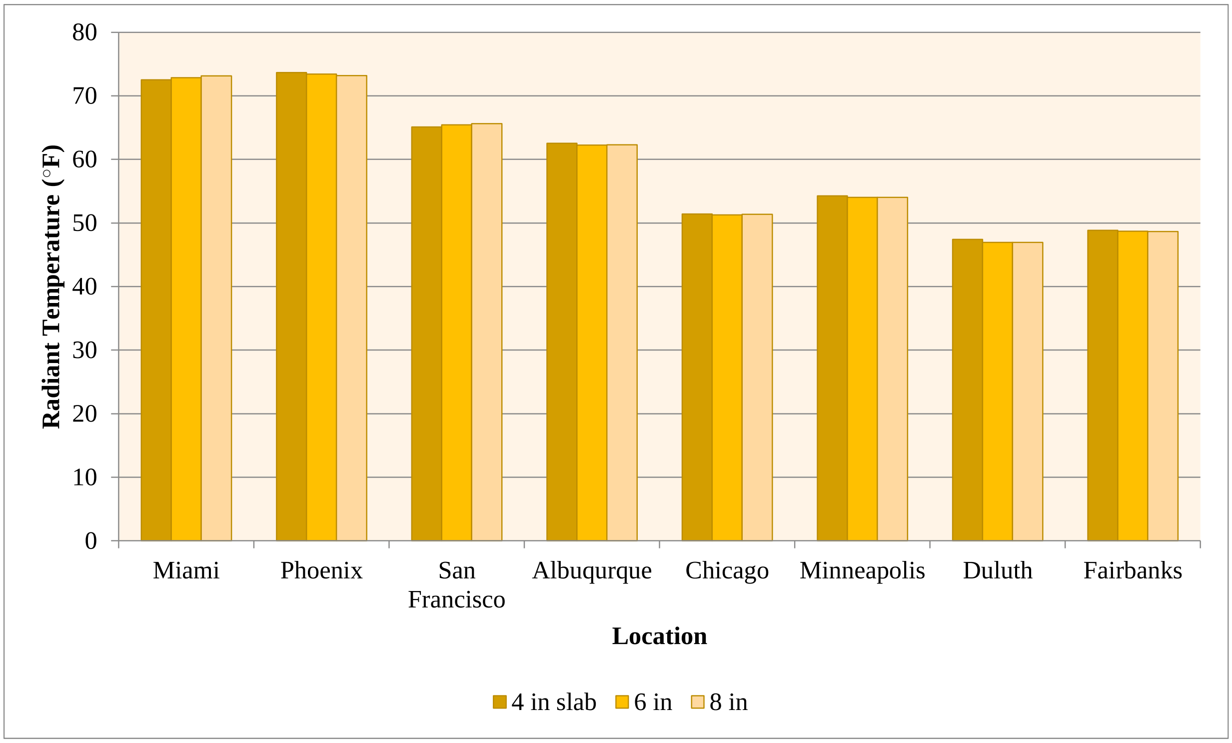


Figure 6.17 Radiant temperature, winter: occupied hours

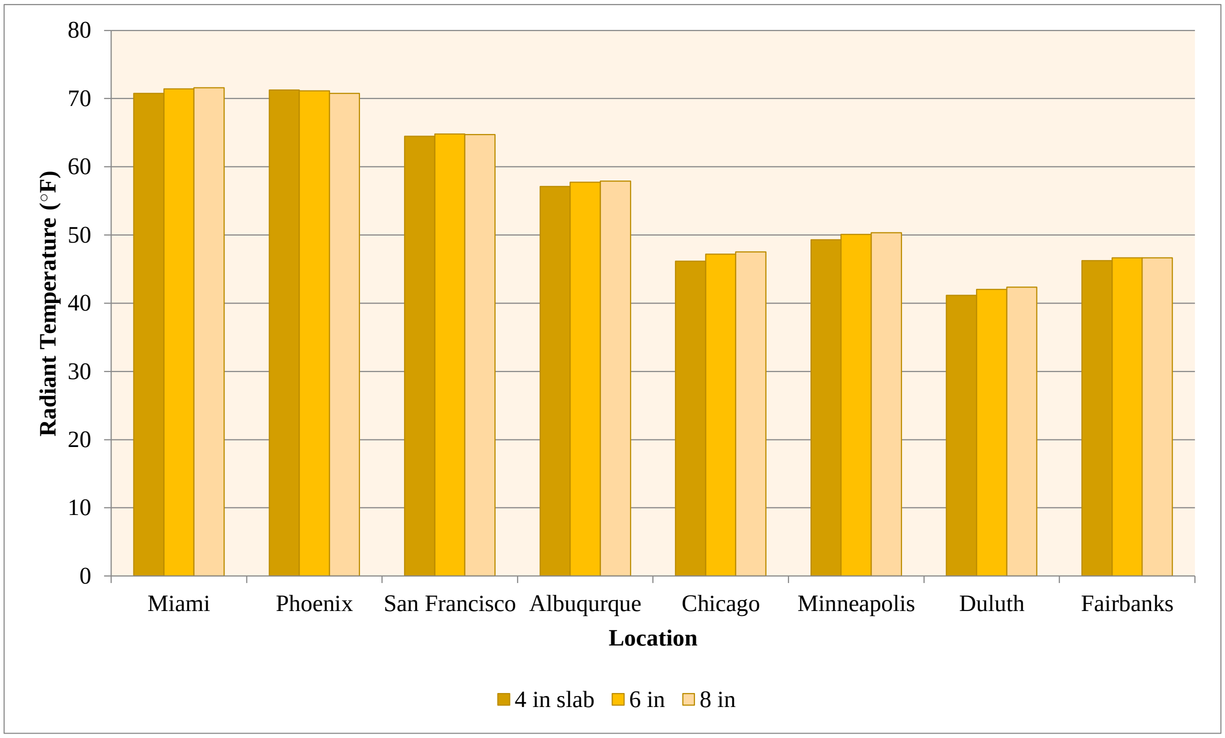


Figure 6.18 Radiant temperature, winter: unoccupied hours

Table 6.17 Reduction of radiant temperature, winter: occupied hours

ST / Location	Percent reduction (increase) of radaint temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.5)	(0.4)
Phoenix	0.4	0.3
San Francisco	(0.5)	(0.3)
Albuqurque	0.5	(0.1)
Chicago	0.3	(0.2)
Minneapolis	0.5	(0.0)
Duluth	1.0	0.1
Fairbanks	0.3	0.1

Table 6.18 Reduction of radiant temperature, winter: unoccupied hours

ST / Location	Percent reduction (increase) of radaint temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.9)	(0.2)
Phoenix	0.1	0.6
San Francisco	(0.5)	0.1
Albuqurque	(1.1)	(0.2)
Chicago	(2.2)	(0.8)
Minneapolis	(1.6)	(0.5)
Duluth	(2.1)	(0.7)
Fairbanks	(0.9)	(0.0)

6.2.3 Operative temperature

As indicated in Chapters 1 and 2, the operative temperature is an average of air and surface radiant temperatures, both of which are affected by the thermal mass property of concrete. Therefore, the operative temperature is a proper indicator of overall thermal level, and hence, comfort level of a room. Figures 6.19 and 6.20 and Tables 6.19 and 6.20 show the change of operative temperature as a result of slab thickness increase in summer during occupied and unoccupied hours.

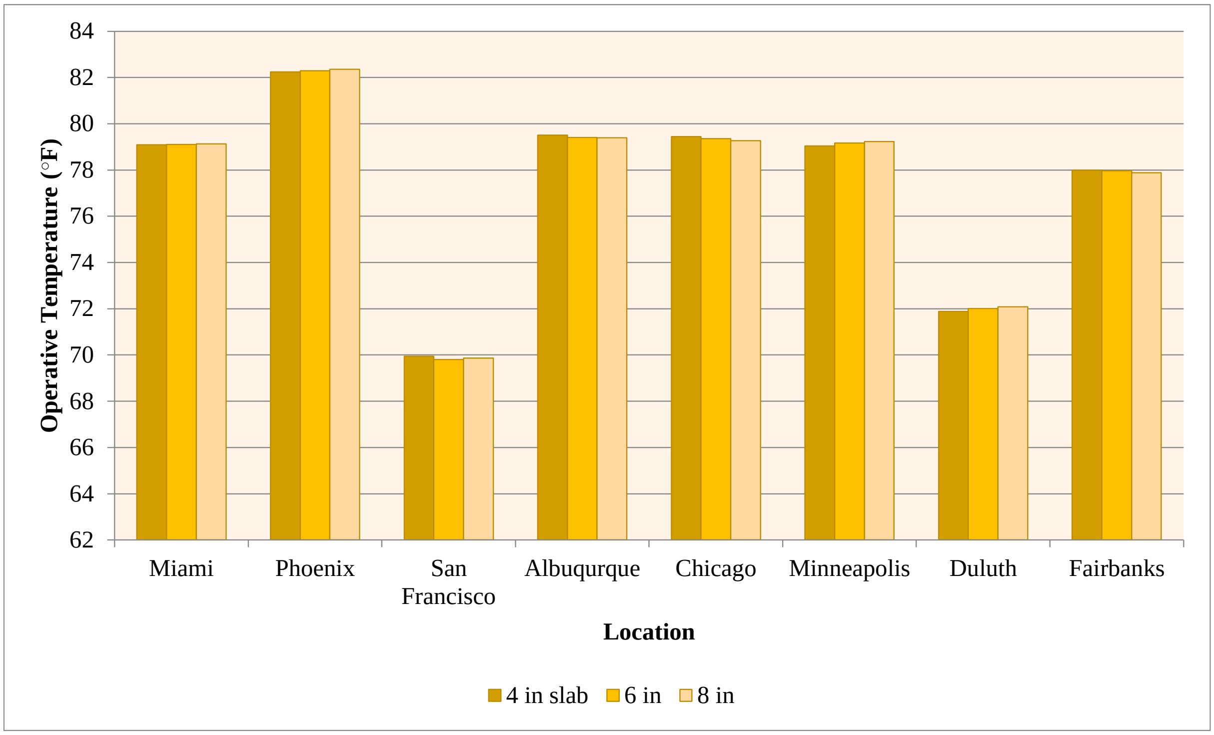


Figure 6.19 Operative temperature, summer: occupied hours

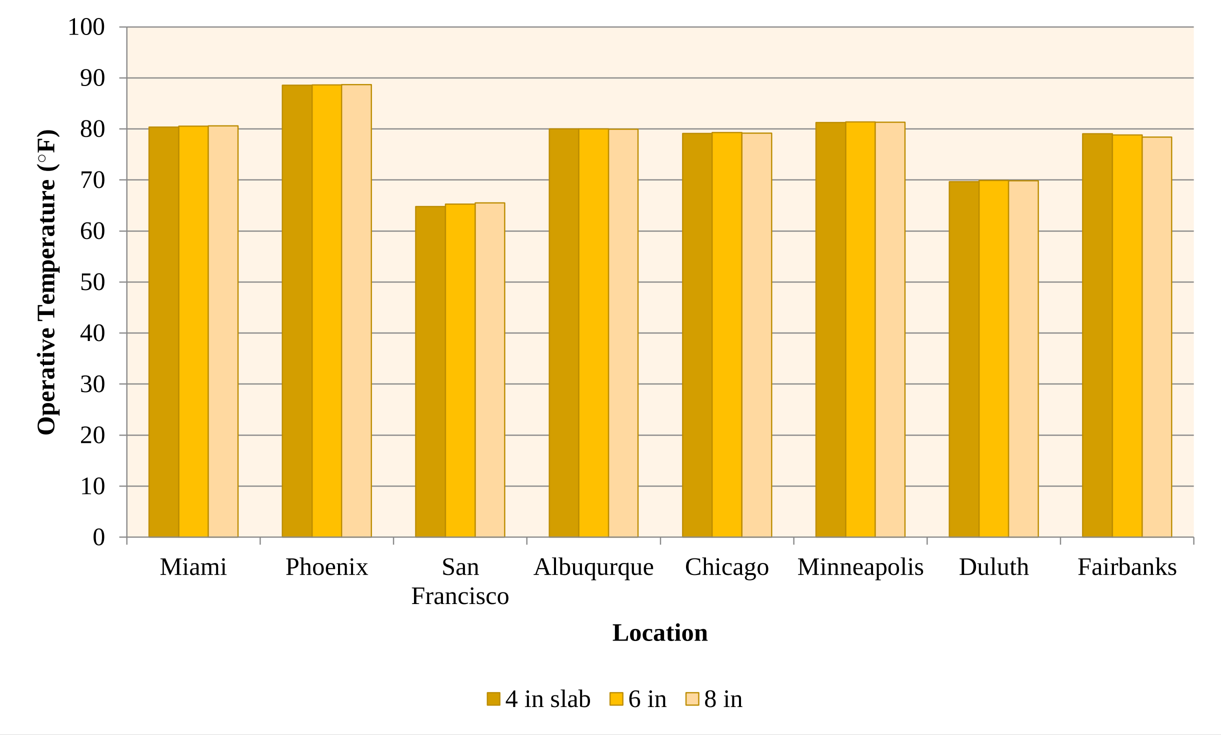


Figure 6.20 Operative temperature, summer: unoccupied hours

Table 6.19 Reduction of operative temperature, summer: occupied hours

ST	Percent reduction (increase) of operative temperature	
Location	4 in - 6 in	6 in - 8 in
Miami	(0.0)	(0.0)
Phoenix	(0.1)	(0.1)
San Francisco	0.2	(0.1)
Albuqurque	0.1	0.0
Chicago	0.1	0.1
Minneapolis	(0.1)	(0.1)
Duluth	(0.2)	(0.1)
Fairbanks	0	0

Table 6.20 Reduction of operative temperature, summer: unoccupied hours

ST	Percent reduction (increase) of operative temperature	
Location	4 in - 6 in	6 in - 8 in
Miami	(0.3)	(0.1)
Phoenix	(0.1)	(0.0)
San Francisco	(0.7)	(0.4)
Albuqurque	(0.0)	0.1
Chicago	(0.2)	0.2
Minneapolis	(0.2)	0.1
Duluth	(0.4)	0.1
Fairbanks	0.3	0.5

It is shown that the pattern of operative temperature reduction is more similar to the reduction pattern observed for the radiant temperature than the air temperature, which highlights the importance of surface temperature effects on thermal comfort.

Figures 6.21 and 6.22, and Tables 6.21 and 6.22 show the operative temperature changes in winter during both occupied and unoccupied hours. Compared to summer time, relatively similar changes of operative temperature are observed when the occupants are present in the building than when they are not. Furthermore, similar to surface temperature, during winter unoccupied hours the increase of slab thickness leads to an increase in operative temperature, which can be beneficial in reducing the heating demands of the buildings.

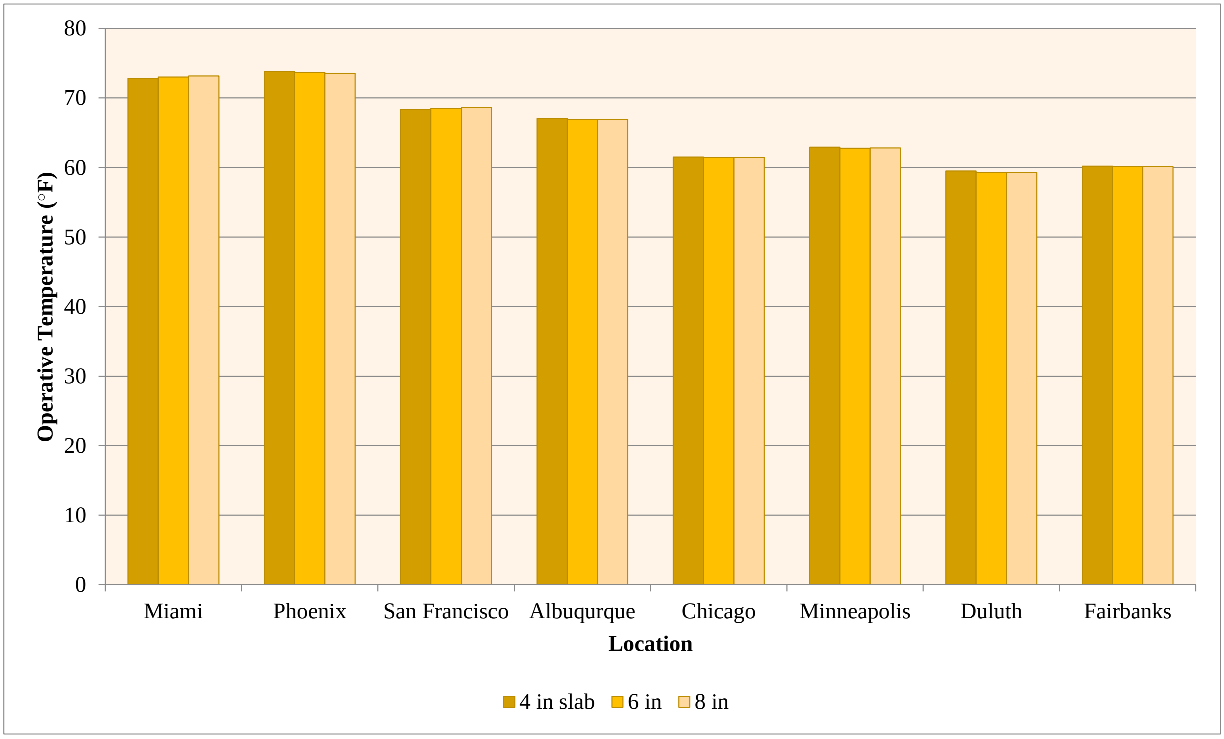


Figure 6.21 Operative temperature, winter: occupied hours

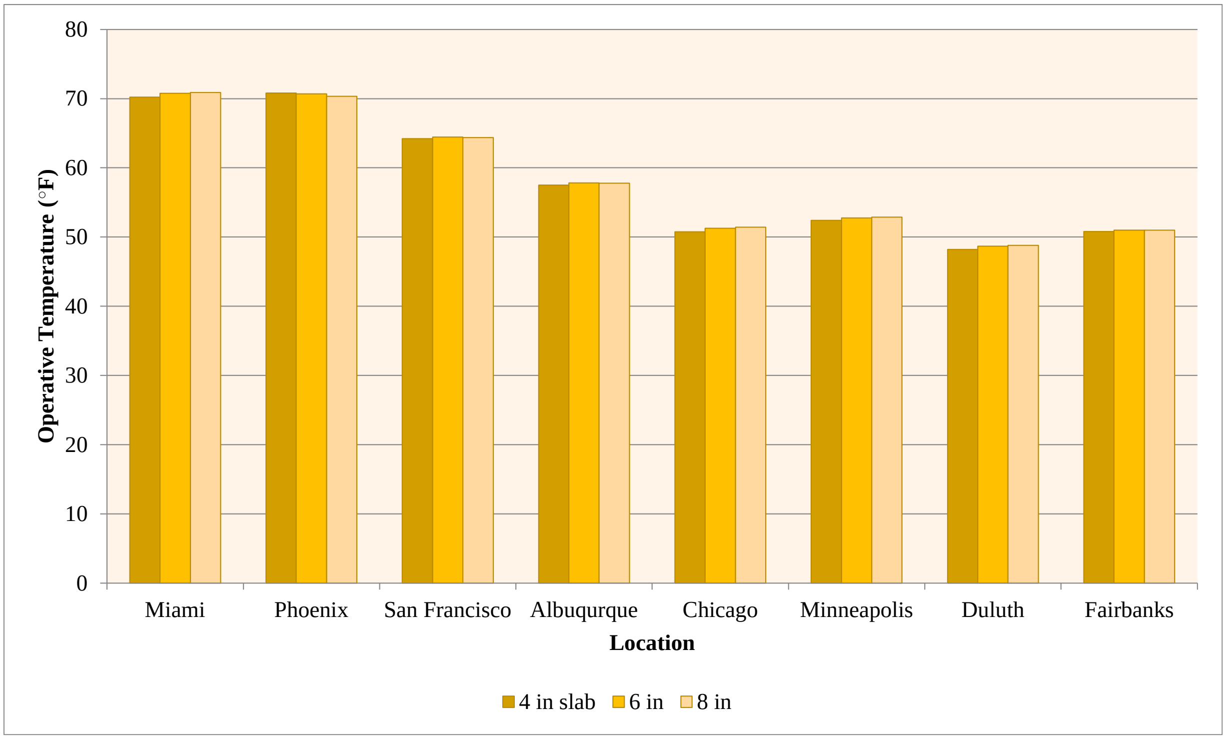


Figure 6.22 Operative temperature, winter: unoccupied hours

Table 6.21 Reduction of operative temperature, winter: occupied hours

ST / Location	Percent reduction (increase) of operative temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.3)	(0.2)
Phoenix	0.2	0.1
San Francisco	(0.3)	(0.1)
Albuqurque	0.2	(0.1)
Chicago	0.1	(0.1)
Minneapolis	0.2	(0.0)
Duluth	0.4	0.0
Fairbanks	0.1	0.0

Table 6.22 Reduction of operative temperature, winter: unoccupied hours

ST / Location	Percent reduction (increase) of operative temperature	
	4 in - 6 in	6 in - 8 in
Miami	(0.8)	(0.2)
Phoenix	0.2	0.5
San Francisco	(0.4)	0.1
Albuqurque	(0.5)	0.0
Chicago	(1.0)	(0.3)
Minneapolis	(1)	0
Duluth	(0.9)	0
Fairbanks	(0.4)	0

6.3 Discussion

In this chapter the increase in the thickness of thermal mass slabs—ranging from 4 in (base case) to 8 in—on building energy use and thermal comfort has been studied. The results have shown that incremental thermal mass area can be relatively effective in changing the building’s energy and thermal comfort performance.

In terms of building energy use, the increase of slab thickness is noted to consistently reduce the heating energy use for all cases, regardless of location. The heating loads are also seen to decrease as a result of slab thickness increase, which is beneficial in downsizing the HVAC heating equipment such as boilers. The cooling energies, on the other hand, tend to increase in hot location such as Phoenix when the thermal mass thickness generally increases or even in cold climates such as Minneapolis when the slab thickness increases beyond 6 in. Unlike the change of HVAC schedule to provide nighttime or full daytime cooling or ventilation, change of building occupancy from office to residential, and consequently having lower internal gains, is noted to have been beneficial to reverse the pattern of cooling increase. Except for Miami, the cooling load decreases as a result of thermal mass increase, which helps reduce the size of HVAC cooling equipment, e.g., chillers. The total energy use of the building is found to generally decrease as a result of slab thickness increase, which is beneficial.

Regarding thermal comfort parameters, the summer air temperature shows a mixed pattern of increase and decrease in different locations although during unoccupied hours the air temperature change shows a decreasing pattern. In the winter, the air temperature generally remains unchanged for different cases during occupied hours but shows slight reductions during unoccupied hours. Similarly, the summer radiant and operative temperatures did not show consistent patterns of either increase or decrease for all locations; however, the magnitudes of temperature changes are observed to be significantly greater than those for the air temperature. During winter, the radiant and operative temperatures generally increase as a result of slab thickness increase, to which the reduction of heating energies can be attributed.

The next chapter focuses on the effectiveness of thermal mass distribution pertaining to interior walls on building energy and thermal comfort performance.

6.4 Summary

This chapter reviews the effectiveness of thickness increase of concrete floor slabs on building energy and thermal comfort performance. The concrete slab thickness was increased from 4 in to 6 in and 8 in and then, the effect of such increase on building energy and thermal comfort performance was analyzed. Given the observed cooling energy increase behavior as a result of slab thickness increase, the building cooling and ventilation schedules were modified to investigate the possibility of internal gain effects on cooling energy increase. Nighttime and fully daytime cooling schedules as well as nighttime and fully daytime ventilation only schedules were studied to determine potential causes that had led to cooling energy increase. The building occupancy was also changed to residential to further assess the impacts of internal gains on building cooling performance as compared to those in office buildings. Compared to primary thermal mass—perimeter wall thickness and thermal mass area on building façade—a secondary thermal mass parameter such as slab thickness is shown to be less effective in affecting building energy performance.

CHAPTER 7:

INTERIOR WALLS and BUILDING PERFORMANCE

Chapter 4 and 5 discussed the primary thermal mass, perimeter wall thickness and thermal mass distribution on building façade, and how effectively they can affect building energy and thermal comfort performance. In Chapter 6, the discussion on secondary thermal mass (interior thermal mass elements) began by assessing the effect of slab thickness increase on building energy and thermal comfort performance. In this chapter, the study of secondary thermal mass continues by considering various interior wall layouts (IWLs) that surrounds the building core and their effects on building energy use and thermal comfort.

A concrete core, which can be used as a structural element for lateral load resistance and circulation core, was added to the open office space. Then, different configurations of the concrete core (Figures7.1, 7.2 and 7.3) including central core (CC), split core on the long (far) sides of the plan (SCL) and split core on the short (near) side of the plan (SCS) were studied and their different effects on building performance were compared to the base case (BC) building, where there are no interior concrete walls in the office space. The thickness of interior walls of 4 in (similar to the BC model) was kept constant for all cases to solely examine the effects of layout of the walls.

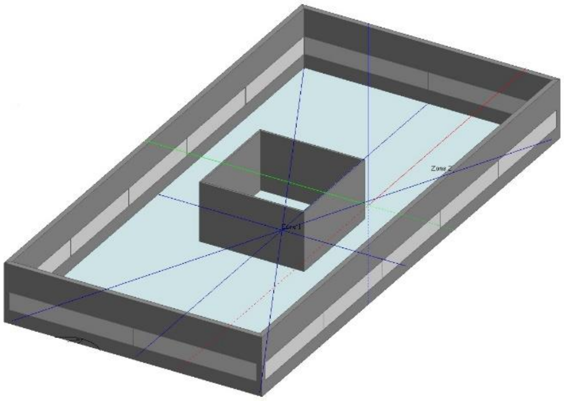


Figure 7.1 Central core configuration

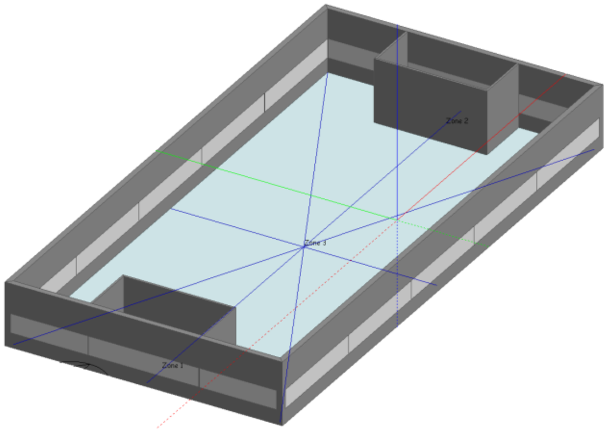


Figure 7.2 Split-core long side configuration

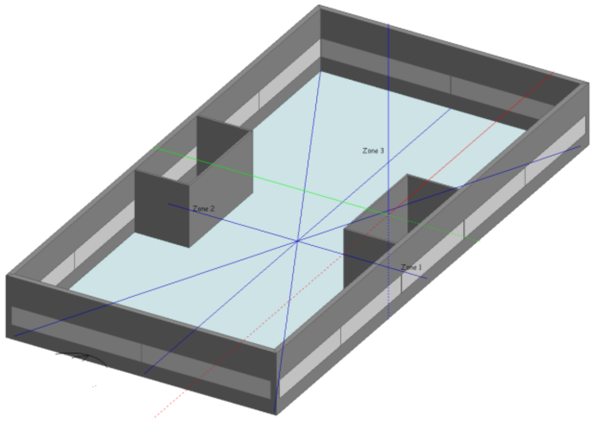


Figure 7.3 Split-core short side configuration

It may be noted that despite different core configurations, the total volume of thermal mass concrete remains unchanged for all cases.

7.1 Energy analysis

In terms of the energy consumption analysis, the annual heating and cooling energies as well as peak heating and cooling loads are the measurements indices used to compare the energy performance of the different models, albeit other design parameters such as thermal mass area or external wall thickness are kept constant in accordance with the BC model (i.e. thermal mass area: 70% of the façade and wall thickness: 4 in)

7.1.1 Heating energy analysis

Figure 7.4 and Table 7.1 show the heating energy performance for different IWLs in eight locations studied in this research.

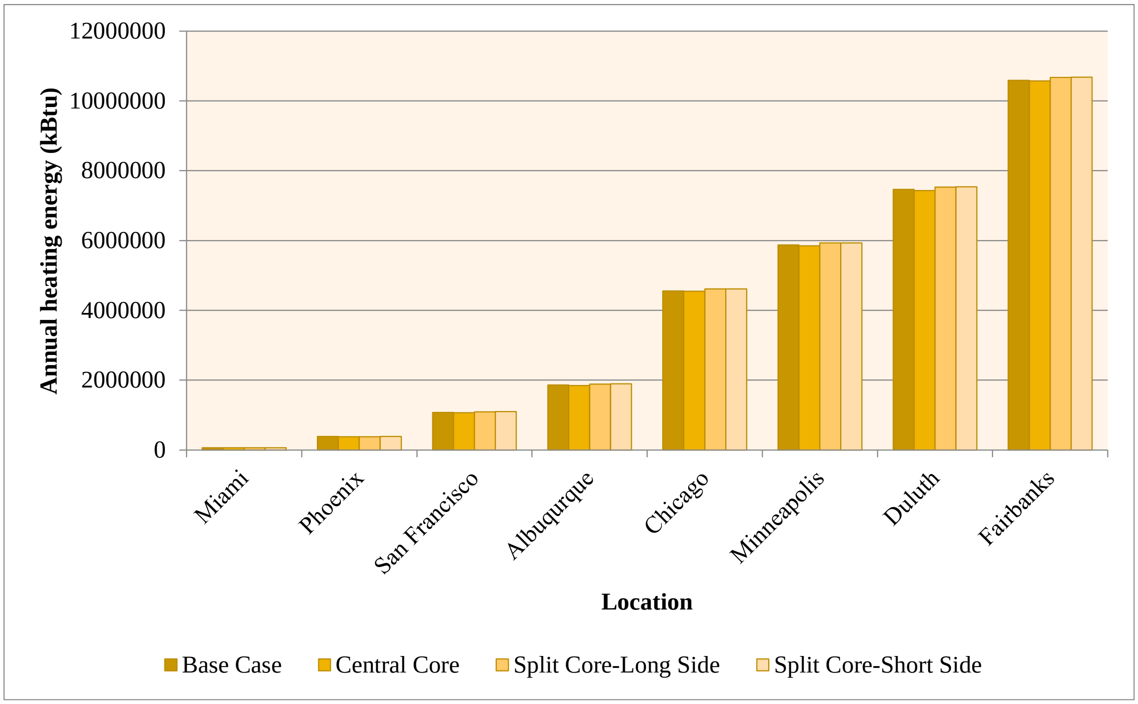


Figure 7.4 Heating energy use comparison

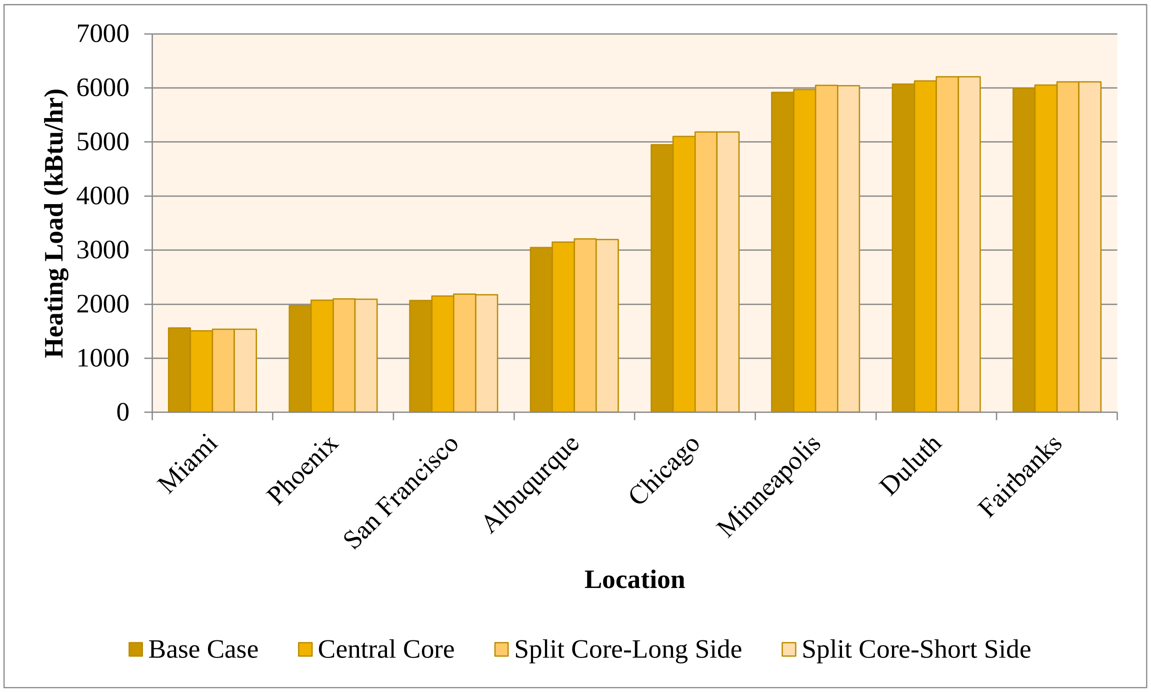


Figure 7.5 Heating load comparison

Table 7.1 Heating energy reductions (increase)

IWL* / Location	**Percent reduction (increase) of heating energy**		
	BC - CC	BC - SCL	BC - SCS
Miami	6.7	7.4	6.7
Phoenix	2.6	1.2	(0.2)
San Francisco	0.6	(1.9)	(2.8)
Albuqurque	1.0	(1.0)	(1.6)
Chicago	0.3	(1.2)	(1.2)
Minneapolis	0.3	(1.0)	(1.1)
Duluth	0.4	(1.0)	(1.0)
Fairbanks	0.1	(0.9)	(0.9)

Table 7.2 Heating load reductions (increase)

IWL / Location	**Percent reduction (increase) of heating load**		
	BC - CC	BC - SCL	BC - SCS
Miami	3.4	1.5	1.6
Phoenix	(4.9)	(6.1)	(5.8)
San Francisco	(4.2)	(5.9)	(5.4)
Albuqurque	(3.3)	(5.2)	(4.7)
Chicago	(3.1)	(4.8)	(4.7)
Minneapolis	(0.9)	(2.2)	(2.1)
Duluth	(0.9)	(2.2)	(2.2)
Fairbanks	(1.0)	(2.0)	(2.0)

Note: IWL, BC, CC, SCL, and SCS stand for IWLs, base case, central core, split core long-side, split core short-side, respectively in this and all other tables.

As shown, the central core cases have mainly resulted in heating energy reductions; however, split core cases, whether on the long or short sides of the plan, have mainly led to an increase of heating energy use. Figure 7.5 and Table 7.2 demonstrate the impact of IWLs on peak heating loads in different climate zones. Except for the Miami, adding interior walls to the open office space, regardless of their locations, is shown to have increased the building heating loads. This increase of heating energies for split core cases can be attributed to the fact that interior walls on either side of the plan would block the sunlight and keep it from entering the space. As a result, the sunlight contribution to the heating energy use and its effect on reducing building heating energy demands would be missing, which in turn, can result in an increase of heating energies as compared to both base case and central core cases, where sunlight can penetrate from fenestrations on all sides of the building façade.

The reduction of heating energies for central core cases is shown to be higher in hot locations such as Miami or Phoenix as compared to the cold climates. This phenomenon was also observed in preliminary design phase, where the reduction of heating demands due to thermal mass is considerably higher in hot climates than it is in cold locations. It is known that temperature swings are considerably higher in hot climates as compared to cold locations. Furthermore, unlike the cold climate zones, all hot locations in this study are also very sunny locations; therefore, exposure to the sun can improve and enhance the effect of thermal mass. Moreover, the building HVAC system (VAV system with terminal reheats) can be another beneficiary from thermal mass. Since the building thermal mass stores heat for a longer period of time, the demand for re-heating the cool air to meet the cooling set-point temperature decreases. Therefore, there can be a lower demand for heating in the building, which in turn, can lead to a reduction in heating energies and heating loads.

7.1.2 Cooling energy analysis

Figures 7.6 and 7.7 and Tables 7.3 and 7.4 show the effects of IWLs on cooling energies and cooling loads. As shown these images, almost all interior wall scenarios have led to an increase of both cooling energies and cooling loads.

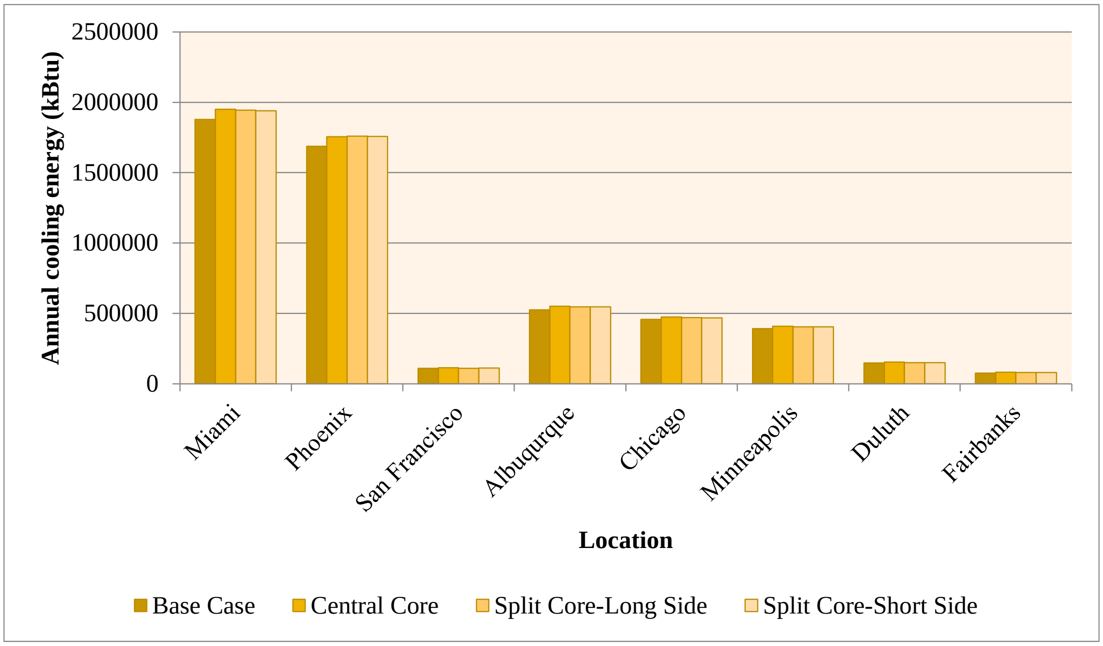


Figure 7.6 Cooling energy use comparison

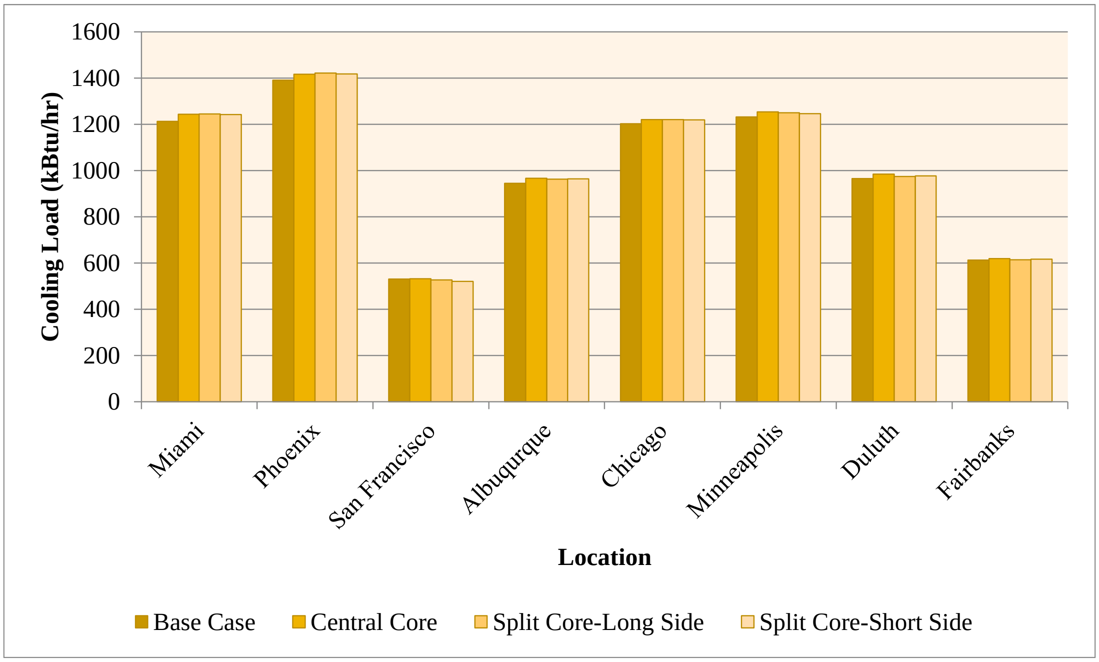


Figure 7.7 Cooling load comparison

Table 7.3 Cooling energy reductions (increase)

IWL	**Percent reduction (increase) of cooling energy**		
Location	BC - CC	BC - SCL	BC - SCS
Miami	(3.8)	(3.5)	(3.2)
Phoenix	(4.0)	(4.2)	(4.2)
San Francisco	(3.6)	1.0	(0.4)
Albuqurque	(4.8)	(3.9)	(4.0)
Chicago	(3.9)	(2.8)	(2.5)
Minneapolis	(4.4)	(3.3)	(3.0)
Duluth	(4.0)	(1.5)	(1.0)
Fairbanks	(7.2)	(4.5)	(3.9)

Table 7.4 Cooling load reductions (increase)

IWL	**Percent reduction (increase) of cooling load**		
Location	BC - CC	BC - SCL	BC - SCS
Miami	(2.6)	(2.6)	(2.4)
Phoenix	(1.8)	(2.2)	(1.9)
San Francisco	(0.2)	0.6	1.8
Albuqurque	(2.3)	(1.9)	(2.0)
Chicago	(1.6)	(1.5)	(1.4)
Minneapolis	(1.7)	(1.5)	(1.1)
Duluth	(1.9)	(0.9)	(1.1)
Fairbanks	(1.1)	(0.3)	(0.7)

It is seen that almost all interior wall layout scenarios have led to an increase in both cooling energies and cooling loads, which is not desirable because of both higher energy cost and greater size of cooling equipment such as chillers.

To further study the effect of interior concrete walls on cooling demands, Phoenix was chosen to run a series of simulations for with different building type. The goal is to determine what other parameters than interior walls may have led to the increase of heating and cooling energies.

7.1.2.1 Change of building occupancy

As discussed in Chapter 4 and 6, the change of building type, i.e. from office to residential buildings, can also affect the building energy performance since the level of internal gains changes from one building type to another. Therefore, the building occupancy was changed from office to residential to investigate the effect of reduced internal gains in residential buildings on building heating and cooling performance. Figure 7.8 and Table 7.5 show the results of adding concrete interior walls to a residential building in Phoenix. No energy reduction was observed for this building occupancy.

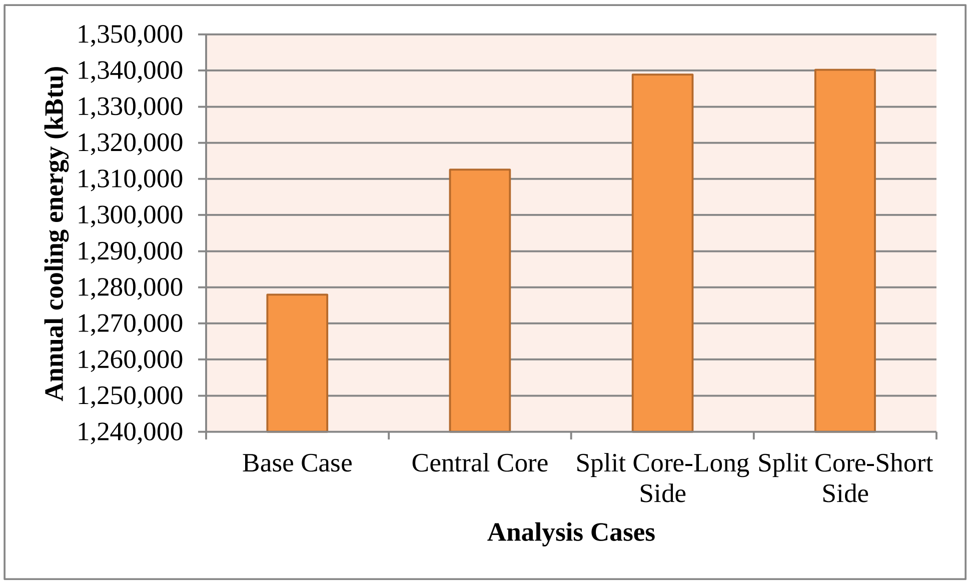


Figure 7.8 Residential energy use comparison

Table 7.5 Residential energy reductions

IWL / Location	Percent reduction (increase) of cooling energy		
	BC - CC	BC - SCL	BC - SCS
Phoenix	(2.7)	(4.8)	(4.9)

The results show that despite the change of building occupancy from office to residential and consequently lowering building internal gains, the cooling energy increased when the interior walls were added to the open office space.

7.1.3 Total energy analysis

As mentioned in the previous sections, both heating and cooling energies are generally shown to have increased as a result of adding interior walls to the office space; therefore, the total energies can also be expected to have increased in almost all interior wall layout cases.

Figure 7.9 and Table 7.6 show the effect of IWLs on a building's total energy performance. As shown, except for a few cases where a central core is added to the plans, different interior wall layout cases have resulted in the increase of building's energy use.

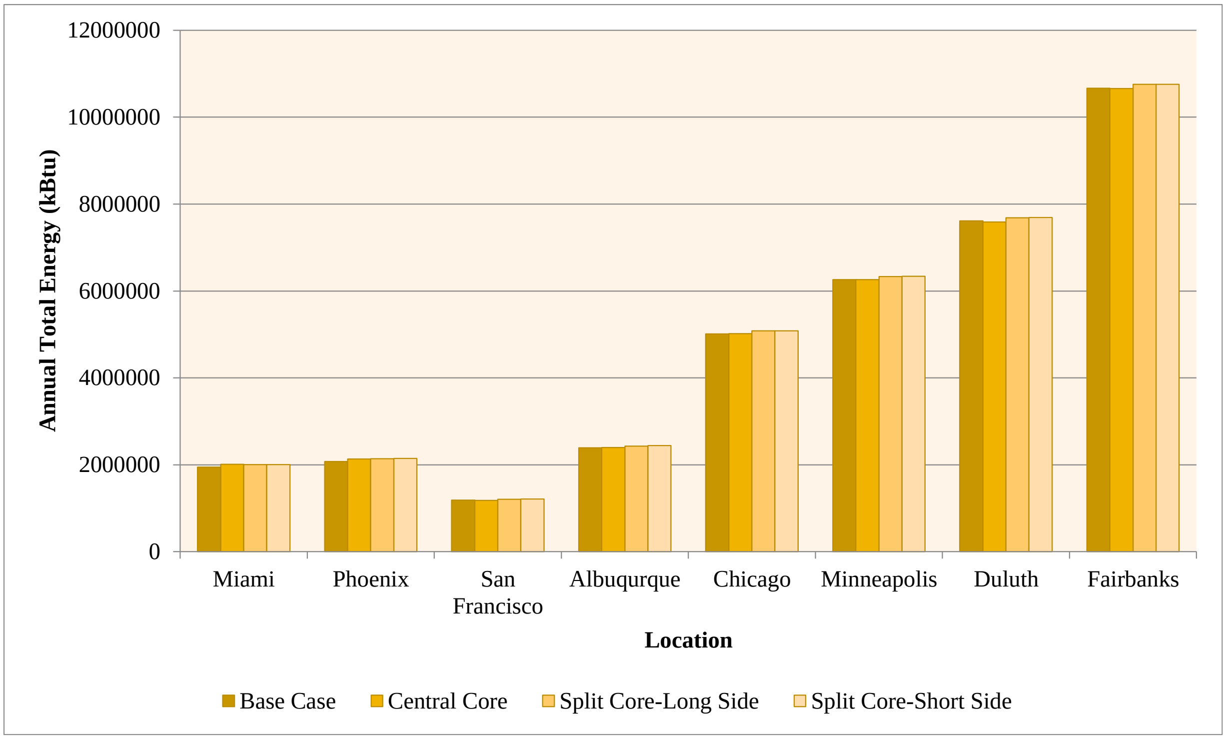


Figure 7.9 Total energy use comparison

Table 7.6 Total energy reductions

IWL / Location	Percent reduction (increase) of total energy		
	BC - CC	BC - SCL	BC - SCS
Miami	(3.4)	(3.1)	(2.9)
Phoenix	(2.8)	(3.2)	(3.4)
San Francisco	0.3	(1.6)	(2.6)
Albuqurque	(0.3)	(1.7)	(2.2)
Chicago	(0.1)	(1.3)	(1.4)
Minneapolis	0.0	(1.1)	(1.2)
Duluth	0.3	(1.0)	(1.0)
Fairbanks	0	(0.9)	(0.9)

7.2 Thermal comfort

To study the effects of ranging thermal mass interior configurations on thermal comfort, the air, radiant and operative temperatures are measured as the comfort indices. To differentiate between seasonal effects on building thermal comfort performance, the first days of summer and winter—June 21st and December 20th of 2013—are chosen to represent the summer and winter conditions. December 20th was taken in lieu of December 21st (actual first winter day) because December 21st is a Saturday in 2013, when occupants were not present in the building. Furthermore, based on the occupancy schedule, the thermal comfort indices are measured in two categories: 1) occupied hours between 7 AM and 7 PM, and 2) unoccupied hours: before 7 AM and after 7 PM.

7.2.1 Air temperature

Figures 7.10 and 7.11 and Tables 7.7 and 7.8 show the change in air temperature as a result of various IWLs in summer during occupied and unoccupied hours.

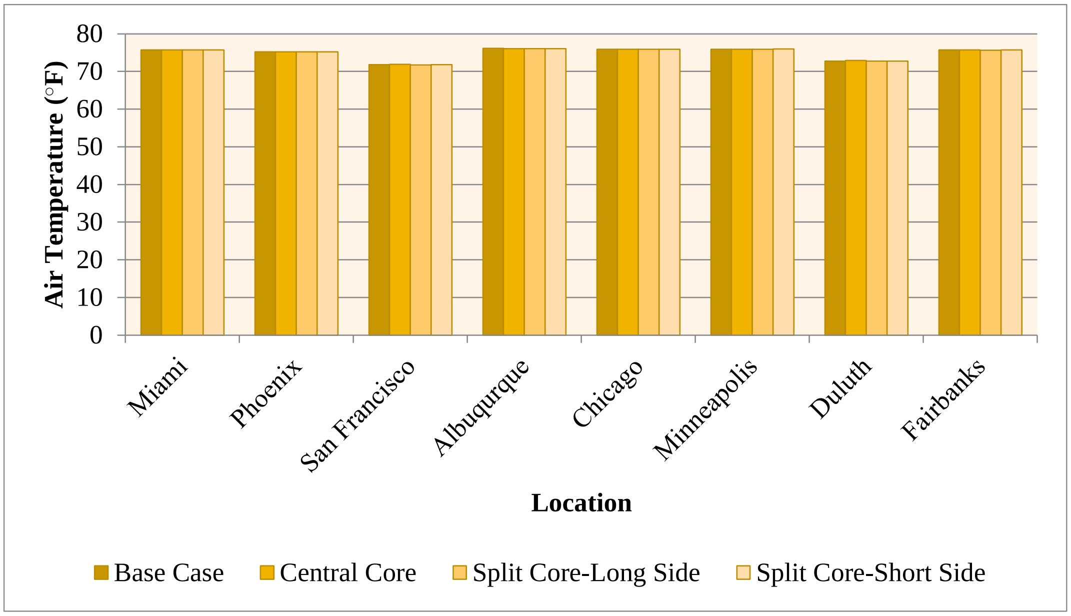


Figure 7.10 Air temperature, summer: occupied hours

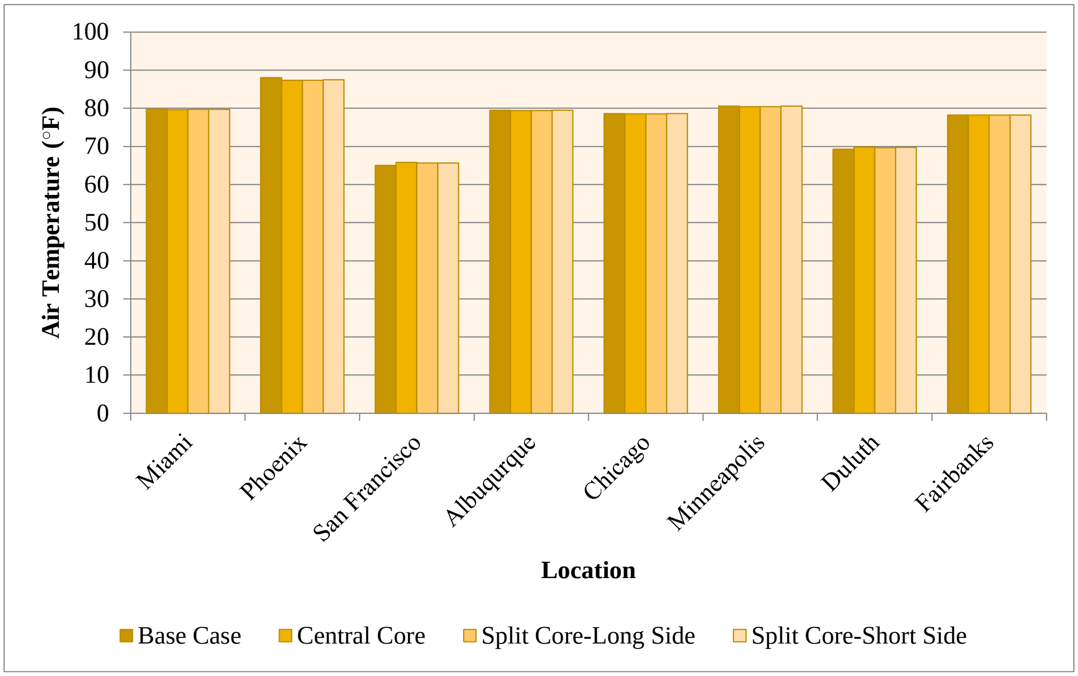


Figure 7.11 Air temperature, summer: unoccupied hours

Table 7.7 Reduction of air temperature, summer occupied hours

IWL / Location	Percent reduction (increase) of air temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.03	0.02	0.02
Phoenix	0	0	0
San Francisco	(0.13)	0.04	(0.02)
Albuquerque	0.07	0.09	0.06
Chicago	0.05	0.05	0.04
Minneapolis	0.04	0.05	(0.08)
Duluth	(0.25)	0.04	(0.03)
Fairbanks	0.02	0.03	0.02

Table 7.8 Reduction of air temperature, summer unoccupied hours

IWL / Location	Percent reduction (increase) of air temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.2	0.1	0.2
Phoenix	0.9	0.8	0.7
San Francisco	(1.2)	(0.9)	(0.9)
Albuquerque	0.1	0.2	0.0
Chicago	0.1	0.1	0.0
Minneapolis	0.3	0.2	0.1
Duluth	(0.8)	(0.6)	(0.7)
Fairbanks	0.1	0.1	(0.0)

During summer occupied hours, it is shown that except for a few cases in San Francisco and Duluth, the IWLs have slightly reduced the air temperature. In summer unoccupied hours, similarly, the effects of IWLs are shown to slightly reduce the indoor air temperature.

Figures 7.12 and 7.13 and Tables 7.9 and 7.10 show the air temperature change in winter during both occupied and unoccupied hours. Compared to the summer time, a considerably less change of air temperature is observed when the occupants are present in the building. In fact, except for a few cases in hot climates, the air temperature relatively remains unchanged in all interior wall layout cases. For winter unoccupied hours, in almost all locations, a slight increase of air temperature is observed as a result of adding interior walls to the plan.

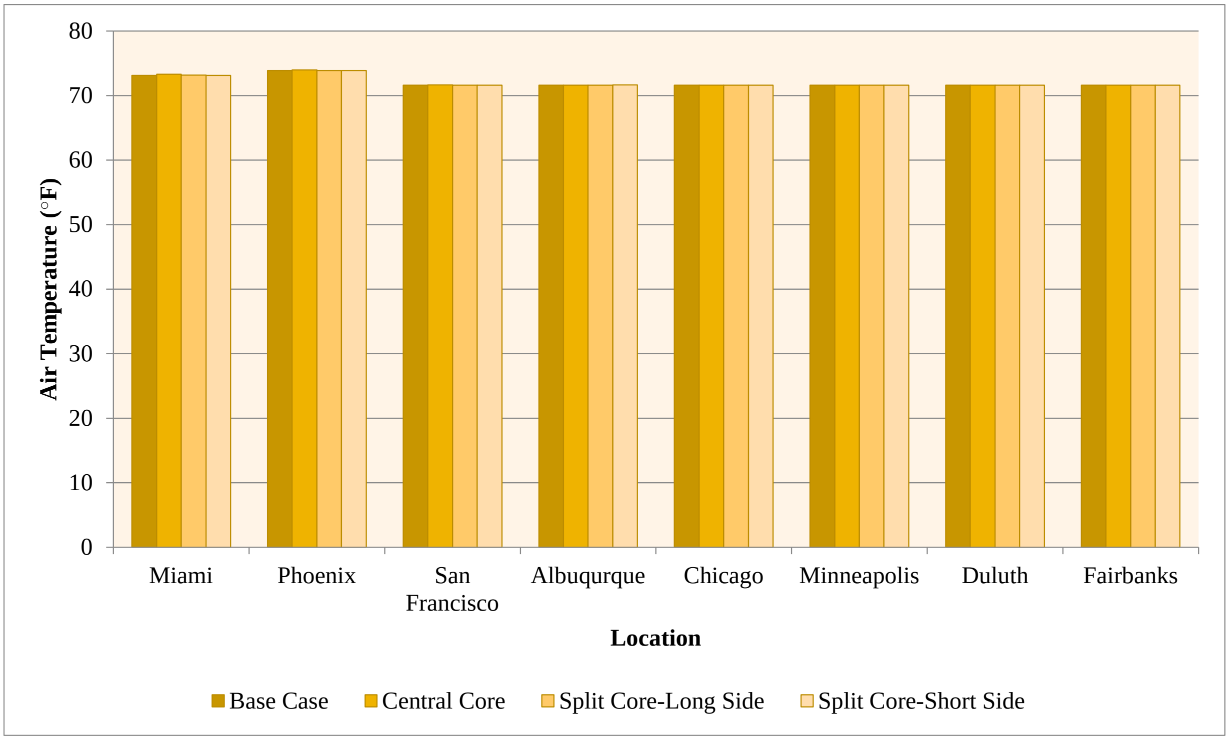


Figure 7.12 Air temperature, winter: occupied hours

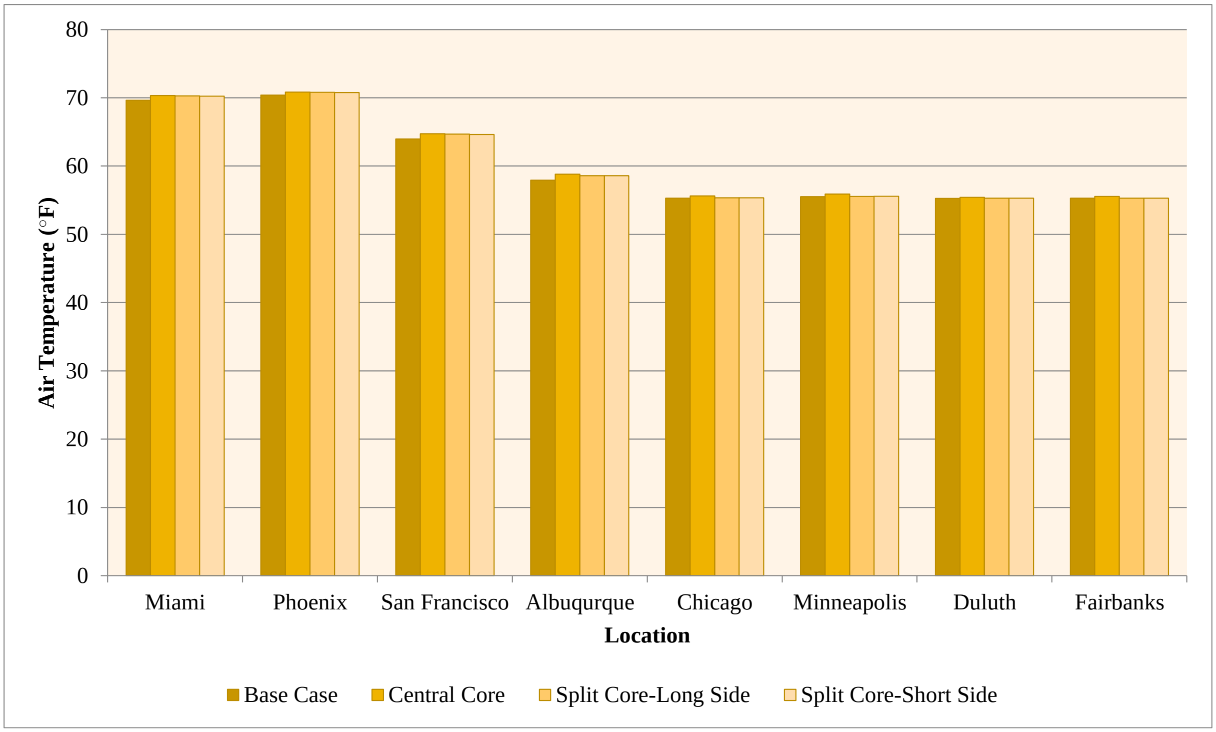


Figure 7.13 Air temperature, winter: unoccupied hours

Table 7.9 Reduction of air temperature, winter occupied hours

IWL	Percent reduction (increase) of air temperature		
Location	BC - CC	BC - SCL	BC - SCS
Miami	(0.23)	(0.06)	0
Phoenix	(0.08)	0	0
San Francisco	(0.05)	0	0
Albuqurque	0	0	(0.1)
Chicago	0	0	0
Minneapolis	0	0	0
Duluth	0	0	0
Fairbanks	0	0	0

Table 7.10 Reduction of air temperature, winter unoccupied hours

IWL	Percent reduction (increase) of air temperature		
Location	BC - CC	BC - SCL	BC - SCS
Miami	(0.96)	(0.90)	(0.82)
Phoenix	(0.62)	(0.59)	(0.51)
San Francisco	(1.18)	(1.11)	(1.02)
Albuqurque	(1.48)	(1.08)	(1.10)
Chicago	(0.54)	(0.03)	(0.03)
Minneapolis	(0.75)	(0.13)	(0.15)
Duluth	(0.29)	(0.02)	(0.02)
Fairbanks	(0.42)	(0.02)	(0.02)

7.2.2 Radiant temperature

As stated in Chapter 1 and 2, surface temperature is an important factor in determining the level of thermal comfort in a room. The stored heat in a thermal mass material can generally result in an increase of surface temperature of the material, thus affecting the thermal comfort of the surrounding environment. Figures 7.14 and 7.15 and Tables 7.11 and 7.12 show the change of radiant temperature as the result of various IWLs in summer during both occupied and unoccupied hours.

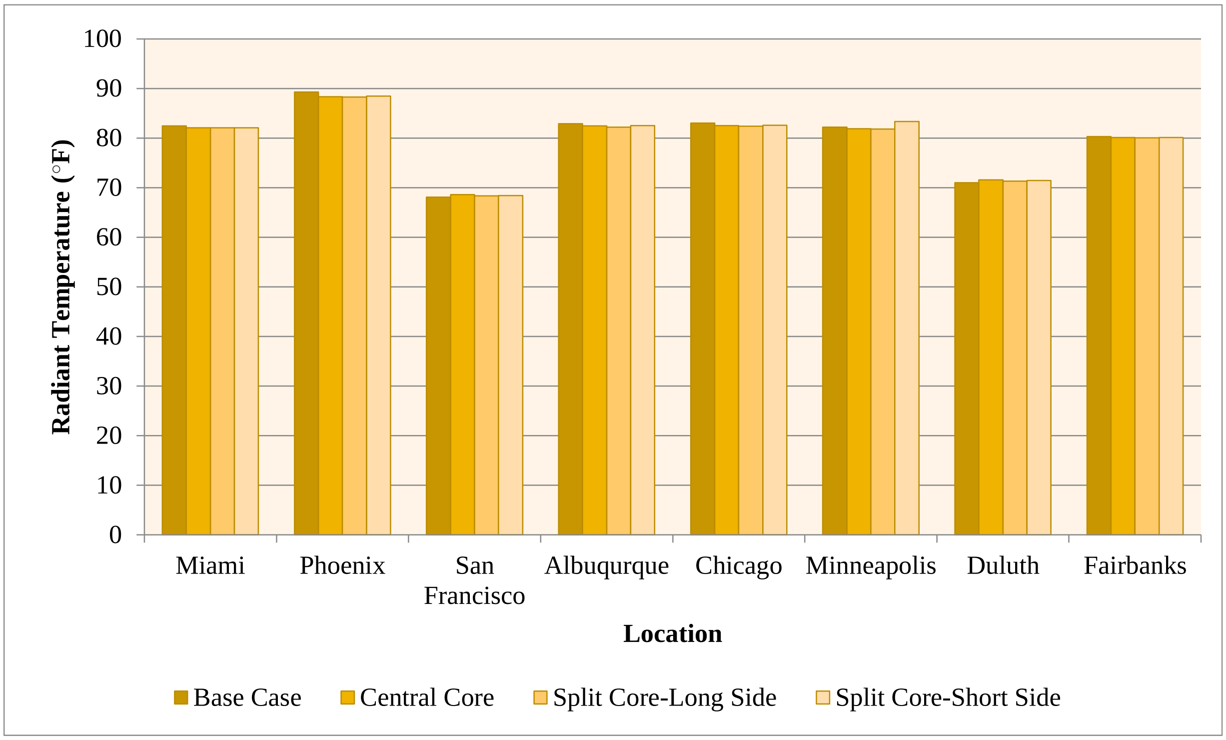


Figure 7.14 Radiant temperature, summer: occupied hours

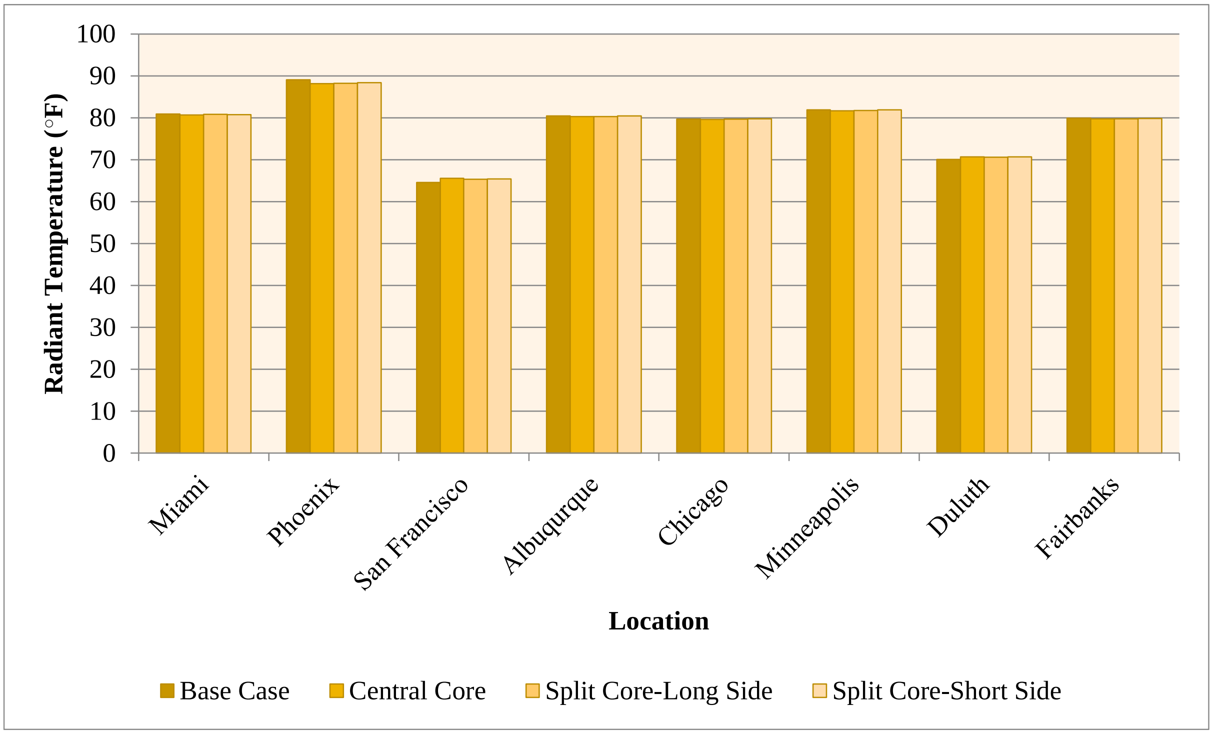


Figure 7.15 Radiant temperature, summer: unoccupied hours

Table 7.11 Reduction of radiant temperature, summer occupied hours

IWL Location	Percent reduction (increase) of radaint temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.5	0.5	0.5
Phoenix	1.1	1.2	0.9
San Francisco	(0.8)	(0.3)	(0.5)
Albuquerque	0.5	0.8	0.4
Chicago	0.6	0.7	0.5
Minneapolis	0.4	0.4	(1.4)
Duluth	(0.7)	(0.4)	(0.6)
Fairbanks	0.2	0.3	0.2

Table 7.12 Reduction of radiant temperature, summer unoccupied hours

IWL Location	Percent reduction (increase) of radaint temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.3	0.1	0.2
Phoenix	1.0	1.0	0.8
San Francisco	(1.5)	(1.2)	(1.3)
Albuquerque	0.2	0.2	0.0
Chicago	0.1	0.0	(0.1)
Minneapolis	0.3	0.2	0.0
Duluth	(0.9)	(0.8)	(0.9)
Fairbanks	0.2	0.1	0.0

It is seen that the surface temperature shows similar patterns of increase and decrease in different locations as compared to the air temperature. During summer, except for a few cases, the radiant temperatures slightly decrease as a result of changes in IWLs, and a similar pattern of temperature increases and decreases is observed for summer unoccupied hours.

Figure 7.16 and 7.17 and Table 7.13 and 7.14 show the radiant temperature change in winter during both occupied and unoccupied hours. In comparison with the summer time, a relatively more change of radiant temperature is observed when the occupants are present in the building and when they are not. For both occupied and unoccupied hours, the IWLs have led to an increase of radiant temperature to variable degrees.

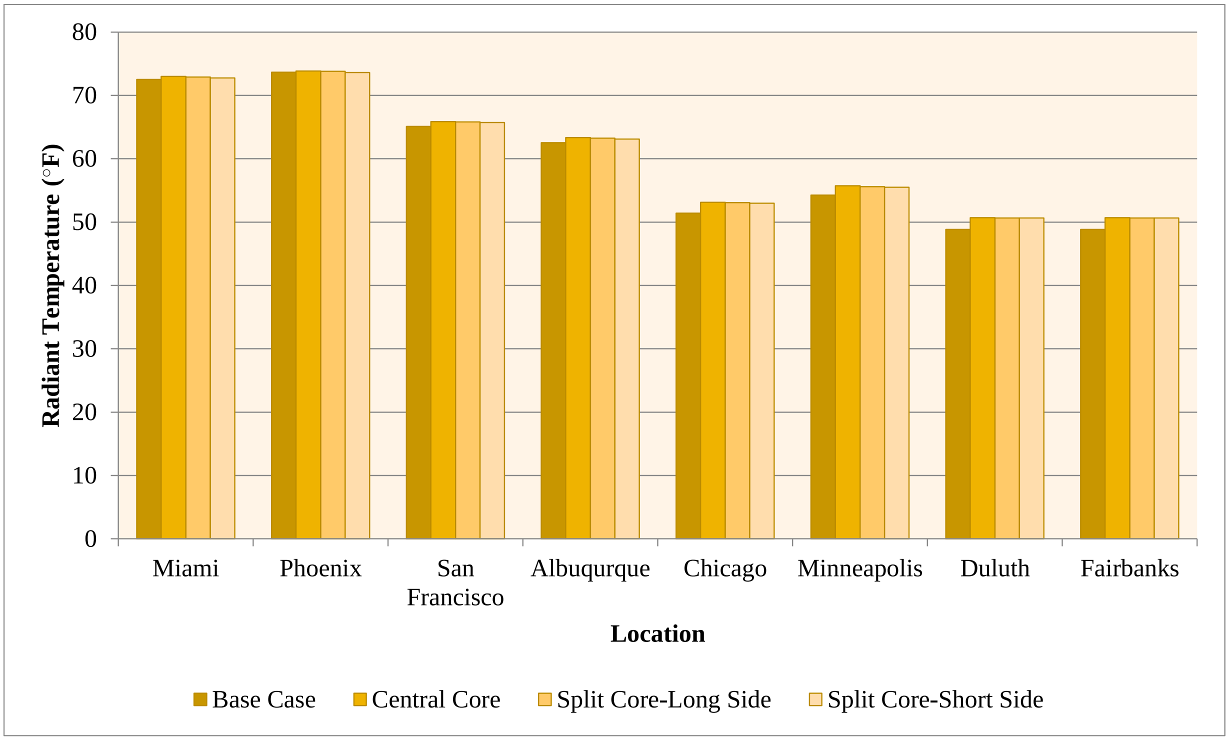


Figure 7.16 Radiant temperature, winter: occupied hours

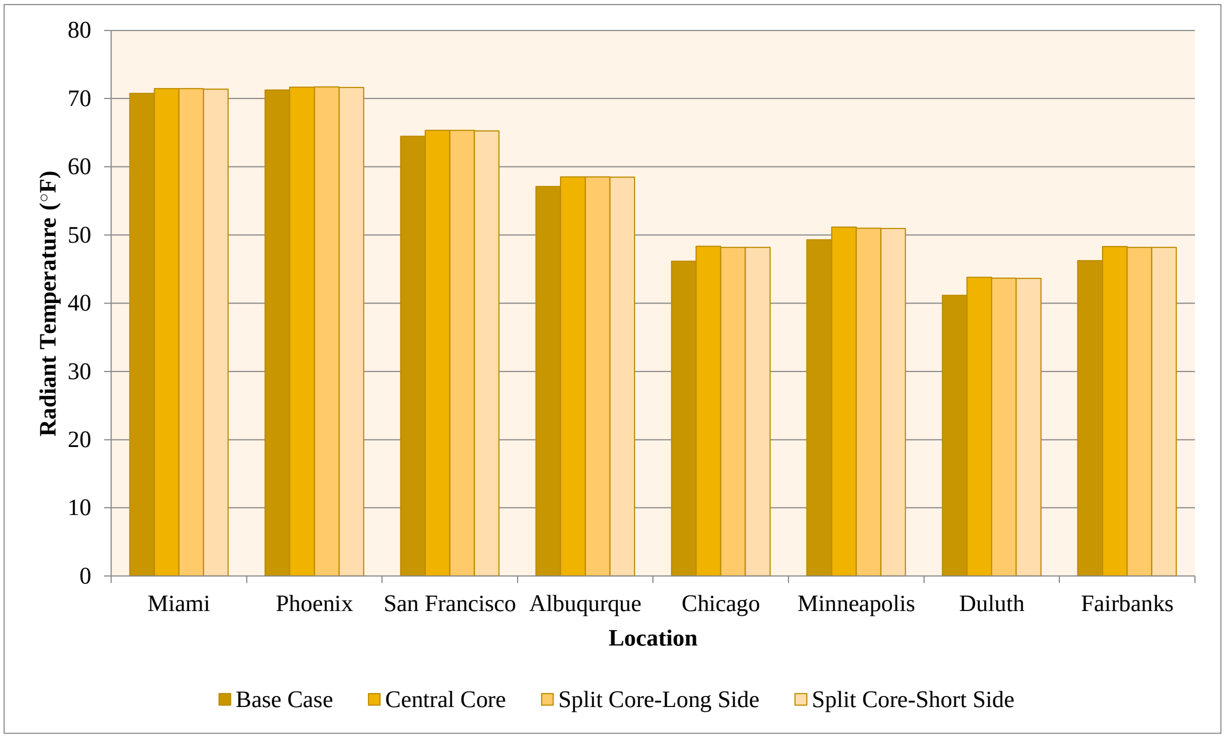


Figure 7.17 Radiant temperature, winter: unoccupied hours

Table 7.13 Reduction of radiant temperature, winter occupied hours

IWL / Location	Percent reduction (increase) of radaint temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	(0.7)	(0.5)	(0.4)
Phoenix	(0.3)	(0.1)	0.1
San Francisco	(1.2)	(1.1)	(1.0)
Albuqrque	(1.3)	(1.1)	(0.9)
Chicago	(3.3)	(3.2)	(3.0)
Minneapolis	(2.7)	(2.5)	(2.3)
Duluth	(3.8)	(3.7)	(3.7)
Fairbanks	(3.8)	(3.7)	(3.7)

Table 7.14 Reduction of radiant temperature, winter unoccupied hours

IWL / Location	Percent reduction (increase) of radaint temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	(1.0)	(1.0)	(0.9)
Phoenix	(0.6)	(0.7)	(0.5)
San Francisco	(1.3)	(1.3)	(1.2)
Albuqrque	(2.5)	(2.5)	(2.5)
Chicago	(4.7)	(4.4)	(4.4)
Minneapolis	(3.8)	(3.5)	(3.4)
Duluth	(6.4)	(6.1)	(6.0)
Fairbanks	(4.5)	(4.1)	(4.2)

7.2.3 Operative temperature

As indicted in Chapter 1 and 2, the operative temperature is an average of both air and surface radiant temperatures, both of which are affected by the thermal mass property of concrete. Therefore, operative temperature is a proper indicator of overall thermal level of a room with respect to temperature. Figures 7.18 and 7.19 and Tables 7.15 and 7.16 show the change of operative temperature as a result of IWLs in summer during occupied and unoccupied hours.

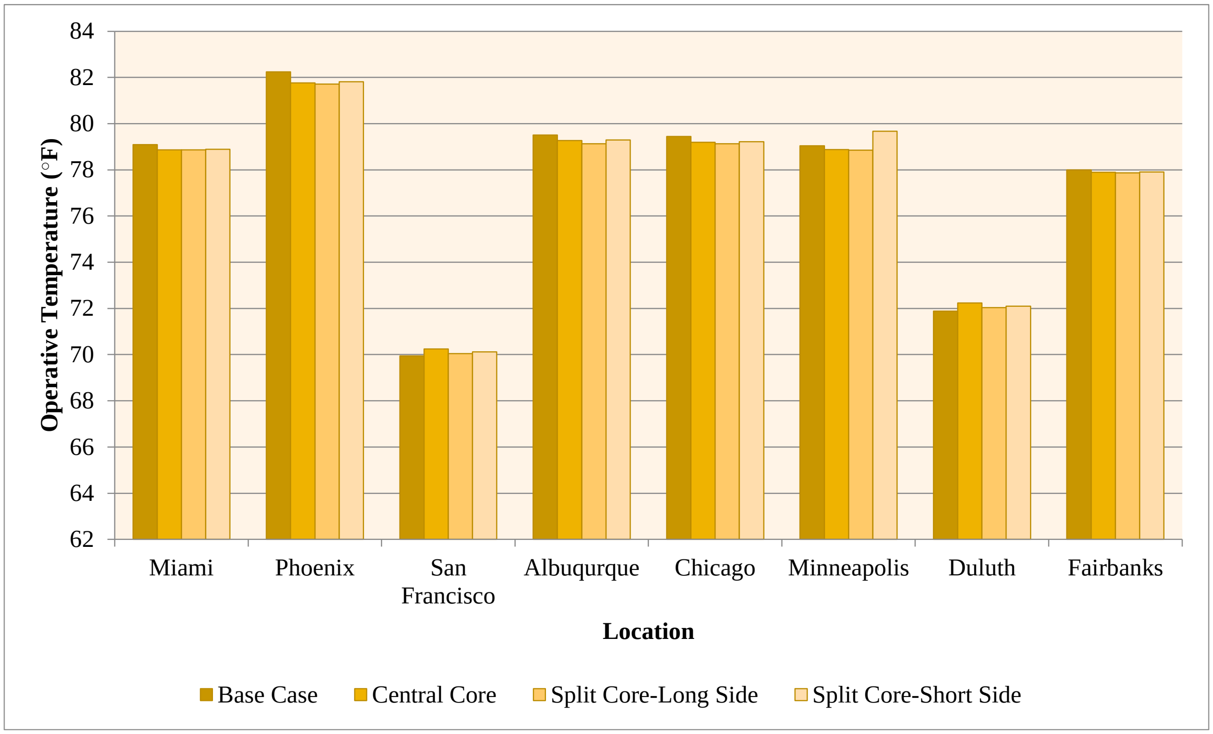


Figure 7.18 Operative temperature, summer: occupied hours

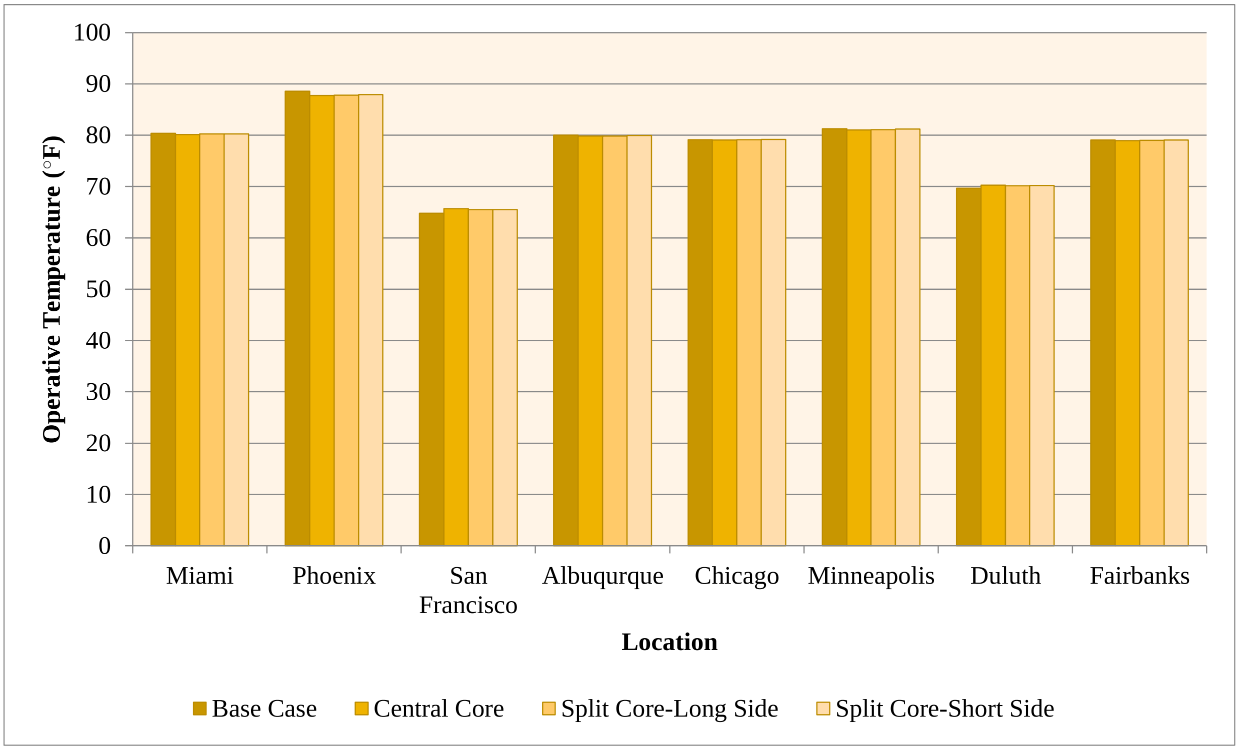


Figure 7.19 Operative temperature, summer: unoccupied hours

Table 7.15 Reduction of operative temperature, summer occupied hours

IWL / Location	Percent reduction (increase) of operative temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.3	0.3	0.3
Phoenix	0.6	0.6	0.5
San Francisco	(0.4)	(0.1)	(0.2)
Albuqurque	0.3	0.5	0.3
Chicago	0.3	0.4	0.3
Minneapolis	0.2	0.2	(0.8)
Duluth	(0.5)	(0.2)	(0.3)
Fairbanks	0.1	0.2	0.1

Table 7.16 Reduction of operative temperature, summer unoccupied hours

IWL / Location	Percent reduction (increase) of operative temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	0.3	0.1	0.2
Phoenix	1.0	0.9	0.7
San Francisco	(1.3)	(1.0)	(1.1)
Albuqurque	0.2	0.2	0.0
Chicago	0.1	0.0	(0.0)
Minneapolis	0.3	0.2	0.0
Duluth	(0.8)	(0.7)	(0.8)
Fairbanks	0.1	0.1	0.0

It is shown that the pattern of operative temperature changes is similar to the pattern observed for the radiant temperature and the air temperature. Figures 7.20 and 7.21 and Tables 7.17 and 7.18 show the operative temperature changes in winter during both occupied and unoccupied hours. Compared to summer time, relatively similar changes of operative temperature are observed when the occupants are present in the building than when they are not. Similar to both air and surface temperature, during both winter occupied and unoccupied hours, the IWLs have led to an increase of operative temperature.

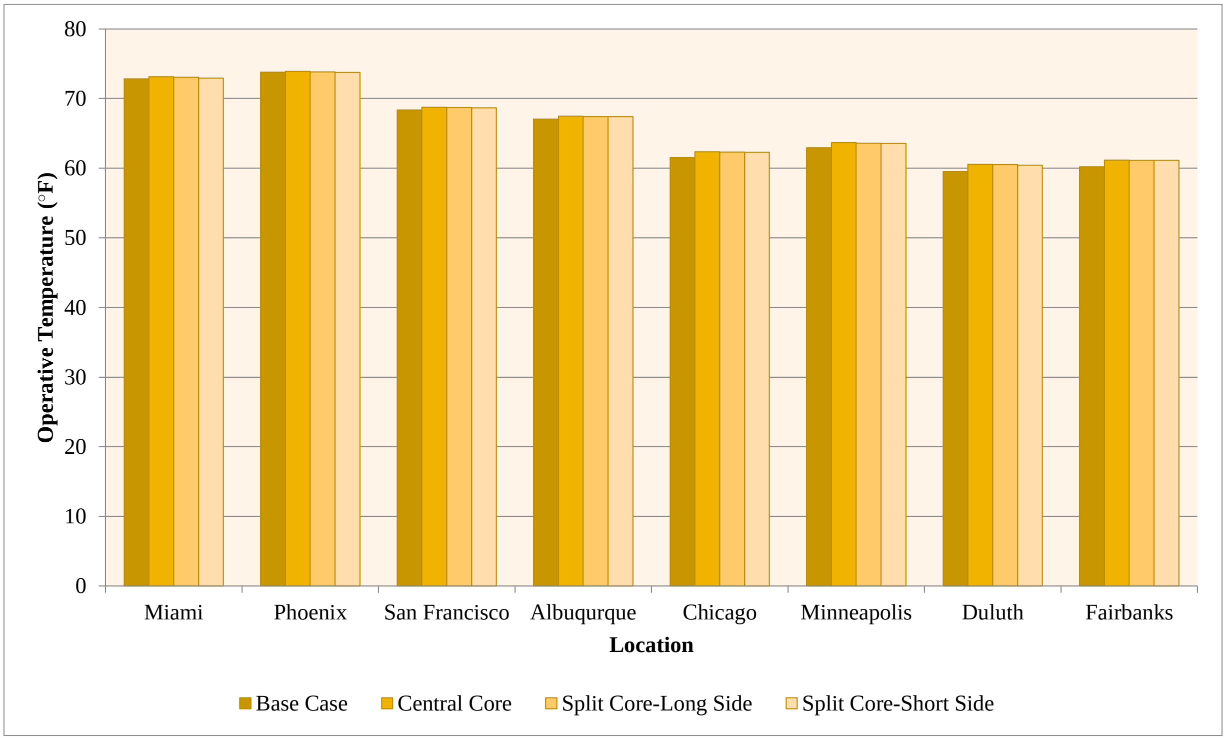


Figure 7.20 Operative temperature, winter: occupied hours

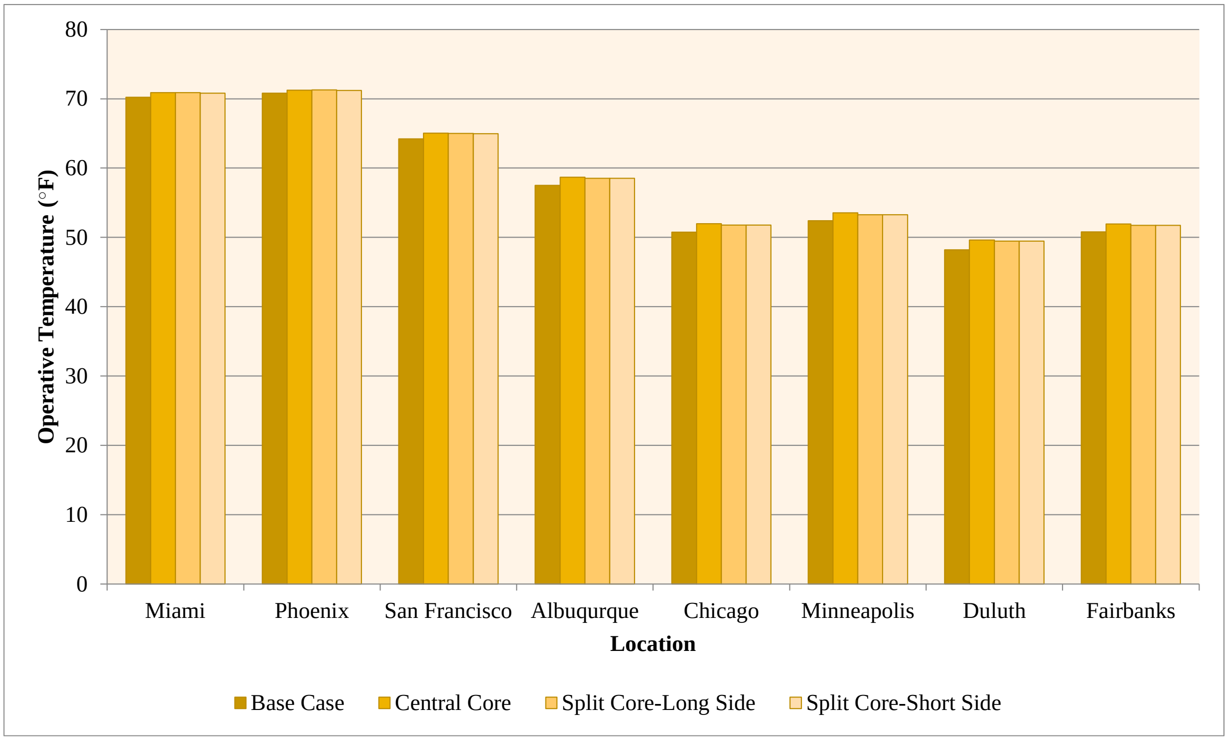


Figure 7.21 Operative temperature, winter: unoccupied hours

Table 7.17 Reduction of operative temperature, winter occupied hours

IWL / Location	Percent reduction (increase) of operative temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	(0.4)	(0.3)	(0.2)
Phoenix	(0.2)	(0.1)	0.1
San Francisco	(0.6)	(0.5)	(0.5)
Albuqurque	(0.6)	(0.5)	(0.5)
Chicago	(1.4)	(1.3)	(1.2)
Minneapolis	(1.1)	(1.1)	(1.0)
Duluth	(1.7)	(1.7)	(1.6)
Fairbanks	(1.6)	(1.5)	(1.5)

Table 7.18 Reduction of operative temperature, winter unoccupied hours

IWL / Location	Percent reduction (increase) of operative temperature		
	BC - CC	BC - SCL	BC - SCS
Miami	(1.0)	(0.9)	(0.9)
Phoenix	(0.6)	(0.6)	(0.5)
San Francisco	(1.3)	(1.2)	(1.1)
Albuqurque	(2.0)	(1.8)	(1.8)
Chicago	(2.4)	(2.0)	(2.0)
Minneapolis	(2.2)	(1.7)	(1.7)
Duluth	(2.9)	(2.6)	(2.6)
Fairbanks	(2.3)	(1.9)	(1.9)

7.3 Discussion

In this chapter the effects of IWLs that make up the core of a building on energy use and thermal comfort have been examined. The results show that adding IWLs to an open office space generally do not necessarily lead to energy savings, but rather it increases the building's energy use.

In terms of energy use, exploring interior concrete walls employed for central core is noted to generally reduce the heating energy use for all cases, regardless of location; however, the same conclusion cannot be drawn for split core walls (SCL and SCS), in which the heating loads are noted to increase as a result of IWLs. In other words, except for CCs where the addition of IWls can reduce heating demands, both SCL and SCS cases have shown an increase of heating energies as compared to BC model. The cooling energies, on the other hand, is shown to mainly increase when interior walls are added to the plan whether as central or split core walls. The total energy use of the building is also found to generally increase as a result of adding interior walls to the space. Even the change of building type to residential did not affect the pattern of cooling energy increase as a result of adding interior concrete walls. In other words, the increase of cooling demands in the presence of interior remains unchanged even when the building occupancy is changed from office to residential occupancy.

Regarding thermal comfort parameters, the summer air temperature generally decreases slightly when interior walls are added to the building plan. In winter, the air temperature generally remains unchanged for different cases, i.e., CC, SCL and SCS, during occupied hours but demonstrates slight increase during unoccupied hours. Similarly, the summer radiant and operative temperatures did not show a consistent pattern of either increase or decrease for all locations although more cases of temperature reductions were observed. During winter, the radiant and operative temperatures are noted to have generally increased as a result of IWLs.

7.4 Summary

This chapter investigates the effectiveness of IWLs on building energy and thermal comfort performance. Three different IWL scenarios including central core, split core on the long side and split core on the short side of the plan were simulated to assess the energy and thermal comfort effects of interior walls. Compared to primary thermal mass, i.e., perimeter wall thickness and thermal mass area on building façade, a secondary thermal mass parameter, i.e., interior walls is seen to be less effective in affecting building energy performance. Adding the interior concrete walls to office space generally increases both heating and cooling demands. To further investigate this phenomenon, the building occupancy was changed to residential to achieve lower internal loads, and possibly a reversal of the pattern of energy increase. Despite change of occupancy, the heating and cooling energies still increased as a result of adding interior concrete walls to the space. In terms of thermal comfort, summer and winter time air, radiant, and operative temperatures were studied in the presence of interior concrete walls and the results were compared with those of an open office space. Summer-time temperatures exhibit a mixed pattern of increase and decrease. During winter, the interior concrete walls increase the surface and operative temperatures.

CHAPTER 8

LIFE CYCLE ASSESSMENT of CONCRETE BUILDINGS

In order to have a better understanding of the life cycle performance of concrete buildings, the effect of thermal mass parameters were investigated. Results of this analysis are presented and demonstrated in this chapter.

Wall thickness and thermal mass area of exterior façade (represented by window-to-wall area ratio-WWAR) have been selected as the thermal mass parameters studied for the life cycle assessment (LCA) analysis using Athena Impact Estimator program. Due to the program's limitation in terms of availability of specific locations selected earlier for this dissertation, the following cities were chosen as equivalent to those locations (except for Minneapolis, which was also available in Athena program): Orlando with total degree days (TDD) of 3996 (representing Miami with TDD of 4912), Atlanta with TDD of 4452 (representing Phoenix with TDD of 5940), Los Angeles with TDD of 2111 (representing San Francisco with TDD of 3079), Toronto with TDD of 7502 (representing Chicago with TDD of 7503) and Minneapolis (weatherdatadepot, 2014). The basic for such selection was the best fit of climate in the region where these cities are situated.

Among all LCA measuring indices, fossil fuel consumption (FFC), global warming potential (GWP) and ozone depletion potential (ODP) have been chosen to assess to effect of thermal mass on LCA of concrete buildings.

8.1 Life cycle assessment and sustainability

Sustainability is a process that begins with the initial idea of a project until the end of its life (Green Buildings and LEED Core Concepts Guide, 2009). This so called LCA process entails planning, design, construction as well as operation and eventually demolition and possibly renewal of the building. This process takes into account the building and its components including materials and other elements from the extraction, manufacture, transportation until use, reuse and recycle of them (Green Buildings and LEED Core Concepts Guide, 2009). The LCA is aimed to minimize the adverse impacts of buildings and land use on occupants and environment. Long with capital and construction cost, LCA also intends to strike a balance between initial and operation cost throughout the life of the building (Green Buildings and LEED Core Concepts Guide, 2009).

To study the effects of thermal mass parameters on building life cycle performance, the following LCA parameters have been selected (Athena Impact Estimator Manual, 2012).

8.1.1 Fossil fuel consumption

Fossil fuel consumption (FFC) is measured in megajoules (MJ). FFC includes “all energy, direct and indirect, used to transform or transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources” (Athena Impact Estimator Manual, 2012). Furthermore, the Athena program considers the indirect energy use, which is associated with processing, transporting, converting and delivering fuel in addition to the operating energy. FFC includes non-renewable fossil fuel as well as feedstock fossil.

8.1.2 Global Warming Potential

Global warming potential (GWP) is expressed on an equivalency basis relative to CO_2 – in kg or tonnes of CO_2 equivalent.

CO_2 is the common standard for global warming. All other greenhouse gases are referred to as having a "CO_2 equivalence effect" which is “simply a multiple of the greenhouse potential (heat trapping capability) of CO_2” (Athena Impact Estimator Manual, 2012). “This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time. As yet, no consensus has been reached among policy makers about the most appropriate time horizon for greenhouse gas calculations. The International Panel on Climate Change100-year time horizon figures have been used here as a basis for the equivalence index” (Athena Impact Estimator Manual, 2012):

CO_2 Equivalent kg = CO_2 kg + (CH_4 kg x 23) + (N_2O kg x 300)

“While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modelling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). Because the Athena Impact Estimator uses data developed by a detailed life cycle modelling approach, all relevant process emissions of greenhouse gases are included in the resultant GWP index” (Athena Impact Estimator Manual, 2012).

8.1.3 Ozone Depletion Potential

“Stratospheric ozone depletion potential (ODP) accounts for impacts related to the reduction of the protective ozone layer within the stratosphere caused by emissions of ozone depleting substances (CFCs, HFCs, and halons). The loss of ozone molecules in atmosphere resulting in increase in harmful solar radiation reaching ground level, which in turn, can threaten the well-being of humans. During 1980s and 1990s, the topic of ozone depletion was the focus of many environmental discussions, however, later on the focus changed to the concept of global warming and climate change. The ODP of each of the contributing substances is characterized relative to CFC-11, with the final impact indicator indicating mass (e.g., kg) of equivalent CFC-11” (Athena Impact Estimator Manual, 2012).

8.2 Life cycle assessment example

To illustrate the effect of building materials of life cycle performance of a building, Athena Impact Estimator has conducted an LCA analysis of a steel and a concrete office building (Athena Impact Estimator Manual, 2012). The gross floor area of both steel and concrete buildings is about 15,000 m^2, while their building life expectancies are 60 years. According to the results of this study, for the steel material in this project, the manufacturing, construction and end-of-life phases result in 1,600,000 MJ, 125,000 MJ and 53,000 MJ, respectively of FFC,. The use of resources such as limestone, coal, oil and natural gas for the steel material differs from one phase of life cycle to another. While the manufacturing stage uses 560,000 kg of resources, construction and end-of-life phases cause 3,000 kg and 1,250 kg, respectively of resource uses. In contrast, for the concrete office building, the manufacturing phase consumes 15,250,000 MJ of fossil fuels, while construction and end-of-life phases result in 600,000 MJ and 400,000 MJ, respectively, of FFC. In addition, in terms of resource uses, the manufacturing uses 5,800,000 kg of resources; the construction phase consumes 14,000 kg, and the end-of-life phase utilizes 9,000 kg of the resources. In terms of the environmental effects, the steel building emits almost 114,000 kg of CO_2 while the concrete construction is responsible for more than 1,160,000 kg of CO_2 emissions.

Form the sustainability standpoint, the steel and concrete office buildings represent different outcomes. It is shown that, in terms of the FFC, the concrete building significantly consumes more energy than the steel construction, especially in the manufacturing phase where the amount of fossil fuel use in concrete building exceeds 10 times the amount for that of steel project. This ratio of consumption stays almost the same for the resource use between these two buildings.

Furthermore, it is noted that except for construction phase where the magnitude of resource use of the concrete building is about five times larger than the steel one, the manufacturing phase of concrete building consumes resources about 10 times more than the steel construction. It appears from this perspective that steel as a construction material can be more environmental-friendly than concrete. In addition, the difference between the amounts of carbon emissions from both projects also confirms the same conclusion. On the other hand, it should be noted that concrete construction generally, provides some unique advantages such as more flexibilities of form in design and higher degree of accommodation for potential future modifications during construction, which may not be as readily available for steel construction. In most countries of the world, the infrastructure for the manufacture of concrete is readily available as opposed to steel and hence concrete buildings are more cost-effective and employed worldwide. In addition, concrete has superior fire-resisting capability that is unavailable to steel, and concrete buildings provide more damping for buildings to dynamic excitation due to lateral and seismic loads.

From a broader sustainability and performance perspectives, these design and construction potentials can improve the efficiency and sustainability of concrete buildings. Furthermore, due to its thermal mass property, concrete can help reduce heating and cooling energies during building operation was discussed in previous chapters, which further highlights the importance of concrete as a sustainable construction material.

8.3 Life cycle assessment analysis

As mentioned in previous sections, for LCA analysis of concrete thermal mass, thermal mass wall thickness and thermal mass exterior surface area were chosen to represent thermal mass variables, and FFC, GWP and ODP were chosen as the measuring indices to assess the effect of variables on building life cycle performance. The building floor area was the same as that of the base case model presented in previous chapters. The life expectancy of the building was set by the Athena program at 60 years as the default life expectancy for commercial buildings.

Figures 8.1, 8.2, and 8.3 show the effects of thermal mass for 8 in and 12 in wall thicknesses on FFC, GWP, and ODP.

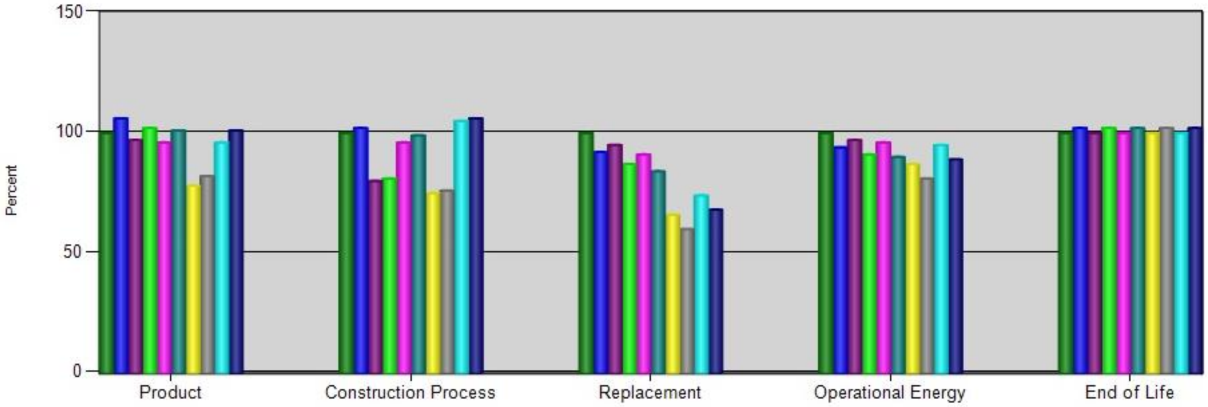


Figure 8.1: Comparison of FFC between 8 in and 12 in walls

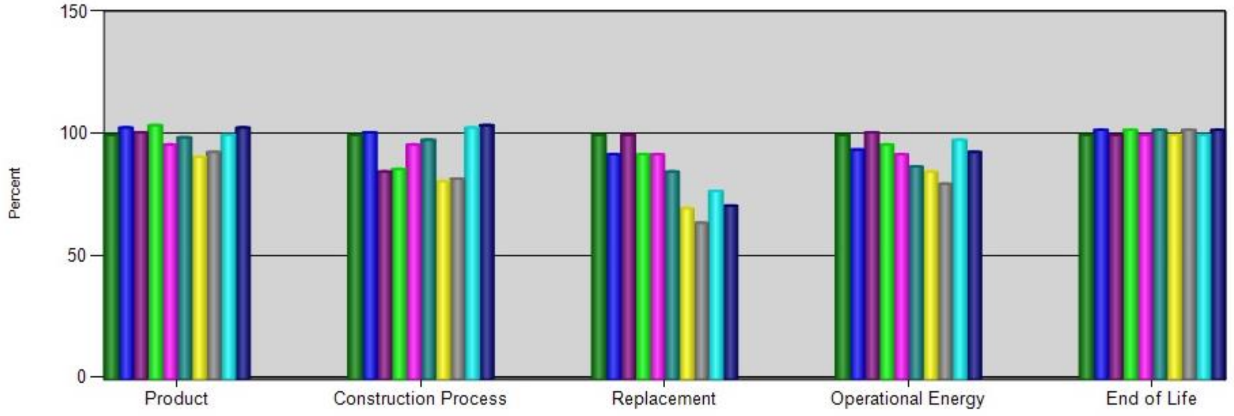


Figure 8.2 Comparison of GWP between 8 in and 12 in walls

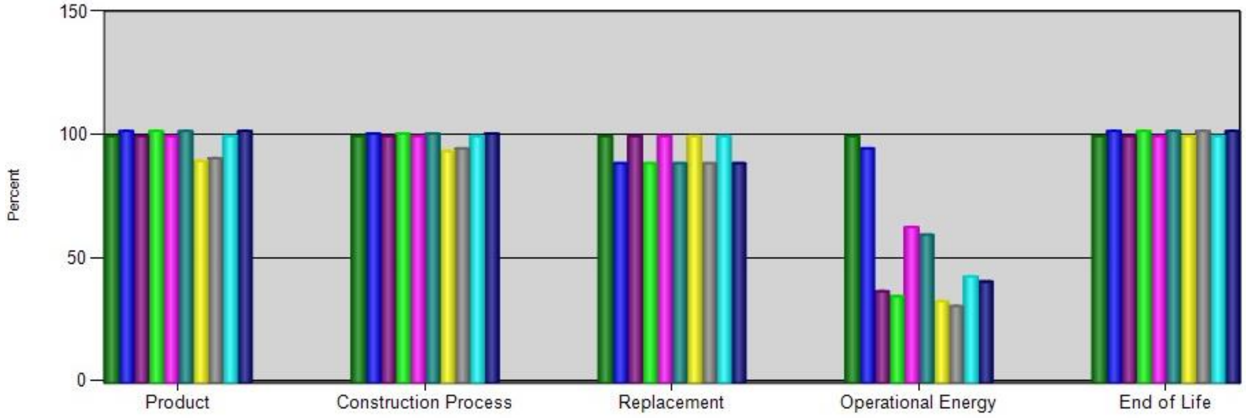


Figure 8.3 Comparison of ODP between 8 in and 12 in walls

These charts compare the FFC, GWP, and ODP indices across selected projects by life cycle stages on a percent basis relative to the baseline project (Orlando, 8 in wall thickness). In these charts, Orlando is represented by OR, Atlanta by AT, Los Angeles by LA, Toronto by TR, and Minneapolis by MN.

It is shown that for all three indices including FFC, GWP, and ODP, 5 phases of LCA including product (i.e., production), construction process, replacement, operational energy and end of life have been analyzed. Regarding FFC, the increase of wall thickness from 8 in to 12 in is shown to have increased the fuel consumption for product and construction process phases. However, it has reduced the FFC for replacement and operational energy phases, which is consistent with the findings in Chapter 4, where the increase of wall thickness consistently resulted in the reduction of total energy consumption of the building. GWP index is showing a relatively similar behavior with FFC, however, ODP shows a significant reduction for 12 in wall cases for the replacement phase. For operational energy phase, except for Orlando, the ODP is significantly lower than that for fossil fuel and GWP indices.

Figures 8.4 through 8.9 show the effects of thermal mass exterior area (represented by WWAR) on building life cycle indices.

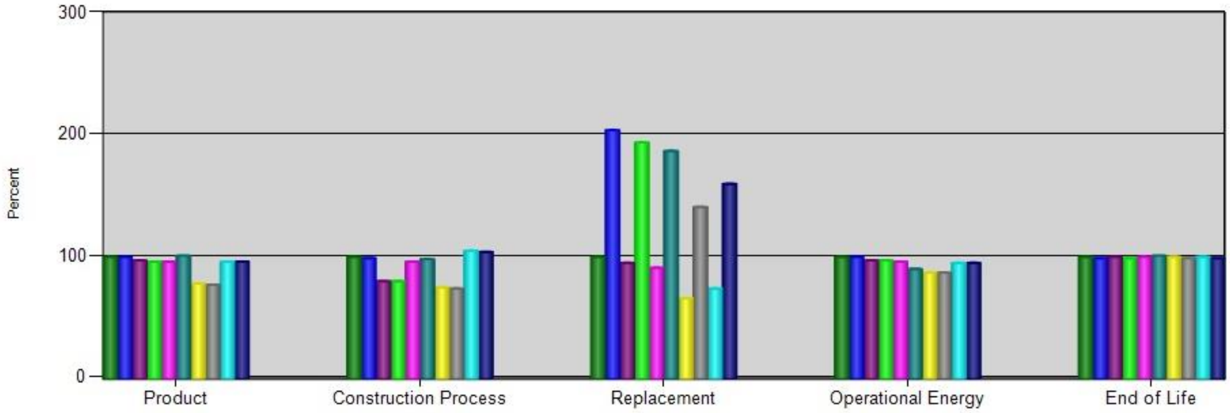


Figure 8.4 Comparison of FFC between 30% and 80% WWAR, 8 in wall

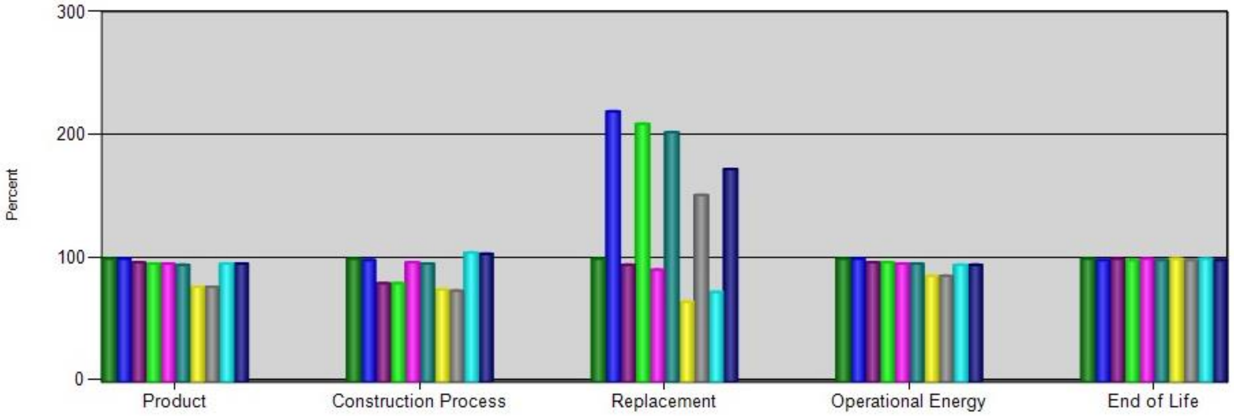


Figure 8.5 Comparison of FFC between 30% and 80% WWAR, 12 in wall

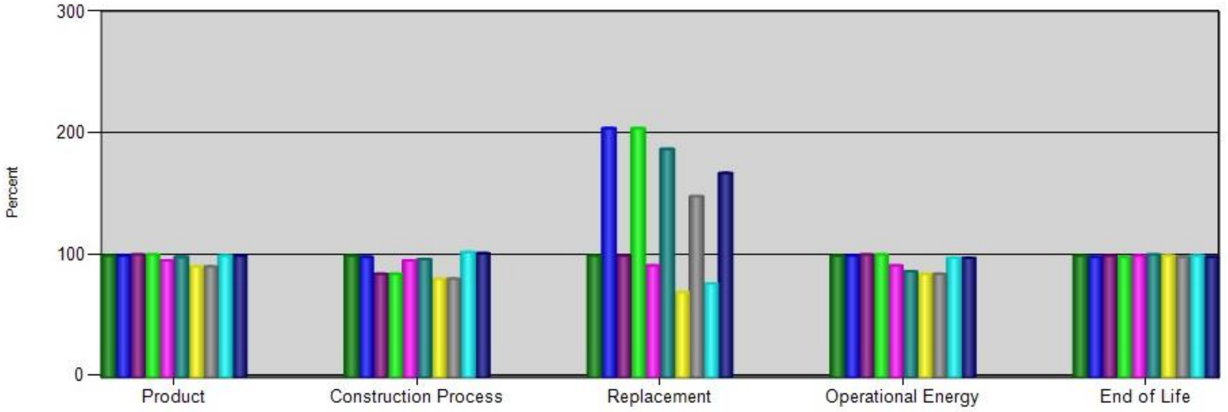


Figure 8.6 Comparison of GWP between 30 % and 80% WWAR, 8 in wall

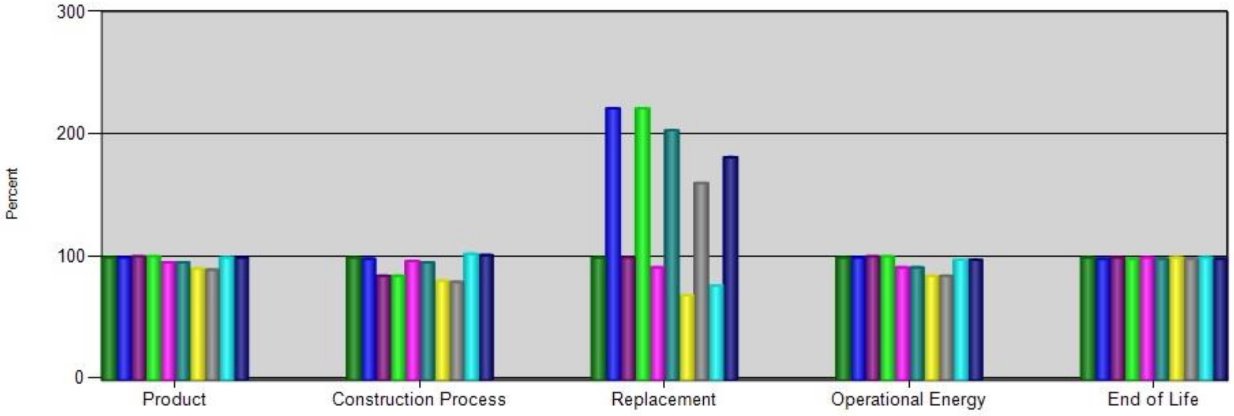


Figure 8.7 Comparison of GWP between 30 % and 80% WWAR, 12 in wall

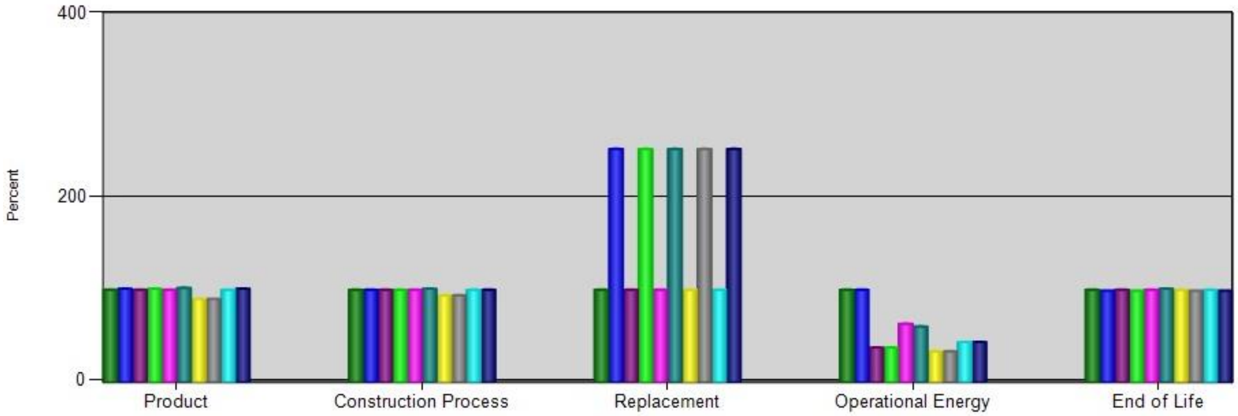


Figure 8.8 Comparison of ODP between 30% and 80% WWAR, 8 in wall

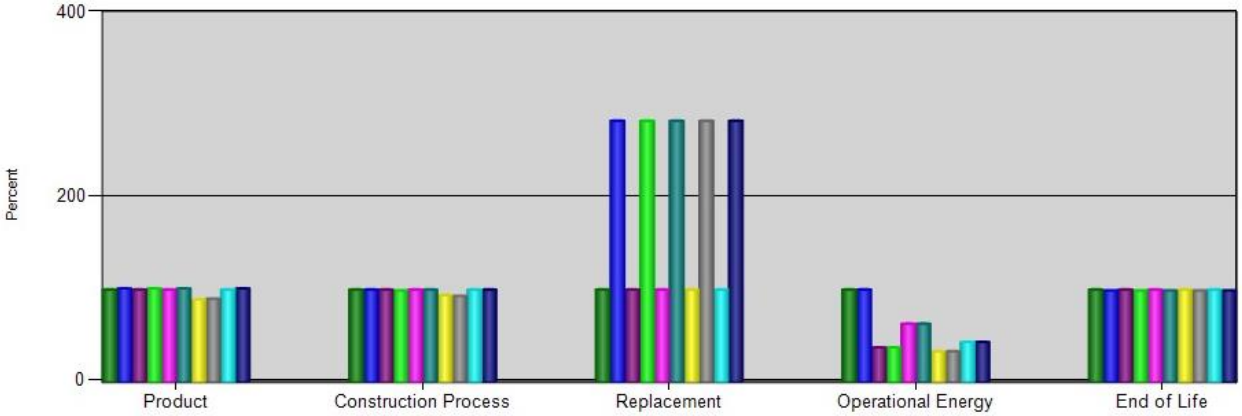
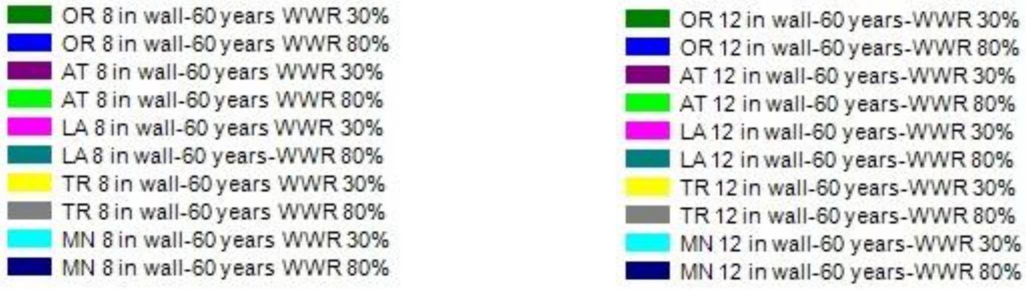


Figure 8.9 Comparison of ODP between 30% and 80% WWAR, 12 in wall



In these cases, the effect of different WWARs on buildings' LCA was studied for both 8 in and 12 in wall thicknesses. In other words, the wall thickness remained constant (i.e., at 8 in and 12 in thicknesses) while the WWAR was changed from 30% to 80% (or thermal mass exterior area from 70% to 20%). It can be seen, unlike wall thickness, the change of thermal mass area may not have a significant effect on building life cycle regardless of location except for the replacement phase, where the reduction of thermal mass area has led to a significant increase of all indices regardless of location. The ODP in general is significantly lower in operational energy phase as compared to FFC and GWP; however, the WWAR is not shown to have a considerable effect of its performance.

8.4 Life cycle cost

Life cycle cost (LCC) analyses are main parts of any LCA analysis and allows for a comparison of different design strategies, their effect on building cost and determine "the best long-term investment" (Green Buildings and LEED Core Concepts, 2009). This method can provide the most cost effective option in line with the project goals. All building expenses are included in this calculation. They can range from initial cost of project design and construction, to operation and maintenance to repayment costs and lastly demolition. LCC analyses have shown that high performance buildings can save more energy in their life time as compared to low performance buildings although their initial cost may be higher (Green Buildings and LEED Core Concepts, 2009).

LCC analysis can estimate the cost of design alternatives ensuring the lowest possible cost for the project without compromising its objectives. If conducted as early as when the design process begins, LCC analysis can give the building owners and designer a chance to refine or reconsider the building design to optimize the life cycle cost. It also can provide them with an opportunity to make informed design and construction decisions with respect to cost (Green Buildings and LEED Core Concepts, 2009).

The LCC analysis can have several components including cost, time, and discount rate (Life cycle cost analysis handbook, 1999). In terms of the project cost, the National Institute of Building Science has established the main building-related costs, which can be categorized as follows: "1) initial costs including purchase, acquisition, and construction cost; 2) fuel cost; 3) operation, maintenance and repair costs; 4) replacement costs; 5) residual values including resale or salvage values or disposal costs; 6) finance charges including loan interests payments; and 7) non-monetary benefits or costs" (Life cycle cost analysis, 2014).

"The capital investment required for land acquisition, construction and renovation are included in the initial costs. Although a detailed estimate of construction cost may not be necessary at the preliminary phase of LCC until the design is sufficiently developed, the detailed cost estimates should be prepared at the submittal stages of design (at 30%, 60%, and 90%) based upon quantity take-off calculations. In addition, the operational expenses including energy and water are based on consumption, current rate and price projection, which may need to be accounted for during the design process based upon the predicted use profiles, occupancy rates and schedules" (Life cycle cost analysis, 2014) .

"By using the base-date cost and escalating base-year amounts to their future time of occurrences, the LCC can also estimate the future replacement costs. The residual values which are basically the values of a system at the end of the study period or replacement time can be calculated by linearly prorating the system's initial costs" (Life cycle cost analysis, 2014). "The finance charges are usually negotiated with energy provider companies. The non-monetary benefits are relatively subjective values, for instance, the productivity gain due to the improved lighting system. Furthermore, time is another influential component in the LCC process. The study period is, in fact, the time period over which ownership and operations expenses can be evaluated" (Life cycle cost analysis handbook, 1999), which may include "any planning, construction, and implementation period as well as the service or occupancy periods" (Life cycle cost analysis, 2014).

The discount rate is “the rate of interest reflecting the investor’s time value of money” (Stephen & Alphonse, 1995) that basically is an “interest rate assuring the investors of an acceptable return on their investment. In fact, the discount rate represents “the investors’ minimum acceptable rate of return” (Stephen & Alphonse, 1995).

The LCC and project sustainability are related. By helping building owners and designers make informed decisions, LCC can increase the degree of efficiency of the project (Green Buildings and LEED Core Concepts, 2009). For instance, LCC can determine that, for a given local soil property, whether matt foundations would be a better choice or pile foundations. As a result, because of the effects of foundation on building long-term settlements, a wisely-selected foundation type can minimize the chance of cracking in the foundation and structure leading to a potentially costly structural repair (Green Buildings and LEED Core Concepts, 2009). One may argue that this approach can lead to a more cost effective and sustainable design in the life time of a project.

8.4.1 Life cycle cost analysis

To illustrate the LCC impact due to thermal mass, two wall thickness cases of 8 in and 12 in (consistent with the LCA analysis) in the City of Chicago were selected. The rate of energy costs was chosen based on North Shore rate, which is about $0.31 for one therm of natural gas (NorthShore, 2014) and based on ComEd rate which are $0.05 for one kWh of electricity (ComEd, 2014). The gas and electricity costs are assumed to be only for heating and cooling purposes, respectively. The construction cost between two different cases was only considered for the increase of concrete volume from 8 in to 12 in wall thickness. The cost of concrete was set at $80 per cubic yard. (L&M Construction Chemicals, 2014). As stated before, the life expectancy of the building was set as 60 years.

For the LCC analysis, first any potential energy cost savings were assessed. Given the relationship between therm and kWh and kBtu, 1 kBtu of natural gas costs about $0.0031 and 1 kBtu of electricity costs about $0.0146. Therefore, given the energy saving effects of wall thickness increases from 8 in to 12 in as discussed in Chapter 4, for the life expectancy of 60 years in Chicago, an estimated $60,297 of heating energy cost would be saved; however, a cooling cost increase of $3,630 would be seen. Therefore, a net total energy cost saving of $56,666 would be achieved (the value of dollar is assumed to stay the same for the period of this analysis).

In terms of the construction cost, given the increase of concrete volume from 4 in to 12 in wall thicknesses, a cost increase of $28,622 would be observed. Comparing the cost and benefit of thermal mass increase, it is shown than a net saving of $28,044 over 60 years would be accomplished, which is more than twice than the initial cost increase. It should be noted that this study was carried out for a 12-story base case building, which is considered a multi-story building. However, in the case of a taller concrete building or a building with larger floor area, the cost saving of concrete can be significantly greater than that of this selected building.

8.5 Final remarks

The effect of thermal mass variables on buildings' life cycle performance in terms of both environmental and financial impacts has been studied in this chapter. The effects of wall thickness and thermal mass area on FFC, GWP and ODP have been examined. Furthermore, the LCC analysis has focused on the cost and benefit of additional wall thickness in the life cycle of the building.

In terms of wall thickness increase from 8 in to 12 in, FFC is seen to have increased for product and construction process phases. However, it has decreased for replacement and operational energy phases, which is consistent with the findings of this study in Chapter 4. GWP index has shown a relatively similar behavior with FFC; however, ODP has shown a significant reduction for 12 in wall cases for replacement phase compared with 8 in wall cases. For operational energy phase, except for Orlando, the ODP is significantly lower than that for fossil fuel and GWP indices.

Regarding thermal mass area on the building façade, it is shown that, the change of thermal mass area may not have a significant effect on building life cycle regardless of location except for the replacement phase, where the reduction of thermal mass area has led to a significant increase of all indices regardless of location. The ODP in general is noted to be significantly lower in operational energy phase as compared to FFC and GWP; however, the WWAR is observed not to have a considerable effect on its performance.

The LCC analysis has also demonstrated that in a cold location such as Chicago, the energy cost saving benefits of wall thickness increase from 8 in to 12 in can significantly exceed the additional costs associated with extra volume of concrete material in the life cycle of the building.

8.6 Summary

This chapter has reviewed and briefly evaluated the effects of thermal mass parameters investigated in earlier chapters in regard to wall thickness and thermal mass exterior surface on buildings' life cycle performance. The life cycle effect on FFC, GWP and ODP have been studied to determine the life cycle effect of thermal mass. The LCC analysis has focused on the cost and benefit of additional wall thickness in the life cycle of the building. The cost savings associated with heating and cooling energy reduction have been compared with additional material cost associated with wall thickness increase and found to be higher than that for the latter.

CHAPTER 9

CONCLUSION

This dissertation has examined the effects of thermal mass property represented by architectural and structural design variables on energy and thermal comfort performance of concrete office buildings. In order to achieve a comprehensive perspective of thermal mass's energy and comfort performance, different climates in the U.S., e.g., hot and humid (Miami), cold and dry (Fairbanks) were chosen.

The preliminary phase of this research has shown that, generally speaking, extreme climates can better exploit the thermal mass properties of materials than mild climates. Increase of thermal mass is seen to generally reduce the heating and cooling requirements regardless of location and occupancy. This is more so for office buildings than residential buildings. For instance, in office buildings, the increase of wall thickness can result in a significant reduction compared to residential buildings. It is noted, however, that the increase of wall thickness beyond 8 in can lead to an increase of cooling requirements in office buildings. Moreover, the increase of window-to-wall area ratios (i.e. reduction of exterior thermal mass) can lessen the effectiveness of thermal mass in reducing building energy consumptions.

The main phase of the research has focused on two principal categories including primary thermal mass, (i.e., exterior thermal mass thickness and surface area), and secondary thermal mass (i.e., slab floor thickness and interior thermal mass walls). For primary thermal mass, the increase of wall thickness has generally led to a reduction of the heating energies and heating loads, regardless of location. It has also been effective in reducing cooling loads in all cases, although the same conclusion cannot be drawn for annual cooling energy use. The higher internal loads generated by occupants, equipment, and lighting in office buildings, as well as excessive stored heat in the thicker walls can be inferred as possible causes of such increase of cooling demands. The results show that lessening the effects of internal gains through providing more cooling or ventilation or even change of building occupancy from office to residential can have limited effects in reversing the pattern of cooling energy increase. For thermal comfort, summer time air, radiant, and operative temperatures result in a mixed pattern of increase and decrease as a result of wall thickness increase, whereas during winter, the increase of wall thickness is noted to have increased all air, surface and operative temperatures, which is beneficial in reducing the building's heating demands.

The results of the study of thermal mass area of the façade show that the increase of this area generally increases the heating energy use for the wall thickness of 4 in to 16 in. However, the increase of thermal mass distribution on the building envelope, when the wall thickness is 20 in, can actually reduce the heating energy use. The cooling energies have been seen to decrease when the thermal mass area increases even with the wall thickness of 4 in. The change of total energy use due to incremental thermal mass area is noted to follow the pattern of either heating or cooling energy changes based on whether the location is heating or cooling intensive. Regarding thermal comfort, air temperature is seen to decrease as a result of incremental thermal mass area during summer; however, during winter these temperature changes are not significant. Radiant temperatures during both summer and winter seasons are found to decrease when the thermal mass area increases, with the exception of increase in radiant temperature during winter in cold climates, operative temperatures are generally observed to decrease as a result of thermal mass area increase except for unoccupied winter hours in cold climates. It was also shown that when the window-to-wall area ratio remains constant, the increase of thermal mass area as compared to a non-thermal mass area can relatively improve building energy performance; especially with respect to cooling demands.

The main phase of this research was further extended by studying the effect of secondary thermal mass, e.g., slab thickness and interior wall layouts, on building energy use and thermal comfort performance. It has been found that compared to primary thermal mass, perimeter wall thickness and thermal mass area on building façade, a secondary thermal mass parameter such as slab thickness has been less effective in influencing building energy performance. The increase of slab thickness is found to generally reduce the heating energies and heating loads, regardless of location. The slab thickness increase generally reduces the cooling loads in many locations; however, the same conclusion cannot be drawn for annual cooling energy use. In fact, the increase of slab thickness is noted to have increased the cooling energies in hot locations. Through energy analysis of residential buildings, which inherently have lower internal loads, it was found that higher internal loads in office buildings and potentially excessive heat stored in the thicker walls can potentially be the cause of such increase of annual cooling demands. As far as the thermal comfort is concerned, summer time air, radiant, and operative temperatures have shown a mixed pattern of increase and decrease as a result of wall thickness increase. During unoccupied hours in winter, the increase of slab thickness increases surface and operative temperatures, which is beneficial in reducing the building’s heating demands.

The last secondary thermal mass variable studied in this research has been the interior concrete walls and how their different layouts and horizontal configurations can affect building performance. Except for central core configuration, adding the interior concrete walls to the office space, especially in proximity to the perimeter wall, has shown to generally increase the heating energies and heating loads, regardless of location. The interior concrete walls have also shown to generally increase the cooling energies and cooling loads in many locations, and even changing the building type to residential, which have significantly lower internal loads, did not show to be able to reverse this pattern of cooling energy increase. Regarding thermal comfort, air, radiant, and operative temperatures during summer show a mixed pattern of increase and decrease as a result of interior concrete walls. During winter time, the interior concrete walls increase surface and operative temperatures.

As discussed in Chapter 1, an energy matrix demonstrating various combinations of thermal mass cases can summarize the results of this research. Table 1 in Appendix B shows the energy matrix, where the total energy consumptions for different thermal mass cases in different climate zones are presented. Figure 1 in Appendix A and Table 2 in Appendix B summarize these results.

It can be seen that the combination case in which the thermal mass variable that has resulted in the lowest energy consumption in each category, e.g., wall thicknesses, slab thicknesses, has considerably reduced the energy consumption with respect to the base case (BC) model. These reductions range from 10.9% in Miami to 24.4% in Albuquerque and 23.1% in Duluth. The lowest energy case among all cases from all categories, on the other hand, shows a mixed behavior of increase or decrease in comparison with the combination case. For Miami, Phoenix, and San Francisco, the combination case is, in fact, the lowest energy consuming case as well. However, the same conclusion cannot be drawn for other locations. Therefore, it can be concluded that although the combination cases can lead to significant energy savings compared to base case models, they are not necessarily always the least energy consuming scenarios.

As discussed in Chapter 1, in this research the thermal insulation was excluded from the construction to avoid its potential interference with the thermal mass mechanism. However, in majority of building projects, the use of insulation is a common practice to increase their thermal resistance, which for a given R-value, is a constant variable and its effect will be more or less constant. The purpose of this research was intended to study the stand-alone effects of thermal mass independent of insulation.

Nonetheless, to get a better some understanding of the effect of thermal insulation in conjunction with thermal mass on building energy performance, a 4 in layer of R-20 thermal insulation was added to the exterior thermal mass elements—perimeter wall and roof—of the combination case for Phoenix and Duluth (two extreme climates), and the results were compared to the base case model with no insulation. As described in Chapter 2, the reason to consider the thermal insulation as an outer layer with respect to the thermal mass and interior space is to allow the thermal mass to be in full contact with the interior thermal conditions, thereby allowing it to better interact with indoor conditions, and hence, store and release the maximum possible amount of heat from and to the space.

To achieve a better comparison, the combination case without insulation and the lowest energy case for both these locations were also added to the analysis. Figure 2 and Table 3 in Appendices B and A demonstrate the results of these comparisons.

It is seen that in both locations, adding the thermal insulation has been, as expected, effective in reducing building energy use. In Phoenix and Duluth, thermal insulation has reduced the building energy use by 17.2% and 11% compared to the lowest energy cases, respectively, and achieved the minimum energy consumption cases among all cases studied in the analysis. This investigation shows that even tough insulation is beneficial for energy efficiency, thermal mass can indeed positively contribute to energy savings.

To determine the optimized energy and thermal comfort cases, Phoenix and Chicago as representative of hot and cold climates were selected and the results of total energy consumption for different thermal primary and secondary mass parameters such as wall thickness or slab thickness were compared with those of operative temperature given the ASHRAE comfort zone. As a reminder, the RH was considered to 50% and clo to be 1.0.

In terms of wall thickness (Figures 3 through 6 in Appendix B), 20 in wall thickness in Phoenix has the lowest energy use and has the closest operative temperature to comfort zone in summer. For winter, on the other hand, it is perfectly within the comfort zone. For Chicago, 20 in wall still has the lowest energy use and the closest operative temperature to the comfort zone in both summer and winter.

As far as the exterior thermal mass area is concerned (Figures 7 through 10 in Appendix B), 80% thermal mass area has the lowest energy use and closest operative temperature to the comfort zone in summer and perfectly within the zone in winter. In Chicago, 20% thermal mass area has the lowest energy consumption but the corresponding operative temperature is outside of the comfort zone in summer. Furthermore, the 80% thermal mass case is the closest to the comfort zone but has the highest energy use. In winter, 20% thermal mass area again is the closest case to the comfort zone.

Regarding slab thickness (Figures 11 through 14 in Appendix B), in Phoenix, 8 in slab has the lowest energy use; however, its operative temperature has the furthest distance from the comfort zone compared to other cases although the magnitude of temperature differences is fairly small. In winter, all cases are within the comfort zone. In Chicago, 8 in slab still has the lowest energy use and has the closest operative temperature to the comfort zone in summer. In winter, all cases are outside and below the comfort zone.

In terms of IWLs (Figures 15 through 18 in Appendix B), in Phoenix, BC model has the lowest energy consumption; however, the corresponding operative temperature is the furthest case from the comfort zone compared to other cases, i.e., central core (CC), split core long side (SCL) and split core short side (SCS). In winter, for all cases the operative temperature is within the comfort zone. In Chicago, BC still has the lowest energy use, but its operative temperature is the furthest from the comfort zone both in summer and winter. It should be noted that, the operative temperatures for all cases in both summer and winter are outside the comfort zone.

As far as the combination cases and their comparison with BC and lowest energy cases are concerned (Figures 19 and 20 in Appendix B), for Phoenix in winter, the combination case provides closest operative temperature to the comfort zone. During winter, all three cases are within the comfort zone. For Chicago, the lowest energy case has in fact, the closest operative temperature to the comfort zone during both summer and winter.

An additional feature of this research has been to study the effects of thermal mass variables on a building's life cycle performance in terms of both environmental and financial impacts. The effects of wall thick ness and thermal mass area on fossil fuel consumption (FFC), global warming potential (GWP) and ozone depletion potential (ODP) haven been investigated. Furthermore, the life cycle cost analysis (LCCA) focused on the cost and benefit of additional wall thickness in the life cycle of the building.

For wall thickness increase from 8 in to 12 in, FFC is seen to have increased for product and construction process phases. However, it has decreased for replacement and operational energy phases, which is consistent with the findings of this study in Chapter 4 in regard to the effect of wall thickness increase on building energy performance. GWP index has shown a relatively similar behavior with FFC; however, ODP has shown a significant reduction for 12 in wall cases for replacement phase. For operational energy phase, except for Orlando, the ODP is significantly lower than that for fossil fuel and GWP indices.

Regarding thermal mass area on the building façade, it is shown that, the change of thermal mass area may not have a significant effect on building life cycle regardless of location except for the replacement phase, where the reduction of thermal mass area has led to a significant increase of all indices regardless of location. The ODP in general is noted to be significantly lower in operational energy phase as compared to FFC and GWP; however, the window-to-wall area ratio is not seen to have a considerable effect on its performance.

The LCCA analysis has also shown that in a cold location such as Chicago, the energy benefits of wall thickness increase from 8 in to 12 in can significantly exceed the additional costs associated with extra volume of concrete material in the life cycle of the building. Given the energy savings, additional cost of construction, and life expectancy of 60 years, an overall cost saving of $28,044 can be achieved for the BC model.

With an integrated approach, this present research addressed three variables: the thickness of concrete thermal mass in the building envelope; the concrete surface area exposed to either ambient environment or internal heat; and the distribution of thermal mass in a building’s configuration and their effects on building energy and thermal comfort performance in one comprehensive and detailed study. Furthermore, the optimization between energy use and thermal comfort in the presence of thermal mass is the unique contribution of this study to the body of knowledge.

Based on the results of this research, the following conclusions can be drawn that can be used as design guidelines by practicing architects and engineers:

1. As expected, primary thermal mass elements, such as wall thickness and thermal mass area, have more effects on building energy and thermal comfort performance compared to secondary thermal mass elements such as slab thickness and interior walls. Therefore, the main thermal mass-related design emphasis needs to be on its implementation in the building envelope, where maximum heat transfer between the outdoor and indoor environment occurs.
2. The increase of perimeter wall thickness can result in heating energy reductions; however, it will lead to cooling energy increase, especially beyond 8 in thickness. Therefore, 8 in can be an optimal thickness for perimeter walls, where cooling design dominates the overall energy design of the building. Despite differences between thermal mass's heating and cooling performance, overall energy use decreases when the wall thickness increases.
3. The increase of thermal mass area on building façade leads to the increases of heating demands, unless the perimeter wall thickness is beyond 16 in. However, there is positive linear relationship between the increase of thermal mass on building façade and the reduction of cooling energies. In other words, the more thermal mass on the building façade, the less the cooling energy demands. If the window-to-wall area ratio remains constant, the increase of thermal mass area as compared to a non-thermal mass area can relatively improve building energy performance; especially with respect to cooling demands.
4. In terms of secondary thermal mass, the increase of slab thickness can reduce the heating energy and heating loads as well as cooling loads, which can help reduce the size of heating and cooling equipment. However, the slab thickness increase can lead to an increase in cooling

energies. Therefore, one may want to consider both positive and negative effects of slab thickness increase on cooling demands in locations where cooling dominates the building's energy design.

5. Adding interior thermal mass walls to open spaces in an office building can lead to an increase of both heating and cooling energies, except for heating design cases where a central core is added to the building plan.
6. In terms of the optimization between energy sue and thermal comfort, for wall thickness, 20 in wall has the lowest energy consumption and closest operative temperature to the comfort zone in both hot and cold climates. For exterior thermal mass area, for hot locations, greater thermal mass area can have better energy and thermal comfort performance; however, for cold locations, less thermal mass area can perform better. As far as the slab thickness, given the slight differences in operative temperature among cases, 8 in slab can be the better choice as it has the lowest energy use. For IWLs, again given relatively similar thermal comfort results among cases, BC can be the better choice since it has the lowest energy use.
7. Thermal mass can significantly contribute to energy performance in conjunction with the employment of thermal insulation with primary thermal mass.
8. In terms of LCA and LCC, in the increase of wall thickness has relatively improved the environmental indices, i.e., FFC, GWP and ODP. It has also helped reduce the cost of building operation in its life cycle.

This research can be extended in the future to further explore the energy and thermal comfort effectiveness of thermal mass. First, the DOE benchmark building (the basis for the BC model) has been a rectangular-shaped building. Given the importance of building forms' effects on energy efficiency and thermal comfort, other design forms such as square or circular footprints can be studied to compare the results of different forms with the findings of this research. This can illustrate to what extent the effects of thermal mass on building performance can be different from one design from to another shape. Second, as observed in Chapter 8 for the LCC analysis of BC model, the change of height from a 12 story building (BC model) to a tall building, e.g., a 60 story building, can have a significant impact on the effectiveness of thermal mass in improving building energy and comfort performance. The scale of tall buildings, the change of wind velocity and air temperature from the ground floor to the top floor can affect the behavior of thermal mass. A future study the focuses on the implementation of thermal mass in tall buildings to improve energy savings and thermal comfort can further advance this research. Third, different types of perimeter wall assemblies as well as different types of glazing, especially with low-e coating can be combined with thermal mass to study the benefits from other energy saving recommendations in conjunction with thermal mass. Fourth, different orientations of building in general and the orientation of thermal mass walls in particular as well as the combination of insulation and thermal mass with respect to different orientations can also be explored. Finally, in terms of LCC, besides the cost of concrete materials, other construction, assembly, maintenance and demolition costs associated with concrete should be determined to assess the actual benefits of thermal mass.

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Appendix A: Tables

Table A.1: Energy Matrix

		Miami	Phoenix	San Francisco	Albuquerque	Chicago	Minneapolis	Duluth	Fairbanks
Wall thickness (in)	4	1,946,280.38	2,073,298.09	1,184,594.63	2,390,774.97	5,014,703.32	6,263,495.10	7,610,105.53	10,661,976.40
	8	1,883,231.04	1,904,310.39	988,618.69	2,081,226.70	4,503,966.57	5,617,937.79	6,787,673.44	9,714,716.62
	12	1,878,279.76	1,840,701.69	871,360.14	1,907,775.18	4,183,930.36	5,213,461.02	6,267,290.91	9,086,664.50
	16	1,885,236.78	1,813,101.11	808,125.20	1,802,184.84	3,964,554.72	4,937,672.98	5,914,196.28	8,644,695.22
	20	1,891,761.67	1,798,153.56	773,190.73	1,736,375.98	3,816,860.62	4,751,084.75	5,677,322.87	8,340,526.36
Thermal mass exterior area (%)	80	1,829,596.12	1,981,063.81	1,270,265.73	2,509,475.07	5,118,163.10	6,400,173.61	7,800,885.19	10,779,613.41
	70	1,946,280.38	2,073,298.09	1,184,594.63	2,390,774.97	5,014,703.32	6,263,495.10	7,610,105.53	10,661,976.40
	55	2,128,093.15	2,227,317.07	1,105,001.01	2,267,046.96	4,851,083.11	6,055,480.50	7,312,401.24	10,463,901.16
	40	2,304,114.56	2,390,365.02	1,082,116.48	2,204,290.81	4,702,570.08	5,859,108.08	7,032,977.45	10,272,030.23
	20	2,523,908.69	2,609,537.47	1,111,362.59	2,197,617.37	4,524,969.44	5,618,933.05	6,688,336.20	10,026,214.26
Slab thickness (in)	4	1,946,280.38	2,073,298.09	1,184,594.63	2,390,774.97	5,014,703.32	6,263,495.10	7,610,105.53	10,661,976.40
	6	1,943,811.50	2,029,494.84	1,087,952.18	2,284,902.38	4,922,944.92	6,155,573.13	7,472,592.75	10,521,219.56
	8	1,952,329.06	2,011,031.73	1,029,864.96	2,222,609.95	4,858,285.27	6,081,161.63	7,376,013.46	10,416,561.28
Interior wall layout	Central core	2,012,469.81	2,131,358.51	1,181,630.20	2,397,624.00	5,019,150.68	6,261,583.19	7,589,432.43	10,656,711.98
	Split core-long side	2,006,671.90	2,139,817.67	1,203,899.14	2,430,872.16	5,080,436.83	6,333,465.45	7,685,373.78	10,756,145.84
	Split core-short side	2,002,362.80	2,144,706.31	1,215,642.30	2,442,239.49	5,082,683.33	6,337,005.14	7,688,389.79	10,756,835.88

⬚

Lowest Energy Case, Unit: kBtu

Step 1:
In each four categories of wall thickness, exterior thermal mass area, slab thickness and interior wall layout, the case of least energy consumption (green cells in the table) was determined.

Step 2:
Then, for each location, a combination of these least energy consumption cases was modeled, and their energy use was compared to the base case model.

Step 3:
The least energy consumption case for each location was also specified and compared to the combination case to determine if the combination of most efficient variables can in fact guarantee the least energy consumption.

Table A.2 Energy use reductions

Cases Location	Percent reduction (increase) of total energy	
	Combination Case vs. Basce Case	Lowest Energy Case vs. Combination Case
Miami	10.9	(5.4)
Phoenix	21.0	(9.8)
San Francisco	41.0	(10.6)
Albuquerque	24.4	3.9
Chicago	20.3	4.5
Minneapolis	20.8	4.2
Duluth	23.1	2.9
Fairbanks	14.5	8.5

Table A.3 Energy use reductions with insulation

Cases Location	Percent reduction (increase) of total energy		
	Combination Case vs. Base Case	Lowest Energy Case vs. Combination Case	Combination Case with Insulation vs. Lowest Energy Case
Phoenix	21.0	(9.8)	17.2
Duluth	23.1	2.9	11.0

APPENDIX B: FIGURES

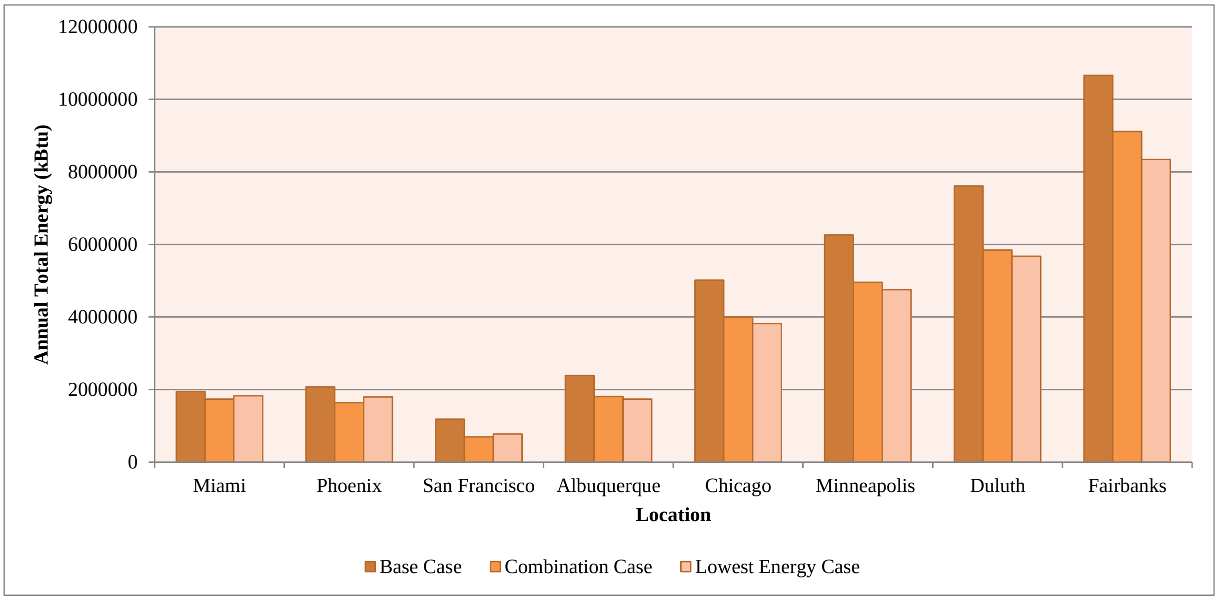

Figure B.1 Energy use comparison

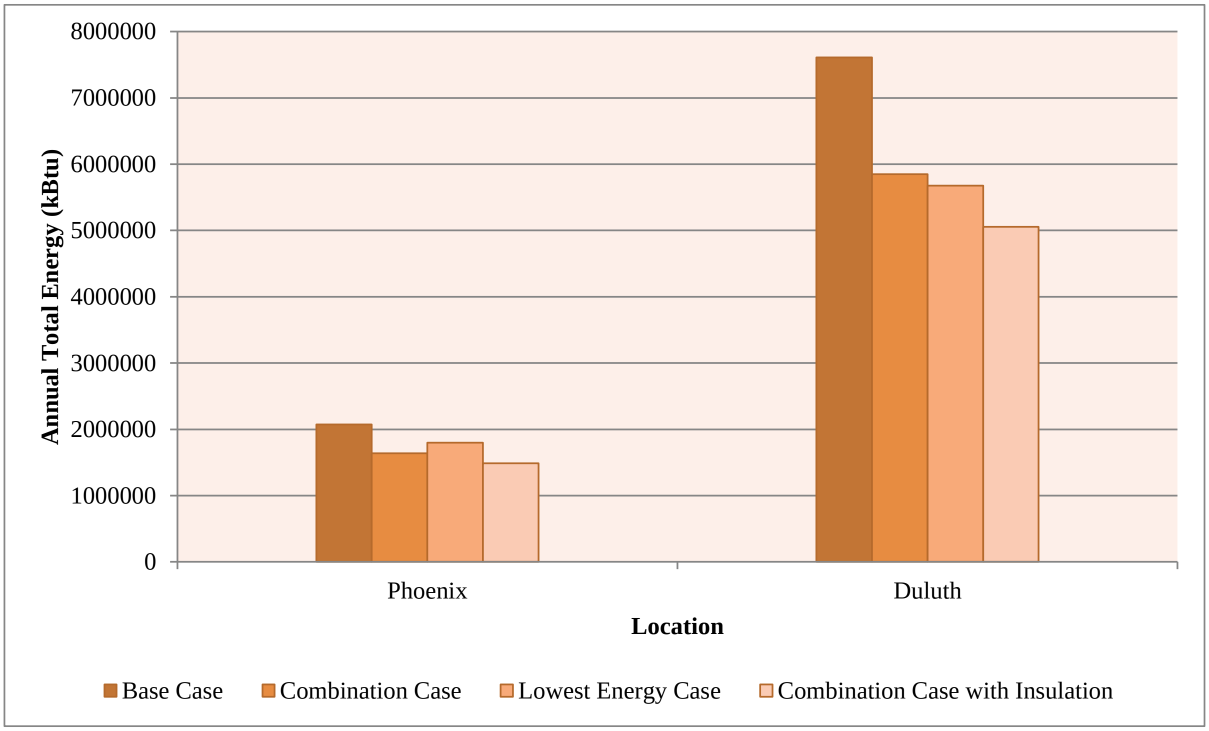

Figure B.2 Energy use comparison with insulation

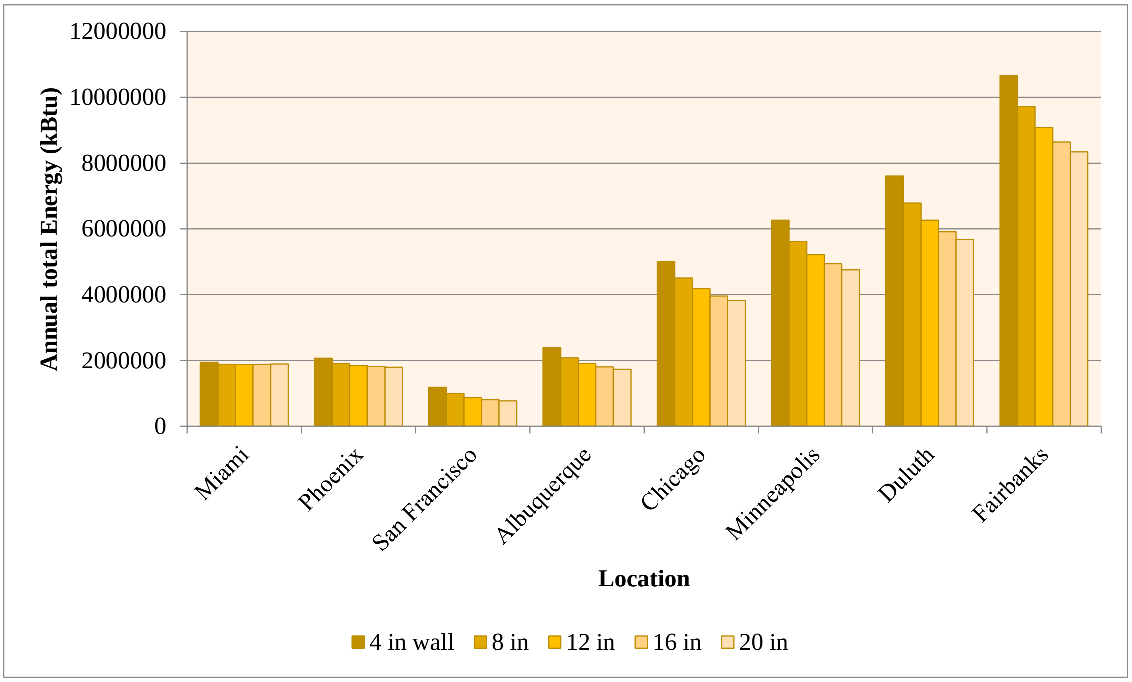

Figure B.3 Total energy use comparison (wall thickness)

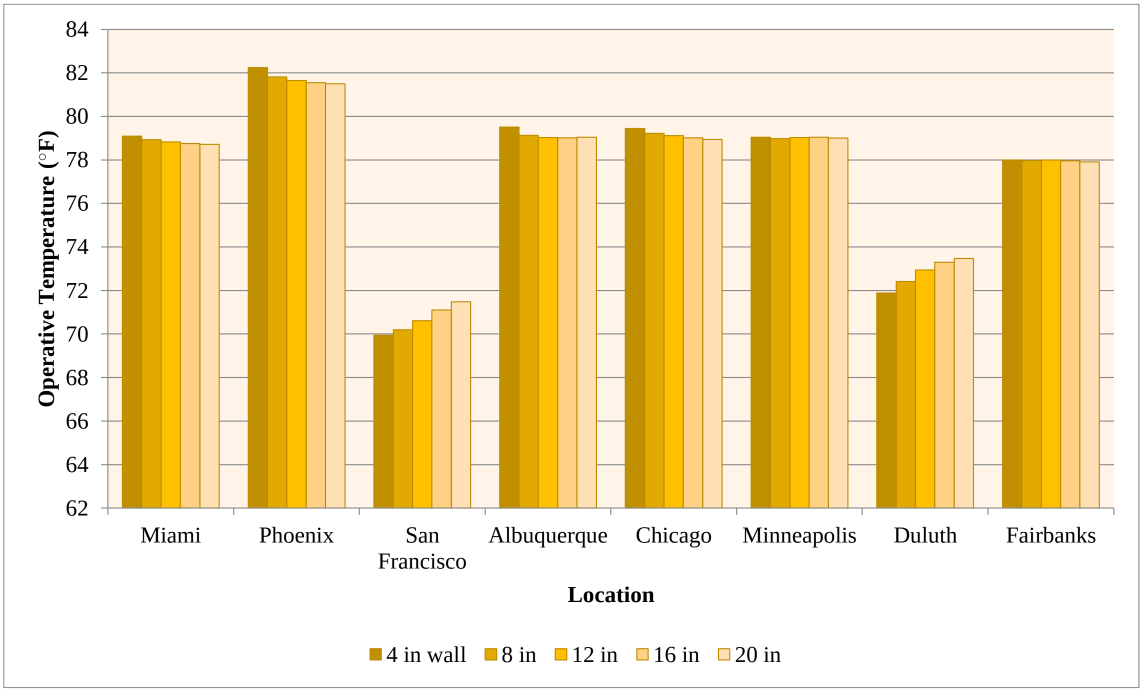

Figure B.4 Operative temperature, summer: occupied hours (wall thickness)

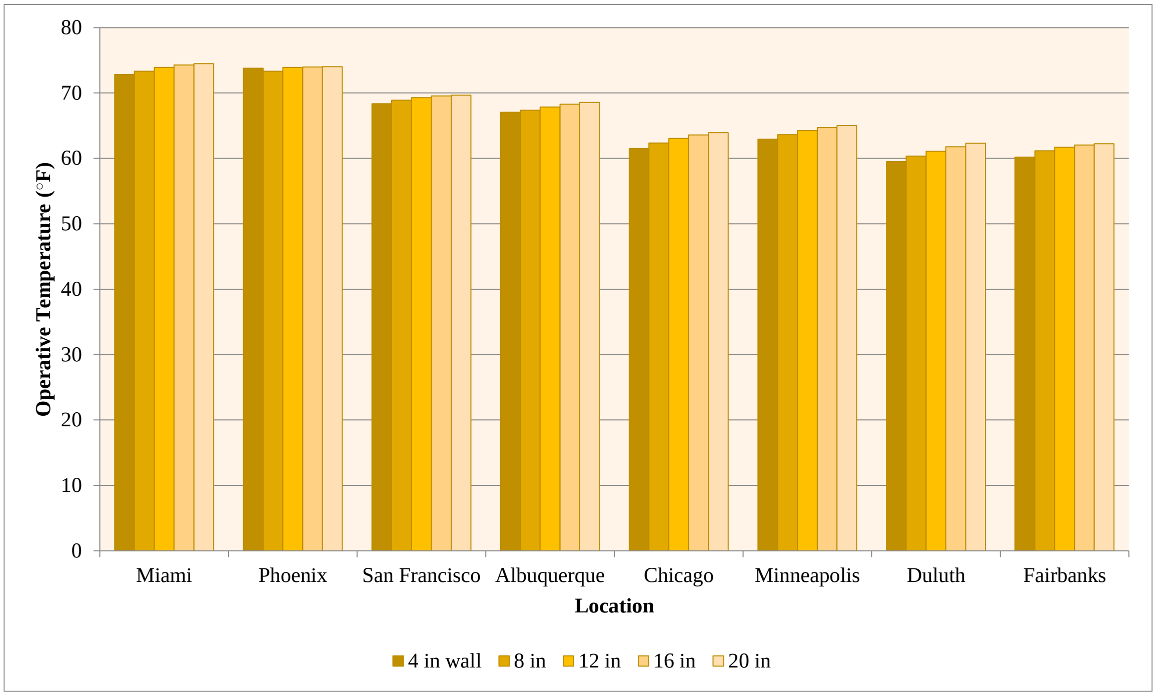

Figure B.5 Operative temperature, winter: occupied hour(wall thickness)

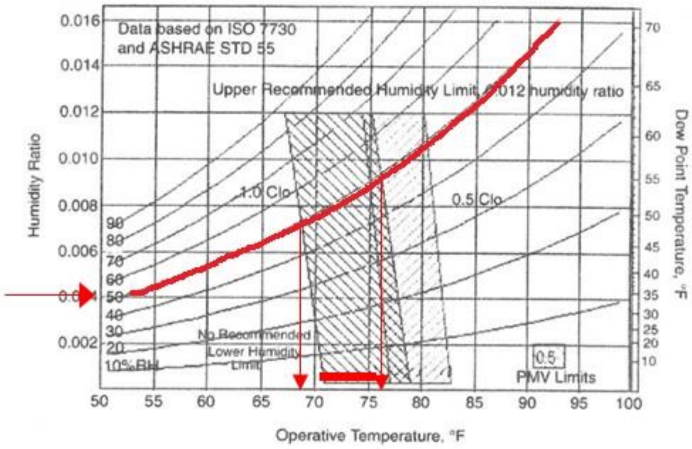

Figure B.6 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

(For RH of 50%, the corresponding operative temperature ranges from 72-77 °F)

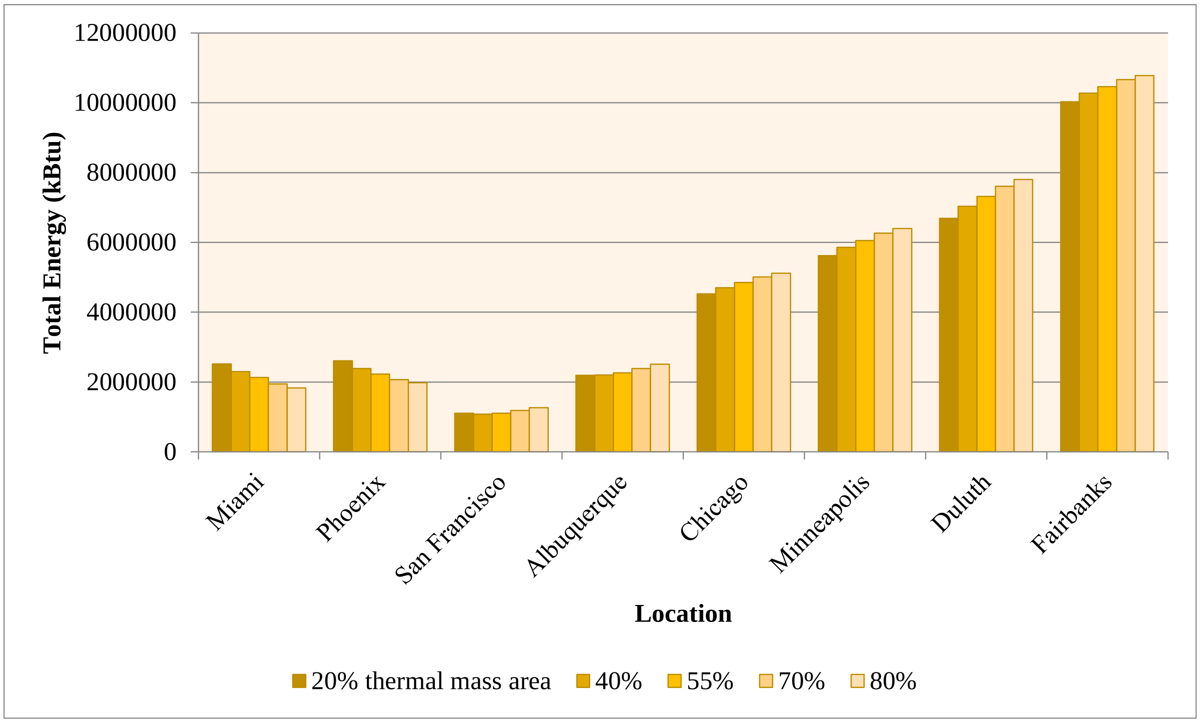

Figure B.7 Total energy use comparison (Thermal mass area)

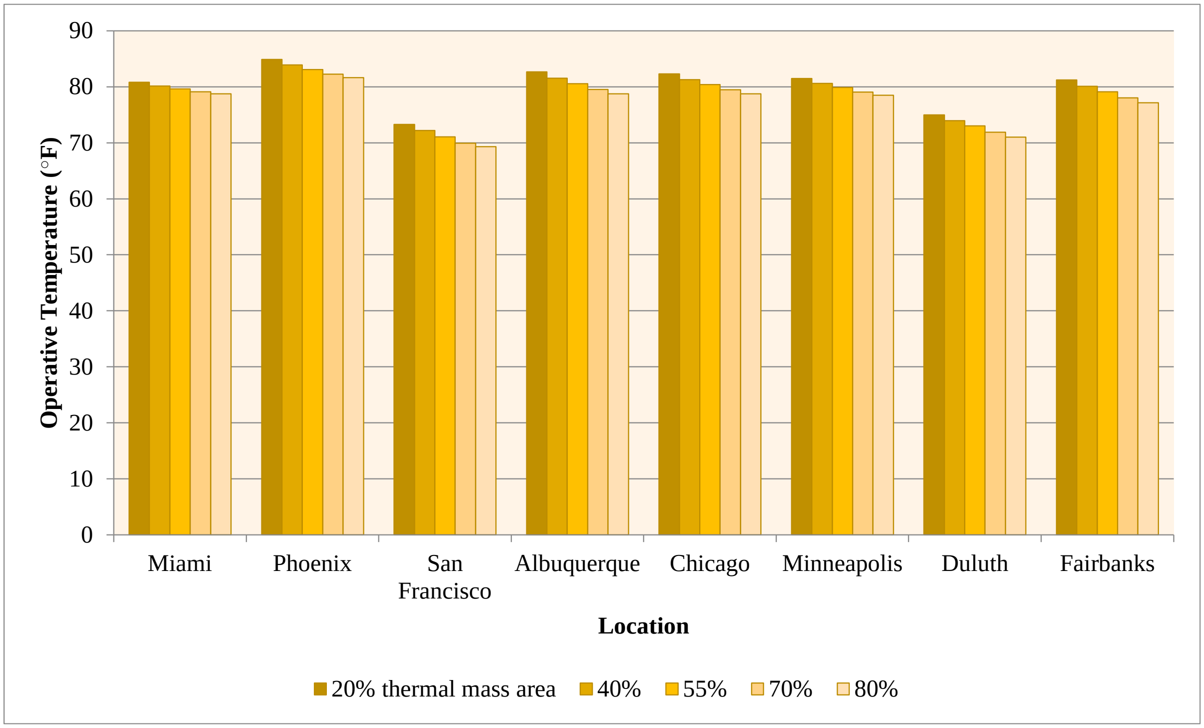

Figure B.8 Operative temperature, summer: occupied hours (Thermal mass area)

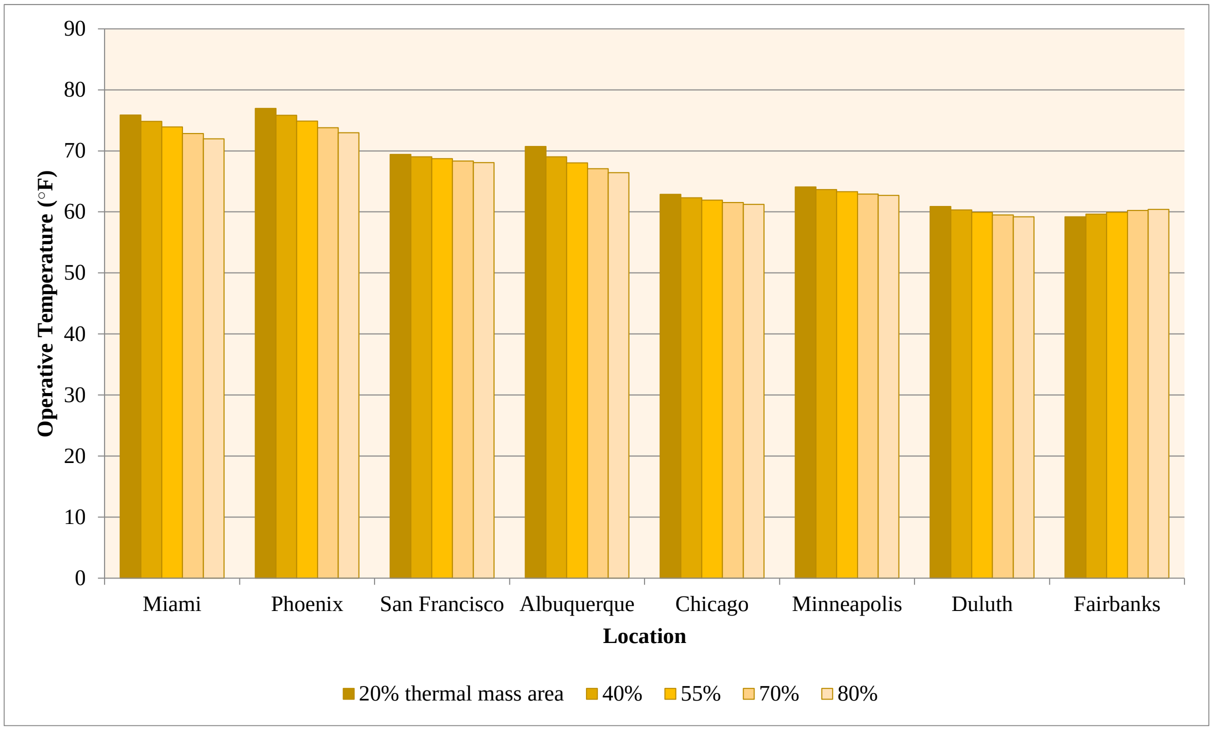

Figure B.9 Operative temperature, winter: occupied hours (Thermal mass area)

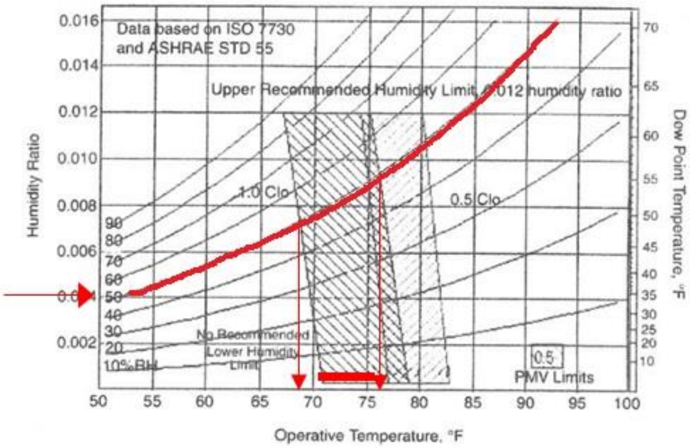

Figure B.10 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

(For RH of 50%, the corresponding operative temperature ranges from 72-77 °F)

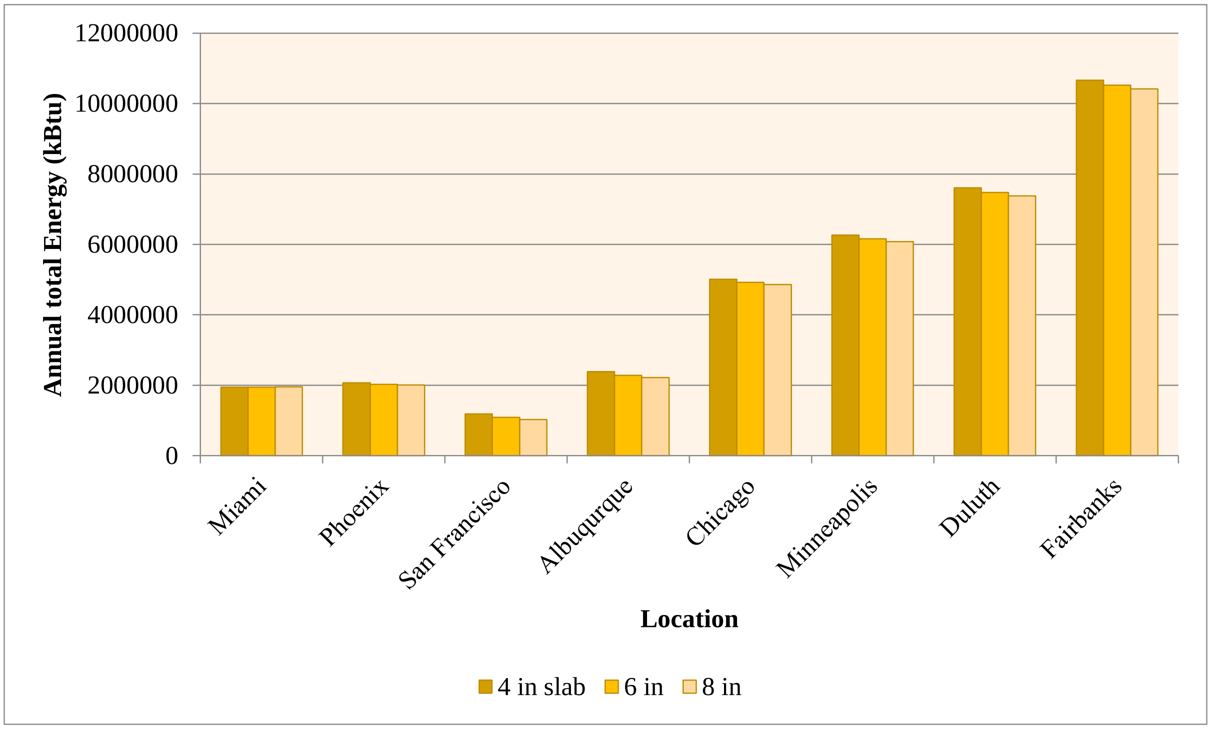

Figure B.11 Total energy use comparison (slab thickness)

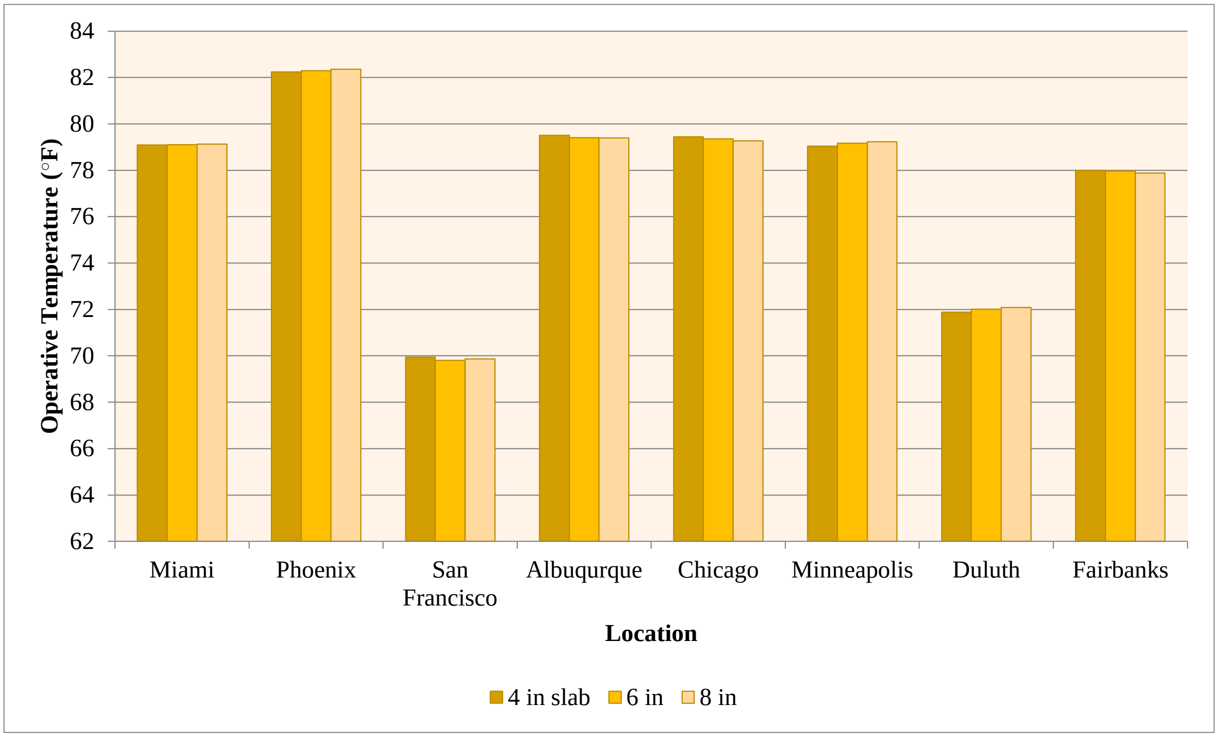

Figure B.12 Operative temperature, summer: occupied hours (slab thickness)

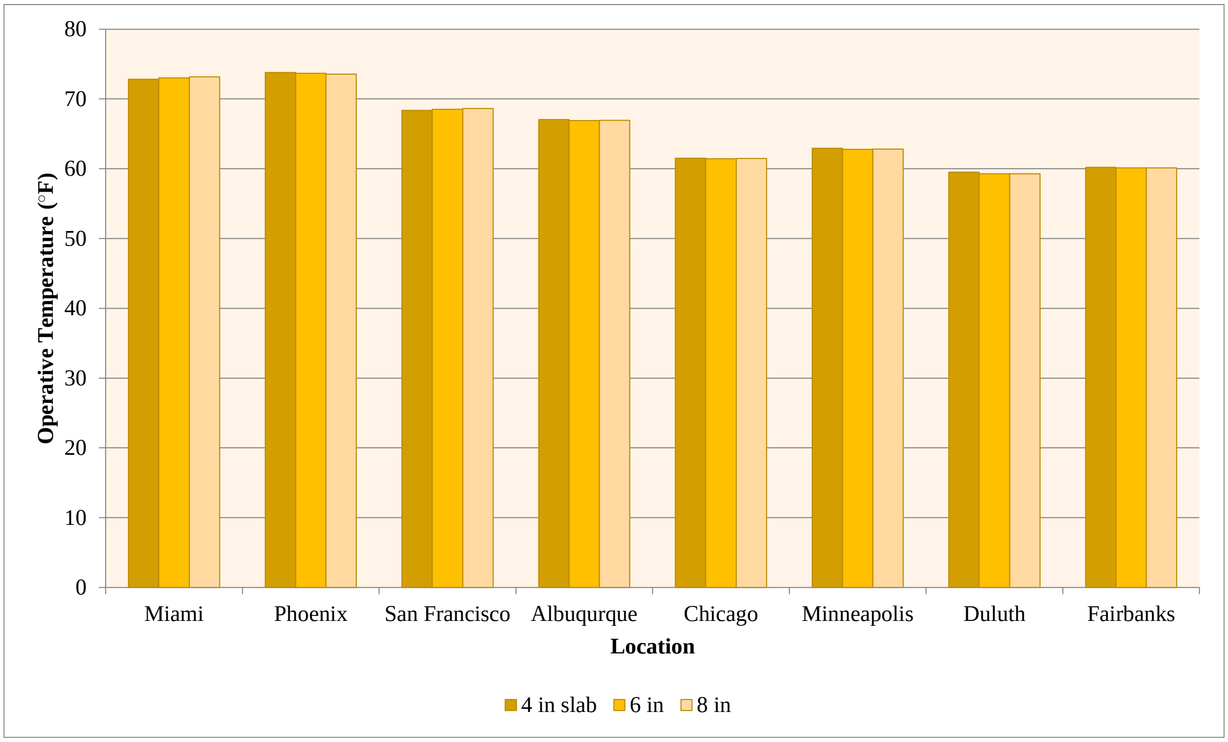

Figure B.13 Operative temperature, winter: occupied hours (slab thickness)

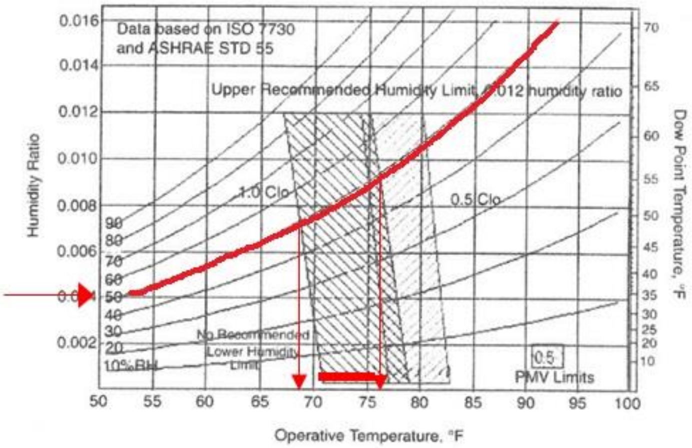

Figure B.14 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

(For RH of 50%, the corresponding operative temperature ranges from 72-77 ºF)

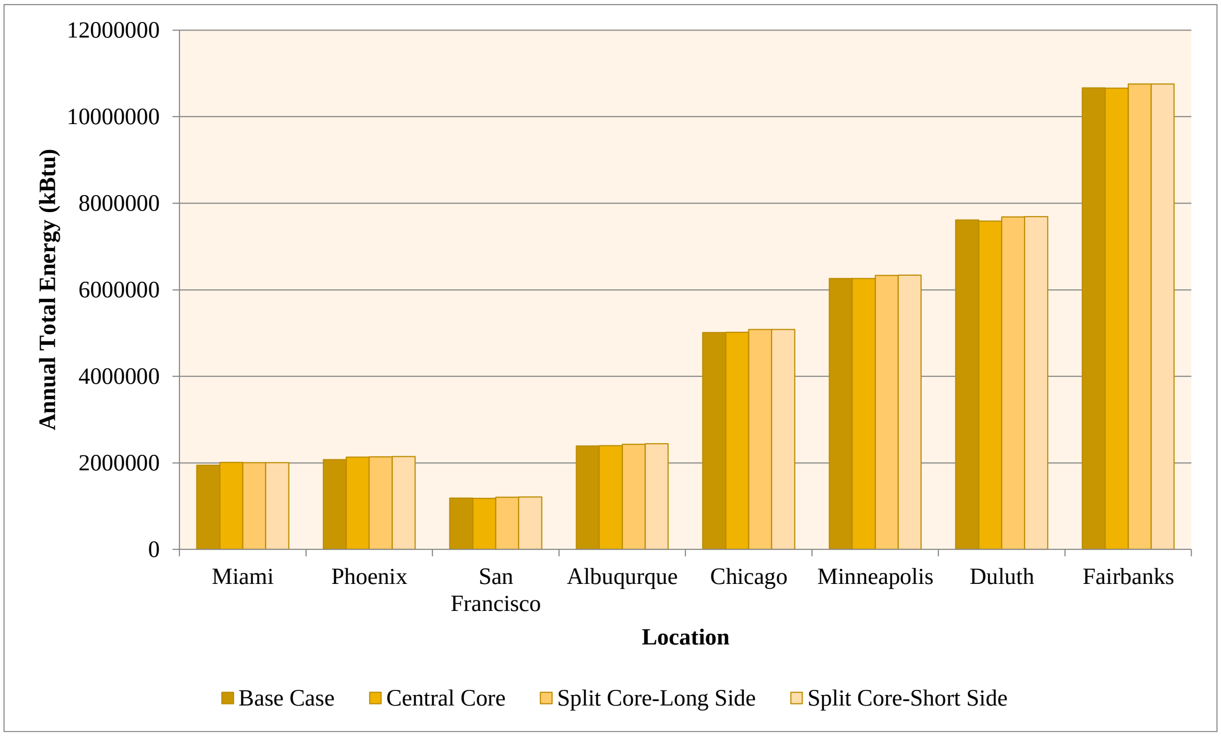

Figure B.15 Total energy use comparison (interior wall layout)

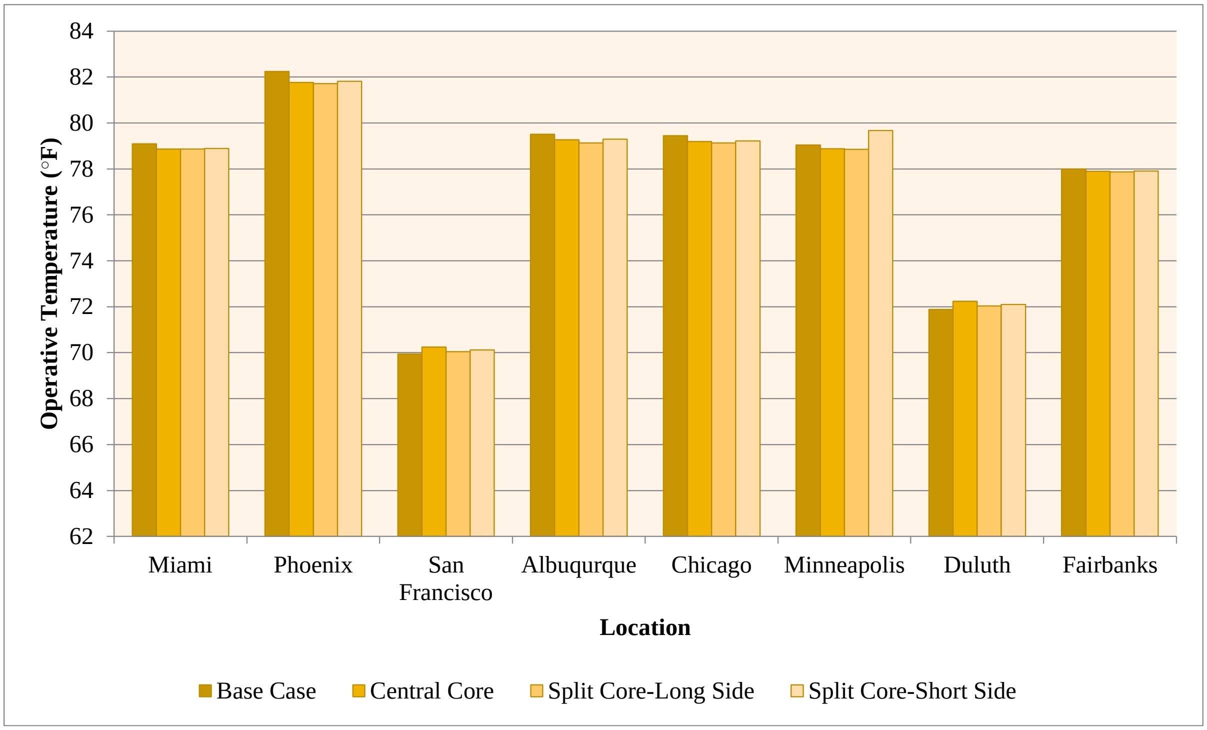

Figure B.16 Operative temperature, summer: occupied hours (interior wall layout)

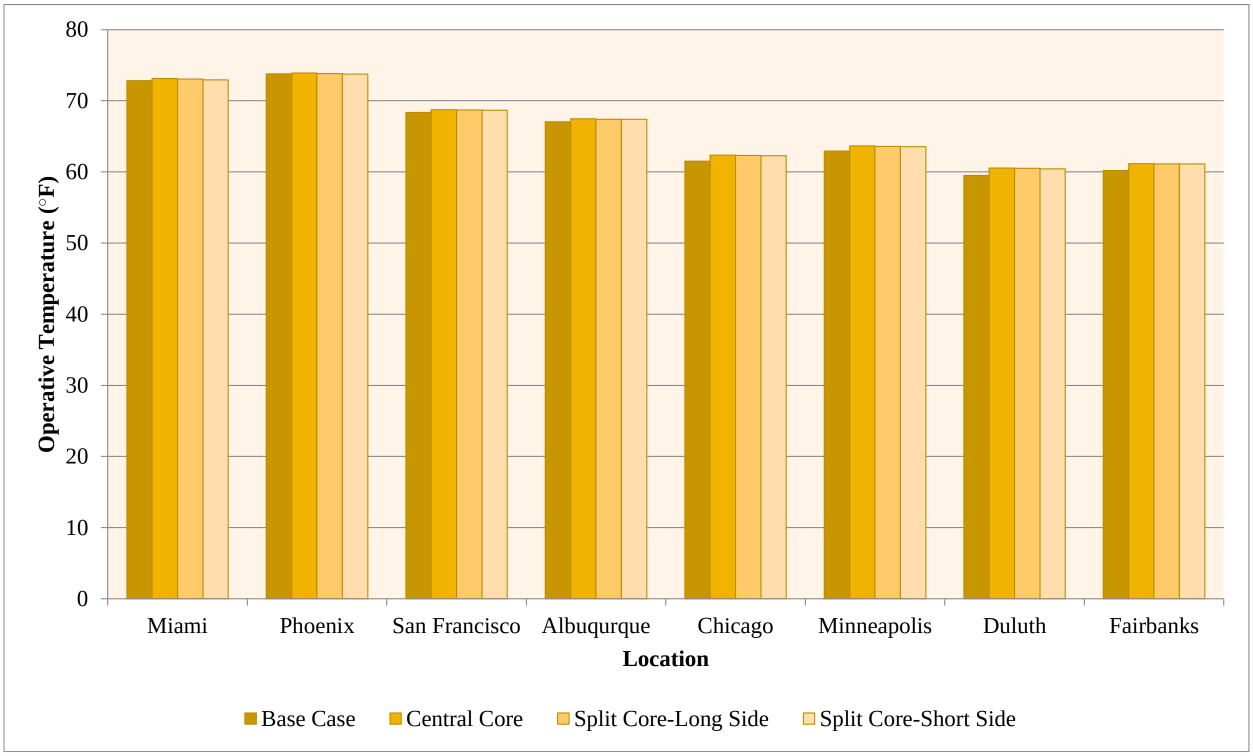

Figure B.17 Operative temperature, winter: occupied hours (interior wall layout)

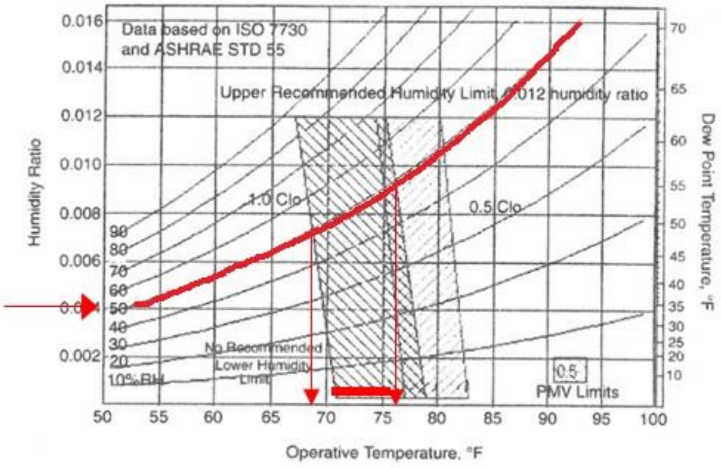

Figure B.18 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

(For RH of 50%, the corresponding operative temperature ranges from 72-77 ºF)

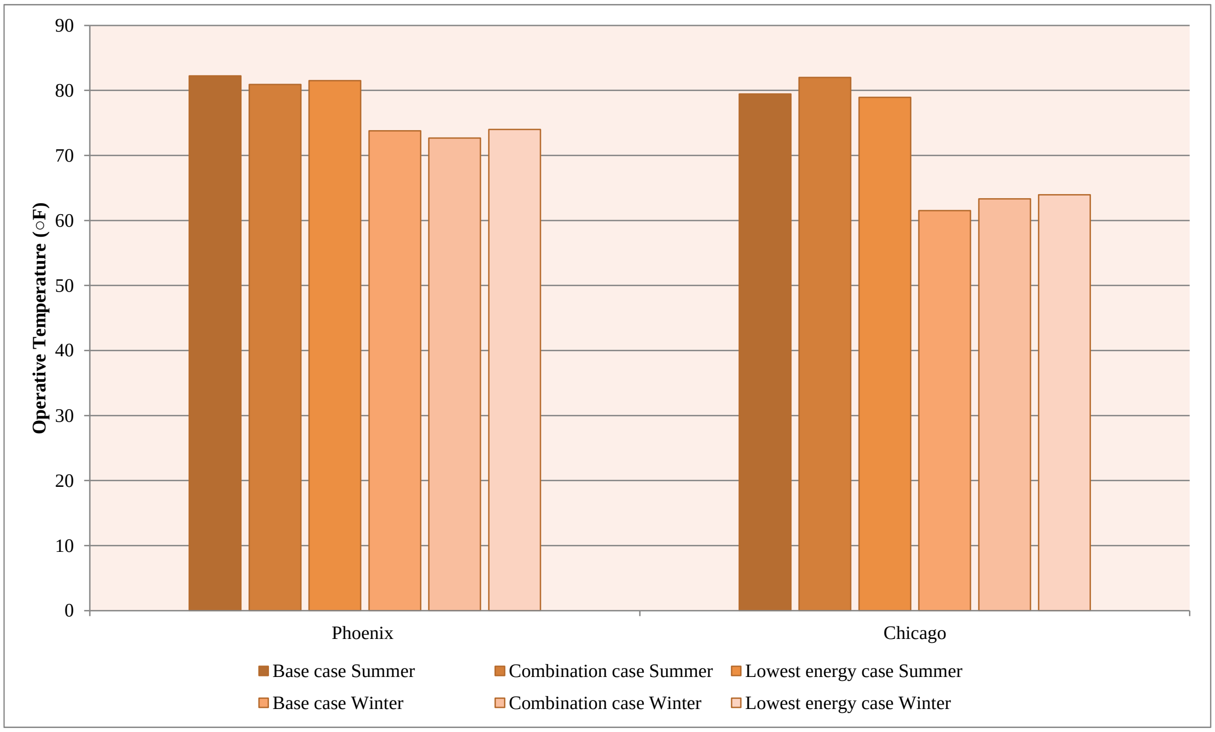

Figure B.19 Operative temperatures, summer and winter (combination cases)

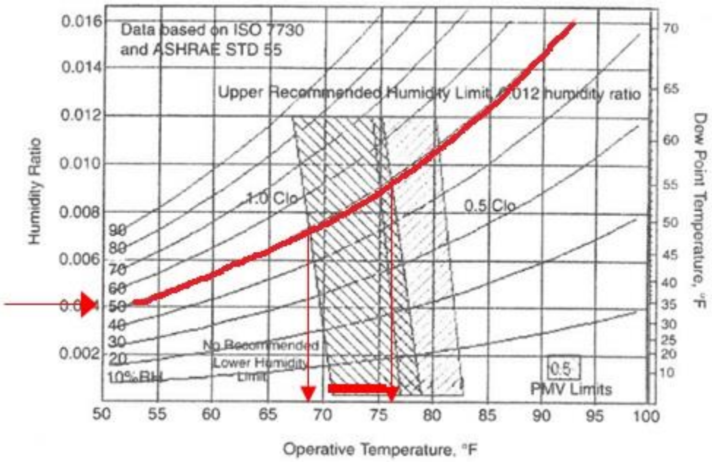

Figure B.20 Thermal comfort zone, *Source: ASHRAE Standard 55-2010*

(For RH of 50%, the corresponding operative temperature ranges from 72-77 ºF)

END