Urban Building Networks' Thermal-Energy Dynamics: Exploring, Mitigating, and Optimizing Inter-Building Effects

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ABSTRACT

Cities occupy 2% of the earth's surface, and yet consume 75% of the world's resources. As a major contributor to rapidly growing global energy expenditures, urban buildings are often designed and operated inefficiently despite their significant contributions to carbon emissions, triggering environmental deterioration locally and worldwide. Moreover, ongoing industrialization and urbanization pose challenges for achieving a more sustained and resilient built environment. The goal of this PhD research is to advance our understanding of urban building networks' thermal-energy dynamics in order to achieve sustainable energy conservation in the built environment. Considering buildings as networks rather than as stand-alone entities highlights the inextricably linked and interwoven relationship between urban micro-climates and buildings. With this approach, I strive to explore, mitigate, and optimize the mutual influences of the Inter-Building Effect (IBE) in dense urban settings through numerical and empirical analyses. My research also draws inspiration for investigating solutions to complex engineering problems from nature, as I seek to understand synergies between building and biological systems to discover innovative connections and integrate biology to transform buildings through sustainable building network designs. This dissertation contains three interdependent projects to explore, mitigate and optimize the IBE, respectively. I first developed a systematic approach to separately assess the complex interactions that constitute the IBE in dense urban settings and conducted cross-regional analyses in a dynamic simulation environment. Having disaggregated, quantified and understood the effects of mutual shading and mutual reflection within a network of buildings, I then, in the second project,

examined different measures to mitigate the negative IBE impact under certain circumstances (e.g. directional reflective optical properties of building façades and thermal storage technologies). These two projects extended prior work that examined the potential for a biological system retroreflective surface to reduce IBE in urban building networks. Therefore, in my third project, I introduced a broad framework that draws parallels between natural and built environment systems through a levels-of-organization perspective leading to the search for an optimal status of the IBE. Inspired from a self-regulating phenomenon of plant density, I presented and discussed an approach to determine optimal urban building network density as an example for how this framework can support cross-level assessment. The findings expand and deepen our understanding of the IBE and provide insights on the strategies to mitigate the negative mutual impact within dense urban building networks. This research contributes a unique and holistic perspective on the interdependencies in the urban building network system. To design density-optimal building networks will become increasingly important to sustainable urban development and smart growth as clusters of dense urban settings continue to grow due to rapid urbanization and population migration in the next few decades.

To Xuan and little MQ

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CHAPTER 1: INTRODUCTION

The built environment is a major contributor to global energy expenditure. The building sector consumes the largest proportion of energy, accounting for as much as 32% of total final energy consumption and nearly 40% of primary energy consumption (International Energy Agency, 2013a). Cities represent the highest concentration of energy use. Although they occupy merely 2% of the earth's surface, their inhabitants consume 75% of the world's resources (Pacione, 2009). According to the latest data from the International Energy Agency (International Energy Agency, 2013b), annual global energy consumption has grown from 4000Mtoe (million tonnes of oil equivalent) to nearly 9000Mtoe during the last 40 years (1971-2011). Over the same period of time, CO^2 emissions have doubled. Rapidly growing world energy expenditure not only causes supply difficulties and depletion of fossil energy resources, but also substantially influences the human living environment by triggering climate deterioration locally (e.g. Urban Heat Island effects) and worldwide (e.g. global warming). In addition, ongoing and upcoming industrial developments and urbanization in fast developing countries and underdeveloped regions will intensify energy usage (B. Li & Yao, 2009). Therefore, efforts to achieve a more sustainable built environment have become a central task for engineers, building researchers, urban planners, and policy makers.

Urban morphology—characterized by building density, size, height, and orientation, and layout—causes considerable variations to the local environment and microclimates. Research has shown that urban microclimates and buildings are inextricably interwoven (de La Flor & Domınguez, 2004; Yao & Steemers, 2013). It is difficult to understand and predict one building's energy performance accurately without considering the close proximity of other buildings. Recent research has demonstrated that the interrelationship between buildings within building networks, namely the Inter-Building Effect (IBE), results in inaccuracies of energy consumption predictions of up to 42% in summer and up to 22% in winter for heating, cooling and lighting (Pisello, Castaldo, Taylor, & Cotana, 2014; Pisello, Taylor, Xu, & Cotana, 2012). The research also demonstrates that the energy performance of one building can be significantly impacted by surrounding buildings through mutual reflection and mutual shading. High density urban development reduces the cost of public services and transportation and is often considered more sustainable and efficient compared to extensive urban sprawl (Ng, 2010). The number of cities and megacities continues to rise, yet IBE effects are amplified in a high-density urban environment owing to the negative impacts of compactness on natural light, solar gain, and ventilation. This challenges the optimal determination of urban morphology due to limitations in urban space and researches and complicates the task of achieving energy efficiency in cities.

In an effort to reduce the negative impact of buildings on energy use, health, the environment, and global development, my research interests lie at the intersection of an holistic understanding of ecologically sustainable building networks and methodologies to reduce energy consumption in inter-building contexts. My PhD research aims to advance our understanding of urban building networks' thermal-energy dynamics to achieve sustainable energy conservation in the built environment. Considering buildings as networks rather than as stand-alone entities highlights the inextricably linked and interwoven relationship between urban micro-climates and buildings. With this approach, I strive to explore, mitigate, and optimize the mutual influences of the Inter-Building Effect (IBE) in dense urban settings through numerical and empirical analyses. This dissertation contains three interdependent projects and its structure follows a three-paper format.

From work completed prior to my dissertation that represents the motivation for this dissertation research, the thermal-energy impact of a directionally reflective property can mitigate the mutual reflection effect of the IBE (Han, Taylor, & Pisello, 2015b). Although early research revealed that the buildings' energy performance can be significantly impacted by surrounding buildings through mutual reflection and mutual shading, as they are two essential components of the IBE (Pisello et al., 2014, 2012), IBE was largely considered as a monolithic effect across building networks. In order to better understanding the complex IBE interactions, a procedure to separately assess mutual shading and mutual reflection that make up the IBE is presented and discussed in Chapter 2. By manipulating the building envelopes, I disaggregated and quantified the influence of mutual shading and mutual reflection to lighting, cooling, heating, and total primary energy consumption within a network of buildings. Both cross-regional cases and realistic urban cases from Italy were studied in a dynamic simulation environment. This study contributes to the IBE discussion by developing a systematic approach to disaggregate the separate and distinct impact from reflection and shading for a more nuanced analysis. The findings expand and deepen our understanding of IBE and may help in the search to minimize mutual influences between buildings that lead to increases in energy consumption in urban environments. This study was first presented as a conference paper at ICAE2015 (the 7th International Conference on Applied Energy) (Han & Taylor, 2015a) and later published in *Applied Energy*, in a journal article entitled "Exploring mutual shading and mutual reflection inter-building effects on building energy performance" (Han, Taylor, & Pisello, 2015a).

The more nuanced analysis in the first project (Chapter 2) found shading to contribute to increased heating loads while reflection increased cooling energy required for spatially-proximal buildings. The monthly analysis revealed that the contribution of reflection and shading varies on a month-to-month basis as the impact of IBE is closely related to geographical location and climatic conditions. However, limited research has sought solutions to mitigate negative thermal energy inter-building relationships. Although directional reflective building envelopes have been investigated to help lessen mutually reflected solar radiation and mitigate UHI effects within urban canyons in warmer areas (Han et al., 2015b), general solutions to address such negative effects within building networks are still largely unrealized, especially for the temperate areas where shading and reflection impact IBE differently depending on the season, or even over the course of a day. With the important characteristic to store and release heat within a certain temperature range, the use of phase change materials (PCMs) can significantly shorten overheated hours and shift peak electricity loads (Belmonte, Eguía, Molina, & Almendros-Ibáñez, 2015; Zhou, Zhao, & Tian, 2012). Previous exploration demonstrated that PCMs have different benefits depending on quantity, types, locations, and climates (Baetens, Jelle, & Gustavsen, 2010; Nkwetta & Haghighat, 2014; Zhou et al., 2012). However, nearly all of them are discussed within the context of a single buildings. In Chapter 3, I evaluated the application of PCMs from the perspective of inter-building relationships that extend beyond a stand-alone building scenario and examined whether PCM-embedded building envelopes could serve as a possible solution to mitigate the negative thermal-energy impact of IBE through parametric numerical analysis. The results suggest PCM building envelopes as possible solutions to mitigate negative inter-building influences and improve energy efficiency within urban building networks, especially in temperate cities. The study was first presented as a conference paper at ICSDEC 2015 (International Conference on Sustainable Design, Engineering and Construction 2015) (Han & Taylor, 2015b) and later published in *Sustainable Cities and Society*, as a journal article entitled "Simulating the Inter-Building Effect on Energy Consumption from Embedding Phase Change Materials in Building Envelopes" (Han & Taylor, 2016).

After the research efforts to better evaluate the mutual influences of the IBE (Chapter 2) and to mitigate the negative mutual influences of the IBE (Chapter 3), I build upon my prior research in bio-inspired buildings to take a step further to search for an optimal status of the IBE in dense urban settings. While researchers have been researching solutions for reducing energy consumption in the built environment from engineering or architectural perspectives, it is possible that answers may lay hidden in nature. Bio-inspiration as a design approach has been explored as a strategy to improve the functioning of the built environment (Gruber, 2008; John, Clements-Croome, & Jeronimidis, 2005). Natural systems are more efficient and robust due to their time-tested structures and mechanisms. In Chapter 4, I introduced a framework that parallels natural systems and built environment systems through a levels-of-organization perspective and categorized a number of current bio-inspired applications in the AEC fields based on the levels-of-organization framework. Inspired from a self-regulating phenomenon of plant density that results from intra- and inter- specific competition for limited resources, I introduce an approach to determine optimal urban building network design and discuss as an example for how this framework can support cross-level assessment. This project not only contributes a unique and holistic framework that strengthens our understanding of the associations between the fields of biology and AEC, but also provides valuable insights on urban building design with optimal levels of density. It will help promote sustainable and resilient urban growth that better integrates natural and built environment systems at and across levels of organization. The article presented in Chapter 4 is in preparation to be submitted to a peer-reviewed journal. It is entitled "Associating Natural and Built Environment Systems - A framework for understanding bio-inspired applications in the built environment from a levels-of-organization perspective".

CHAPTER 2: EXPLORING MUTUAL SHADING AND MUTUAL REFLECTION INTER-BUILDING EFFECTS ON BUILDING ENERGY PERFORMANCE[1]

2.1 Abstract

The built environment contributes significantly to rapidly growing world energy expenditure and tighter spatial interrelationships can exacerbate this effect in cities. The concept of the Inter-Building Effect (IBE) was introduced to understand the complex mutual impact within spatially proximal buildings. Our research sought to develop a systematic approach to disaggregate and quantify the influence of mutual shading and mutual reflection within a network of buildings. We built an urban building network model and conducted cross-regional simulations under different climatological contexts by examining mutual shading only and mutual reflection only, respectively. We then expanded our investigation by examining two realistic urban contexts in Perugia, Italy. We found the shading effect played a more significant role in terms of impact on energy consumption. The results of the simulations in varying climatological contexts also revealed consistent trends of greater impact on the IBE for shading and reflection in warmer climatic cities. These findings expand and deepen our understanding of inter-building effects and may help in the search to minimize mutual influences between buildings that lead to increases in energy consumption in urban environments.

[1] This paper was co-authored with Prof. John E. Taylor and Prof. Anna Laura Pisello. It was published in *Applied Energy*.
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2.2 Introduction and Background

Rapidly growing world energy expenditure has raised global concerns and became a central topic of research and public debate over the last several decades. Cities represent the highest concentration of energy use (Hui, 2001). Buildings alone account for as much as 32% of total final energy consumption and nearly 40% of primary energy consumption (International Energy Agency 2013). To address building energy consumption, numerous research efforts have focused on how to achieve a more sustainable built environment from perspectives such as renewable energy (Connolly, Lund, Mathiesen, & Leahy, 2011; Pehnt, 2006), adaptive building envelopes and materials (Berardi, GhaffarianHoseini, & GhaffarianHoseini, 2014; Caldas & Norford, 2003; Loonen, 2015), occupant efficiency (Jain, Taylor, & Peschiera, 2012; Xu, Culligan, & Taylor, 2014), advanced building information technologies (Azhar, 2011; Hong, Chou, & Bong, 2000) and building automation systems (Dibowski, Ploennigs, & Kabitzsch, 2010; Široký, Oldewurtel, Cigler, & Prívara, 2011), sustainable rating strategies (Azhar, Carlton, Olsen, & Ahmad, 2011) and energy policies (Jacobsson & Lauber, 2006), among others. Urbanization—referred as the migration of rural dwellers toward towns, cities and megacities for the promise of a better life—is creating profound effects in the urban environment, including; the quality of urban air, urban temperature, energy consumption and water supply, pollution and waste products, loss of bio-diversity, conversion of agricultural to developed land, etc. (Santamouris, 2013). A recent report from the United Nations projected the population in urban areas to reach 6.3 billion in 2050, 72%

greater than the 3.6 billion urban dwellers in 2011 (UNDESA, 2011). Urban built settings are evolving toward much tighter spatial interrelationships, which could exacerbate urban energy consumption, and also influence the surrounding microenvironment and microclimate. The motivation of this research is to examine and deepen our understanding of inter-building relationships in dense urban settings resulting from urbanization and the related impacts on building energy consumption.

Urban morphology—characterized by building density, size, height, orientation, and layout—causes considerable variations in the local environment. Urban microclimates affect a building's performance in terms of energy consumption and indoor living environment, while buildings affect the urban microclimate within their building networks (Chow, Li, Lee, & Lam, 2013; de La Flor & Domınguez, 2004; Krüger, Pearlmutter, & Rasia, 2010; B. Li & Yao, 2009). Early research largely focused on the energy behavior attributed to individual buildings to understand and optimize the energy efficiency of an individual building by describing indoor thermal behavior, energy consumption, and building envelope features. However, to treat buildings as stand-alone entities does not accurately represent a building's energy performance since it does not consider the nearby buildings which could exert a mutual influence on thermal dynamics. One example is that reflective envelopes could reflect daylight to the neighboring buildings and surrounding areas and create problems such as glare and overheating, which may result in visual and thermal discomfort to building occupants (Yang, Grobe, & Stephen, 2013). Thus, building networks and urban street canopies should be taken into consideration, and have drawn attention by building researchers to holistically understand energy issues. He et al. studied the impact of the local outdoor environment to building thermal-energy behavior, indicating that it is not sufficient enough to assess a building's energy dynamics solely based on building features (He, Hoyano, &

Asawa, 2009). To evaluate solar rights and shading requirements in an urban environment, Shaviv and Yezioro developed a CAD tool that can analyze the mutual shading between buildings and surrounding objects, such as trees (Shaviv & Yezioro, 1997), and it was later extended by Li and Wong to study the daylighting and energy implications from nearby obstructing buildings (D. H. W. Li & Wong, 2007). Golany brought an urban design view of the relationship between urban design morphology and the thermal performance of the city concerning street orientation, building geometry and urban proportions (Golany, 1996). Taking the idea of urban design morphology to the next step, Conceição António et al. proposed an approach on the optimal placement of buildings that favors the use of solar energy (Conceicao Antonio, Monteiro, & Afonso, 2014).

To understand the complex interactions within spatially proximal urban building networks, the concept of the Inter-Building Effect (IBE) has been introduced and further studied over the last several years (Han et al., 2015b; Pisello et al., 2014, 2012). Pisello et al. (2012) employed IBE indexes to demonstrate the interrelationship between buildings within building networks which could result in substantial inaccuracies (up to 42% in summer, and up to 22% in winter) of energy consumption predictions for space heating and space cooling. The research also revealed that the buildings' energy performance can be significantly impacted by surrounding buildings through mutual reflection and mutual shading (Pisello et al., 2012). Thus, in order to accurately predict the energy performance of a single building, the IBE created by the spatially proximal buildings should be considered. IBE research was later expanded to examine primary lighting energy consumption using daylight analysis and through the use of empirical data for model calibration (Pisello et al., 2014). Higher values of the IBE indexes were found for the lighting energy consumption, indicating lighting is also impacted by surrounding buildings within inter-building contexts. With foreseeable urbanization in the next several decades, tighter spatial interrelationships between buildings in urban settings will exacerbate the IBE and this necessitates a more nuanced analysis of its effects. Although shading and reflection have been discussed as two essential components of the IBE (Pisello et al., 2014, 2012), previous research has largely considered the IBE as a monolithic effect across building networks. More research is needed to disaggregate the impact in order to explore which factors may be largely dependent on the local climatic environment and which could be addressed separately through urban planning and building designs.

The research presented in this paper builds upon previous IBE efforts (Han et al., 2015b; Pisello et al., 2014, 2012) concerning the study of energy and thermal behavior of buildings in a dense urban context to further analyze and understand the effect of mutual impact by the IBE in a micro-urban environment. Our objective is to develop a procedure to separately assess the complex interactions, i.e. mutual shading and mutual reflection, that make up the IBE. Through comparative simulation and analysis, we sought to disaggregate and quantify the influence of mutual shading and mutual reflection with respect to space heating, space cooling energy and lighting energy consumption within a network of buildings in urban contexts. The findings of a more nuanced analysis of IBE could lead to better understanding the inter-building thermal-energy relationship and lead solutions to mitigate the negative impact of the IBE in urban micro-environments.

2.3 Methodology

2.3.1 Simulating the IBE in a Dynamic Environment

Simulation tools offer powerful functionalities to predict and improve building energy consumption for both research and design purposes. Of current mainstream simulation environment and platforms, EnergyPlus (Crawley et al., 2001), an energy analysis and thermal load simulation engine distributed by the U.S. Department of Energy, has become a popular building energy performance simulation tool owing to its sophisticated and validated functions. It was utilized for previous IBE research and dynamic building network analyses (Han et al., 2015b; Pisello et al., 2014, 2012). Early IBE simulation efforts were conducted based on a realistic physical urban block in New York State (Pisello et al., 2012). The research demonstrated that buildings could mutually influence the energy dynamics of near buildings, especially for cooling and heating, and cause substantial energy prediction inaccuracies over the course of a year. Later research further investigated the energy discrepancies in lighting and validated the IBE, as an important effect to be modeled in situations where buildings are surrounded by other nearby buildings (Pisello et al., 2014). Experiment and empirical data were used to calibrate and verify the simulation work.

Inherited from previous IBE research, we first developed a procedure to separately assess the shading effect and the reflection effect in EnergyPlus which is described in Section 2.3.2. With that, we built a hypothetical nine-building network model to analyze the thermal-energy behavior of the middle control building with combined IBE, IBE without shading, and IBE without reflection, respectively, under different climatological conditions. This is described in Section 2.3.3. We then examined two realistic dense urban contexts located in Perugia, Italy using the same procedure for this disaggregate analysis. This is described in Section 2.3.4.

2.3.2 Procedure for Disaggregating Shading and Reflection from the IBE

Shading and reflection have been evidenced as major contributors that make up the IBE (Pisello et al., 2014, 2012). Therefore, we sought to develop a procedure to disaggregate mutual shading and mutual reflection and assess them separately in the numerical simulation and analysis. The control building was modeled with heat-transferring surfaces and its energy performance was monitored over the course of the simulation. Shading surfaces, an essential geometric element for shading and reflection in the EnergyPlus environment, were used to model neighboring buildings within the studied building networks, to satisfy our simulation needs and avoid of excessive inputs and prohibitive running times for zone calculations.

The EnergyPlus simulation environment uses a ray-tracing method to account for reflections in solar gain and daylight calculation (US Department of Energy, 2010). When solar radiation is diffusely reflected onto each of a buildings' exterior surfaces, the "receiving surfaces" will generate a set of rays proceeding into the outward hemisphere at each receiving point, and determine whether each ray hits the sky, ground, or an obstruction. The radiance at the hit point from the reflection of incident beam is calculated, and contributes to the radiance of its receiving surface. The setting in the field of "Solar Distribution" determines how EnergyPlus treats solar radiation that is reflected from exterior surfaces and then strikes the building (US Department of Energy, 2010). It has five parameters, including; "MinimalShadowing", "FullExterior", "FullInteriorAndExterior", "FullExteriorWithReflections", and "FullInteriorAndExteriorWithReflections". This functionality enables us to test mutual shading alone by eliminating reflection calculations. Such application is usually utilized for less-detailed schematic analysis because reflection calculations can be time-consuming and error-prone. From this, shadow patterns on the control building's exterior surface caused by neighboring buildings are computed, and the reflected solar radiation from its surroundings is neglected.

The effects of shading from the surrounding environment are computed using detailed surface geometry. For shading surfaces, the "bi-directional" shading effect can be manipulated by changing the value of "Transmittance Schedule" with a range from 0.0 to 1.0 (US Department of Energy, 2010). This schedule can be used to allow daily or seasonal transmittance change of a shading element such as deciduous trees that have higher transmittance in winter and lower in summer when their leaves are fully extended. The default transmittance value is 0.0 which means the shading surface is opaque at all times. However, setting it to 1.0 can make the surface transparent and yet keep the reflective properties intact to test reflection when the "WithReflections" option is chosen for "Solar Distribution" (Ellis & Torcellini, 2005; US Department of Energy, 2010). In this way, the shading effect is excluded within the inter-building environment.

With the approach to turn on and off shading and reflection features by manipulating the shading surfaces in the dynamic simulation environment, we could then create different urban micro-environment within building networks, i.e. with combined IBE, IBE without reflection effect, and IBE without shading effect, and test how different scenarios would influence the energy behavior of the control building. It is important to note that for all instances, the control building remained the same to solely test the energy impact caused by the changes we made to the urban microenvironment settings. We implemented OpenStudio (Guglielmetti, Macumber, & Long, 2011), a graphical third-party application developed by the National Renewable Energy Laboratory (NREL) to support whole building energy modeling, to visualize and to build precise models in a SketchUp interface.

2.3.3 Case Study 1: Hypothetical Urban Building Network

We built a hypothetical building network for the first case study as illustrated in Figure 1. It is a nine-building block that contains one reference building in the center of the building network and eight surrounding shading-surface buildings. The morphology of each building was the same for all buildings within the network. The control building was modeled as a three-story commercial building with a square shape of 10 meters per side. The distance between buildings was set to be 5.25 meters (Height/Width ratio= 2) for both the East-West direction and the North-South direction. For the credibility of the simulation results, we also utilized information about construction materials, temperature set-points, and schedules for lighting, equipment, and occupants from previously published IBE research (Pisello et al., 2014, 2012). Some key parameters are listed as below. The opaque envelope of the reference building consists of external brickwork (0.10m), XPS extruded polystyrene (0.080m), lightweight concrete block (0.010m), and internal gypsum plasterboard (0.013m), with a global thermal transmittance of 0.314W/m^{2}K. The roof contains an internal layer of plasterboard (0.015m), an air gap and roof structure (0.20m), glass wool insulation (0.15m) and asphalt (0.010m), with a global thermal transmittance of 0.250W/m^{2}K. The internal ceiling consists of gypsum plasterboard (0.015m), lightweight cast concrete (0.10m), elastomeric foam (0.005m), and lightweight plywood (0.020m), with a global thermal transmittance of 1.122 W/m^{2}K. The ground floor includes wooden flooring (0.020m), mineral wool (0.15m), floor structure (0.20m), and external rendering (0.025m), and it represents a global transmittance of 0.246W/m^{2}K. The external windows are modeled as double clear glass panes (6mm-6mm with 6mm air). The main working hour schedule is from 8am to 6pm during weekdays. The internal heat gain from people and lighting are 6W/m^2 and 10W/m^2, respectively.

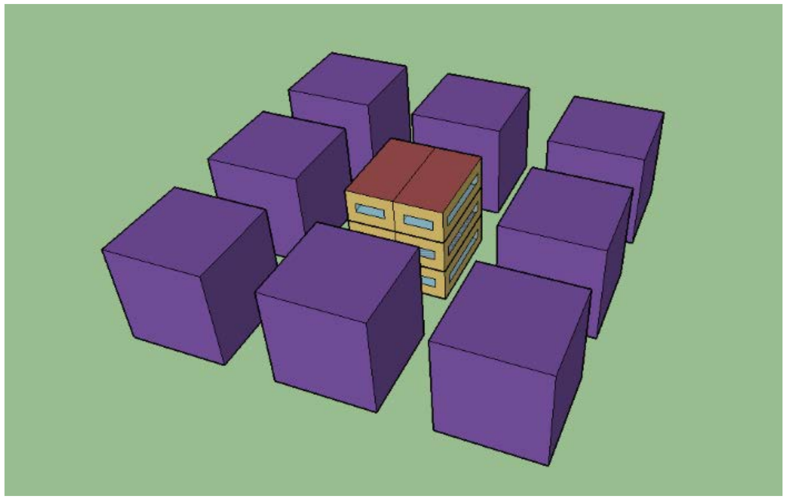

Figure 1: Hypothetical Urban Building Network for Case Study 1

Early IBE research found that IBE effects vary by climatological context (Han et al., 2015b; Pisello et al., 2012; Xu et al., 2014). Therefore, three typical and climatologically distinct U.S. cities, Miami, FL, Minneapolis, MN, and Washington, D.C. were selected for a pilot cross-regional analysis. Miami and Minneapolis represent the extreme climate conditions where heating and cooling loads are largely concerned, while Washington, D.C. has a distinctive and roughly equal length seasons as a typical temperate city. Using the weather profile of each city, several case studies were conducted to test the IBE without reflection, the IBE without shading, and the combined IBE, respectively. We then expanded our analysis to include a total of eight cities covering all six climate zones in the U.S. containing populous cities. For all instances, the control building remained the same and was being monitored in terms of energy and thermal performance over the course of the simulation period. Monthly and annual results were reported, analyzed, and discussed in the following sections. The diffuse solar reflectance of the exterior building envelopes was set to 40% with ground reflectance set to 20%.

2.3.4 Case Study 2: Real Urban Building Networks in Italy

To examine the shading/reflection effect in a more realistic urban morphology characterization, we chose to study two distinct urban building networks in Perugia, Italy. Perugia is a city in central Italy with a temperate climate that has not only severe winter but also hot summer climatological conditions. The choice of the two representative urban contexts (Pisello, Taylor, & Cotana, 2013) were guided by both urban and technical-architectural reasons. The two cases are illustrated in Figure 2. The urban context (a) located at the historical center of the city was characterized by a Middle Ages layout representing a very dense urban context (Height/Width ratio>4). The reference building was a four-story XVI century residential building. The opaque envelope of the reference building consists of two layers of medium weight masonry (0.20m+0.15m) and an inner layer gypsum plastering (0.02m), with a global thermal transmittance of 0.949W/m^{2}K. The other context (b) is located at the close periphery of the city, where many residential buildings were built around 1960-1970, before the enforcement of the first Italian building energy efficiency regulation. The reference building is a five-story residential building, and the opaque envelope consists of an external layer of cement plaster (0.02m), an innermost layer of gypsum plastering (0.15m), and two layers of brick (0.18m+0.12m) separated by an air gap (0.05m), with a global thermal transmittance of 1.202W/m^{2}K. The glazing systems were modeled as double clear glass panes (6mm-6mm with 13mm air) for both the urban context (a) and (b). The windows have a global thermal transmittance of 2.665W/m^{2}K and a direct solar transmission of 0.604. For each context, the representative building was selected based on architectural topology, envelope material, and thermal energy performance. Each reference building is circled in Figure 2 (a) and (b). For the two case study models, an iterative calibration method and validation process have been implemented by the integrated analysis of mean bias error and the variation of the root mean squared error in terms of energy use and indoor thermal behavior (Pisello et al., 2013). The majority of Italian residential buildings are made of non-insulated envelopes, which makes this study more representative of the built Italian panorama.

(a)

(b)

Figure 2: Satellite Images of Two Dense Urban Neighborhoods in Perugia, Italy

2.4 Analysis and Results

2.4.1 Case Study 1: Control Building's Energy Behavior within Hypothetical Building Network

In the first case study, year round energy analysis was conducted. Annual results of control building energy consumption including lighting, space heating, space cooling, and total primary energy are reported in Table 1, Table 2, and Table 3 for Miami, FL, Washington, D.C., and Minneapolis, MN, respectively. In the tables: "IBE" stands for the combined IBE situation as baseline values; "IBE w/o R" represents the results when reflection is turned off for a comparable simulation; similarly, “IBE w/o S” denotes an inter-building environment without considering the shading effect. In the rows of “IBE w/o R” and “IBE w/o S”, variation percentages were also calculated according to the baseline combined IBE value. A “+” sign indicates an increase in energy usage while a “-” sign means that savings would occur for that particular situation, indicating less energy is being used. For instance, the “+34.1%” in Table 1 indicates an increase of 34.1 percent for primary cooling energy consumption required for the reference building within the building network under the weather profile of Miami without the mutual shading effect.

Table 1: Control Building’s Energy Consumption in Miami, FL

Simulation Type	Lighting (kWh)		Heating (kWh)		Cooling (kWh)		Total (kWh)	
IBE	4287.0		12.1		36765.2		41064.3	
IBE w/o R	4350.3	+1.5%	15.7	+30.1%	34237.5	-6.9%	38603.5	-6.0%
IBE w/o S	4132.2	-3.6%	4.6	-61.7%	49299.1	+34.1%	53435.9	+30.1%

Table 2: Control Building’s Energy Consumption in Washington, D.C.

Simulation Type	Lighting (kWh)		Heating (kWh)		Cooling (kWh)		Total (kWh)	
IBE	4477.8		12491.9		13813.9		30783.5	
IBE w/o R	4572.2	+2.1%	13121.7	+5.0%	12436.2	-10.0%	30120.0	-2.2%
IBE w/o S	4261.9	-4.8%	9212.7	-26.3%	21219.6	+53.6%	34694.2	+12.7%

Table 3: Control Building's Energy Consumption in Minneapolis, MN

Simulation Type	Lighting (kWh)		Heating (kWh)		Cooling (kWh)		Total (kWh)	
IBE	4572.1		28228.7		10756.4		43557.1	
IBE w/o R	4676.3	+2.3%	28986.1	+2.7%	9575.6	-11.0%	43237.9	-0.7%
IBE w/o S	4309.8	-5.7%	23504.1	-16.7%	17580.1	+63.4%	45394.1	+4.2%

Our first observation from Tables 1-3 is that the patterns of the "+" and "-" signs stay the same across the three simulated cities, indicating that for different climatic regions, removing the reflection effect could increase the control building's lighting and heating energy consumption while decreasing its cooling loads. Conversely, lighting and heating loads drop and at the same time cooling loads climb when the shading effect is disaggregated (in rows of simulation type "IBE w/o S"). However, we notice that, for all instances, the shading effect plays a more significant role in terms of the impact on energy consumption compared to the reflection effect. This resulted in substantial variations of the control buildings' energy consumption when the shading effect was disaggregated from the IBE. For example, in Washington, D.C. (Table 2), the absolute values of the variation percentage of the lighting, heating, cooling and total primary energy consumption are 26.3%, 53.6%, and 12.7%, respectively, when the shading effect is turned off, more than four times the percentages for simulations without reflection (5.0%, 10.0%, and 2.2%).

The results of total energy consumption in varying climatological contexts also revealed consistent trends of greater impact on the IBE for shading and reflection in warmer climatic cities. Miami has a higher percentage "+30.1%" for simulation without the shading effect, while Washington, D.C. and Minneapolis amount to "+12.7%" and "+4.2%", respectively. Similarly, when reflection is disaggregated, Miami has a "-6.0%" in total energy consumption which is a higher percentage compared to Washington, D.C. ("-2.2%") and Minneapolis ("-0.7%").

We then further broke down annual energy consumption to the monthly level for a more nuanced analysis. The results are tabulated in Table 4. This indicates in which month disaggregation would positively or negatively impact a building's energy behavior for a particular city. Favorable results (with negative variation percentage numbers) for each month are indicated with a grey background. In Miami, taking off reflection always causes less energy usage all year owing to its tropical weather condition, which has a long summertime and a mild winter. On the other hand, seven months (April, May, June, July, August, September, and October) benefit from shading while reflection is favorable to the other five months (January, February, March, November, and December) for the case of Washington, D.C. with roughly four equal length and distinct seasons. In Minneapolis, which is characterized by a long, cold winter and a hot, humid summer, the control building has better energy performance in five months (May, June, July, August, and September) without reflection and seven months (January, February, March, April, October, November, and December) without shading.

Table 4: Control Building's Energy Consumption Monthly Results

	Miami, FL			Washington, D.C.			Minneapolis, MN		
Month	IBE (kWh)	IBE w/o R (kWh)	IBE w/o S (kWh)	IBE (kWh)	IBE w/o R (kWh)	IBE w/o S (kWh)	IBE (kWh)	IBE w/o R (kWh)	IBE w/o S (kWh)
Jan.	1700.3	-9.4%	+47.5%	4826.2	+2.5%	-14.7%	9820.9	+1.3%	-10.8%
Feb.	1981.3	-9.0%	+36.6%	3146.4	+4.8%	-20.4%	5925.3	+2.7%	-15.9%
Mar.	2515.0	-9.3%	+38.5%	1629.5	+4.6%	-6.4%	3295.2	+5.2%	-20.4%
Apr.	3163.6	-7.6%	+35.7%	1258.7	-6.8%	+35.6%	2033.3	+1.7%	-1.4%
May	4049.8	-5.9%	+27.3%	2305.9	-9.4%	+42.3%	1791.1	-10.1%	+48.9%
Jun.	4484.7	-5.4%	+21.8%	3276.5	-8.0%	+34.8%	2659.2	-9.8%	+44.7%
Jul.	5036.9	-5.4%	+21.8%	3929.6	-7.3%	+31.7%	3515.4	-7.8%	+34.9%
Aug.	4504.5	-5.5%	+23.2%	3411.7	-7.7%	+31.8%	2464.8	-9.5%	+46.6%
Sep.	4328.3	-5.8%	+21.6%	2091.7	-9.2%	+39.6%	1614.7	-7.3%	+38.8%
Oct.	3812.9	-6.6%	+24.2%	1002.0	-2.6%	+30.4%	1488.7	+4.6%	-6.4%
Nov.	2635.5	-6.8%	+31.2%	1655.3	+5.7%	-16.9%	4845.0	+2.2%	-14.8%
Dec.	1732.1	-8.7%	+46.5%	4575.9	+2.8%	-18.0%	8450.8	+1.1%	-8.7%

In order to deepen our analyses of these impacts within the studied building network, we expanded to a more thorough cross-regional energy analysis of eight cities in the U.S. (Xu et al., 2014). The selected eight populous cities cover all four U.S. census regions (Northeast, Midwest, South, West), and zones 1-6 of the eight climate zones defined by International Energy Conservation Code where zone 7 and 8 represent the coldest areas in the United States with no populous cities. They are Los Angeles, CA (zone 2) and San Francisco, CA (zone 3) from the West Region; Chicago, IL (zone

5) and Minneapolis, MN (zone 6) from the Midwest Region; New York, NY (zone 4) and Boston, MA (zone 5) from the Northeast Region; and Houston, TX (zone 2) and Miami, FL (zone 1) from the South Region.

Table 5: Cross Regional Comparison of Reference Building's Energy Consumption

Regions/Cities		IBE	IBE w/o R		IBE w/o S	
Midwest	MN	43557.1	43237.9	-0.7%	45394.1	+4.2%
	CHI	37673.1	37199.1	-1.3%	40445.2	+7.4%
Northeast	BOS	31909.0	31619.9	-0.9%	33712.7	+5.7%
	NYC	31658.1	31046.4	-1.9%	35091.4	+10.8%
West	SF	13377.5	12187.8	-8.9%	21463.2	+60.4%
	LA	19152.9	17098.0	-10.7%	30180.9	+57.6%
South	HOU	32526.6	30802.9	-5.3%	41954.7	+29.0%
	MIA	41064.3	38603.5	-6.0%	53435.9	+30.1%

The eight-city cross regional analysis is reported in Table 5 and contains the total energy consumption (including space heating, space cooling and lighting) and the corresponding variation percentage for the IBE without reflection and the IBE without shading. The numbers in this table are consistent with our previous results and further support our observation in terms of the pattern of energy consumption change ("+" or "-" energy impact) and the dominant factor (shading effect) for this hypothetical building network. The four cities from the Midwest region and the Northeast region have less energy variations when shading or reflection is disaggregated from the IBE, especially for the coldest northernmost Minneapolis, MN and Boston, MA which both have less than 1% and 6% when the reflection factor and shading factor are turned off, respectively. Although we identified a larger variation and IBE impact in the hottest South region, the most significant change of energy consumption actually occurs in the West region where the energy loads in San Francisco, CA and Los Angeles, CA drop as much as 10.7% when the mutual reflection effect is not considered, and increase as much as 60% without mutual shading within the studied environment. This could be due to the solar positions and relatively less baseline energy consumption values in the West region. Overall, this expanded cross regional analysis supported the trends we identified in Miami, FL, Washington, D.C., and Minneapolis, MN.

2.4.2 Case Study 2: Reference Building's Energy Behavior within Two Dense Urban Contexts in Perugia, Italy

In Case Study 2, two representative urban contexts in Perugia, Italy were selected to study the shading/reflection effect in realistic urban building networks. The urban context (a) is an extreme dense area in the historical center of Perugia; the other context (b) represents a neighborhood at the close periphery of the city. Year-round analysis was conducted under the local weather profile of the temperate city, and the annual results of lighting energy consumption, space heating energy consumption and space cooling energy consumption are reported in Table 6 and Table 7 for contexts (a) and (b), respectively. The same notations ("IBE", "IBE w/o R" and "IBE w/o S") and symbols ("+" and "-") are used to indicate the different simulation scenarios and results in the tables.

Table 6: Reference Building's Energy Consumption in Perugia Urban Context (A)

Simulation Type	Lighting (kWh)		Heating (kWh)		Cooling (kWh)		Total (kWh)	
IBE	2177.5		19960.6		600.1		22738.1	
IBE w/o R	2240.7	+2.9%	20908.7	+4.7%	447.2	-25.5%	23596.5	+3.8%
IBE w/o S	1810.4	-16.9%	17438.1	-12.6%	2025.6	+237.6%	21274.1	-6.4%

Table 7: Reference Building's Energy Consumption in Perugia Urban Context (B)

Simulation Type	Lighting (kWh)		Heating (kWh)		Cooling (kWh)		Total (kWh)	
IBE	25338.1		67799.4		11200.6		104338.0	
IBE w/o R	25641.4	+1.2%	69036.1	+1.8%	10167.3	-9.2%	104844.8	+0.5%
IBE w/o S	24015.4	-5.2%	65526.4	-3.4%	12877.0	+15.0%	102418.8	-1.8%

The patterns of "+" "-" signs remain identical to our hypothetical building network analysis presented in Table 6 and 7, indicating the shading effect contributes to lighting and heating energy consumption while the reflection effect increases cooling energy within building networks. This supports our earlier assertions regarding shading and reflection impact on building primary energy consumption. For both cases in Perugia that have distinct urban contexts, the disaggregation of the shading effect results in larger variations of the studied buildings' energy consumption. This again supports our assertion that the shading effect ("IBE w/o S") has a larger impact compared to the reflection effect ("IBE w/o R") in each individual energy component (lighting, heating, and cooling). Shading dominates more in higher density urban blocks that have significant amounts of energy variation for lighting, space heating and space cooling as the results showed in case (a).

However, this case study showed more complicated outcomes could occur in a real-life urban environment. We noticed an unusually high amount of cooling energy increase (237.6%) when the shading effect was eliminated in the Perugia urban context (a). The interpretation of this number could be the low baseline value of cooling energy consumption (600.1 kWh) as well as the substantial impact due to shading in high-density contexts (extremely high height/width ratio in the neighbourhood). Despite the fact that the reference building in the urban context (b) is larger than that in the urban context (a) and consumed nearly five times more in terms of total energy consumption, we also observed that the lighting surpassed cooling as the second largest energy consumption factor in both cases. This realistic urban building network case study resulted in different building energy behavior through disaggregate analysis.

2.5 Discussion

A great deal of research effort has focused on reducing building energy consumption and achieving a more sustainable built environment (Golany, 1996; He et al., 2009; D. H. W. Li & Wong, 2007; Shaviv & Yezioro, 1997; Yang et al., 2013). However, the majority of this research treats each building as a stand-alone entity without considering the neighboring buildings that may substantially influence energy consumption. Recent research has demonstrated that one building's energy performance is influenced by its nearby micro-environment, and the concept of IBE has been introduced and discussed within spatially-proximal building networks (Han et al., 2015b; Pisello et al., 2014, 2012). Although mutual shading and mutual reflection have been identified as two primary components that make up the IBE, such impact has to date been considered as a monolithic effect. Given the important IBE implications for urban design and building and environmental energy assessment, the research presented in this paper contributes to the discussion by developing a systematic approach in a dynamic simulation environment to disaggregate the separate and distinct impact from reflection and shading for a more nuanced analysis. Through cross-regional analyses of our hypothetical building network and realistic urban context case studies in a temperate city in Italy, we found shading to contribute to increased heating and lighting loads while reflection increased cooling energy required for spatially-proximal buildings in all scenarios. We identified a consistent trend indicating that when mutual reflection is turned off, shading has a relatively larger contribution to IBE within building networks. In our hypothetical building network study, we found the IBE to have a larger impact in warmer areas, with variation percentages from baseline use always being the largest in the tropical city of Miami, and the smallest percentage was for Minneapolis, the coldest metropolitan city. We expanded our analysis to more cities covering different climate zones, and interestingly found that two cities in the West region—San Francisco, CA and Los Angeles, CA—have the most significant change of energy use when shading or reflection is disaggregated out of the analysis. One reason for this could be the lower baseline value of the energy consumption in those two cities that have neither severe winters nor summers. The solar position could also be another important factor of IBE. The angle of incident beam due the azimuth and the altitude of the sun could influence the impact of mutual shading and mutual reflection within spatially-proximal buildings. In general, we observed larger variations of the energy impact in warmer areas when shading and reflection are disaggregated within a building network. Thus, it extends previous studies on the shading effect (D. H. W. Li & Wong, 2007; Shaviv & Yezioro, 1997) and suggests that future research on practical measures should focus more on shading interventions, especially in cities under warmer climatic conditions.

We further broke down our analysis to a monthly basis. This revealed that the contribution of reflection and shading varies on a month-to-month basis. Building energy performance in warmer climatic cities like Miami with a longer summer, longer daylight time and more demand for cooling energy would benefit when the reflection effect is mitigated all year round. However, in the cities that have four distinct seasons, reflection and shading could be either detrimental or favorable for different months. The impact is closely related to the geographical location and weather condition. From the simulated results, general recommendations can be provided for urban planning and building designs, which could help promote sustainable and energy-responsive building networks. By implementing optical features to building envelopes (Han et al., 2015b), we may be able to control the negative effect of reflection in tropical cities. On the other hand, thermal storage techniques (Ascione, Bianco, De Masi, de' Rossi, & Vanoli, 2014) could help shift peak energy loads neutralizing the month-to-month mutual impact variations. These findings, taken together, expand and deepen our understanding of the IBE and may help in the search to minimize mutual influences between buildings that lead to increases in energy consumption in urban environments.

The intent of the two cases in Italy is not only to interpret the IBE disaggregate analysis with respect to urban morphology characterization in a realistic urban environment, but also to investigate the impact of increasing urban density level. By employing the disaggregate methodology to examine the variances of year-round energy performance of reference buildings in two distinct Italian urban contexts, we found support for our hypothetical model analyses that mutual shading always contributes to increases in heating and lighting loads and mutual reflection contributes to increased cooling energy consumption. Different and more complicated building energy behavior was observed through disaggregate analysis. The shading effect, as the larger impact factor of IBE, is more dominant in denser urban blocks. The Italy case study further demonstrates the impact of urban building network' morphology and the importance of local climatic context impact for IBE research. It also contributes how such analyses enable the planning of more efficient building networks in urban practical applications. We demonstrated that primary building energy consumption can be influenced by the complex and dynamic urban micro-environment. Thus, urban building designs should adopt a more holistic consideration of the building network in which a designed building will be situated. There is the potential to introduce shading design interventions and/or reflection design interventions—depending on the climatological context—that will positively impact the cooling, heating, and lighting energy consumption of the building being designed, as well as possibly positively impacting neighboring buildings.

The purpose of this research was to separately assess mutual shading and mutual reflection for a better understanding of the complex inter-building relationships resulting from urbanization. EnergyPlus has become a popular and reliable research tool for building energy simulation and empirical studies have been used to calibrate and validate the simulation results, particularly for the heating and cooling energy consumption (Ellis & Torcellini, 2005; Pisello et al., 2012; Rodrigues, Gaspar, & Gomes, 2014). The model information used in this research was built upon previous research (Han et al., 2015b; Pisello et al., 2012) and an ideal loads air system setting was implemented without considering the mechanical efficiency. Through cross-regional comparison, the results provide us a more explicit understanding of inter-building relationships. In executing the simulation, a human-based check was conducted to ensure the accuracy of the dynamic simulation result. No exception outputs or process warning were observed over the course of the simulation. Nevertheless, the modeling and simulation efforts resulted in some limitations. The network of buildings was nine buildings for the hypothetical building network disaggregate analysis to keep the research scope reasonable but sufficiently detailed to develop the proposed approach. The realistic case study was limited to one city with one specific weather condition and two different urban contexts. We observed that real life cases could lead to peculiar outcomes. It is possible that more complicated outcomes due to different or larger urban scales may exist and, if so, were neglected in the research. In future research, we will examine scaled building network models empirically with different orientations and building envelope properties. We will use thermal sensor data combined with weather station data to further validate the simulation results. With optimization measures drawing more attention in building energy research recently, future research should address these limitations as well as seek out measures to mitigate the negative impacts of the IBE and optimal placement of network buildings considering local climatological contexts.

2.6 Conclusions

The research in this paper built upon and extended previous IBE approaches (Han et al., 2015b; Pisello et al., 2014, 2012) that studied energy consumption predictions in dense urban building networks, and continued exploring complex and dynamic urban microclimates (de La Flor & Domınguez, 2004; Krüger et al., 2010; Yao & Steemers, 2013). It contributes a systematic approach to separately assess the complex interactions that make up the IBE. By manipulating the building envelopes, we disaggregated and quantified the influence of mutual shading and mutual reflection within a network of buildings. Cross-regional case studies of a hypothetical urban building network were established and simulated in the dynamic EnergyPlus environment for energy assessments, followed by two realistic urban context case studies in Perugia, Italy. The findings of energy consumption in the reference building demonstrate that shading has a relatively larger individual impact compared to reflection within the building's microenvironment. We found shading to contribute to increased heating and lighting loads while reflection increased cooling energy required for spatially-proximal buildings. Although we found the discrepancies of energy use due to disaggregate analysis to largely depend on the local climatological conditions, the results revealed consistent trends of greater impact on the IBE for shading and reflection in warmer climatic cities. Tropical cities that have high demand for cooling energy would benefit when reflection is mitigated all year round, while such impact in other cities is closely related to geographical location and climatological context. Understanding the distinct impacts of shading and reflection and addressing them separately could lead to optimization of the thermal-energy performance within spatially proximal buildings, and will become increasingly important as urbanization creates increasingly dense urban environments in cities around the world.

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CHAPTER 3: SIMULATING THE INTER-BUILDING EFFECT ON ENERGY CONSUMPTION FROM EMBEDDING PHASE CHANGE MATERIALS IN BUILDING ENVELOPES [2]

3.1 Abstract

The built environment contributes significantly to rapidly growing world energy consumption. Along with urbanization, buildings continue to escalate this trend owing to their tighter spatial interrelationships and the influence of their surrounding micro-environment. The concept of the Inter-Building Effect (IBE) was introduced to understand complex mutual impacts within spatially-proximal buildings. Recent research has revealed that inter-building reflection or shading can have nuanced effects on a month-by-month basis depending on the climatological context. The application of phase change materials (PCMs) has begun to be examined by researchers due to its ability to store and release heat within a certain temperature range. In this paper, we sought to explore and understand if PCM-embedded building envelopes could potentially mitigate negative thermal-energy impacts within spatially proximal buildings. Building upon previous IBE research and simulation models, we conducted several building network simulations with different PCM settings in different climatological contexts. The results showed considerable improvements (up to 17%) of annual HVAC energy consumption when PCM-embedded building envelopes were used in the control building. The findings expand and deepen our understanding of the IBE, and

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may help minimize negative mutual influences across buildings that lead to increases in energy consumption in urban environments.

Keywords: *Building Networks; Energy Efficiency; Inter-Building Effect; Phase Change Material; Simulation*

3.2 Introduction

Energy and its impact on the environment has become a central issue facing society. According to the latest energy data statistics from the International Energy Agency (International Energy Agency, 2013a), annual global energy consumption has grown from 4000 Mtoe (million tonnes of oil equivalent) in 1971 to nearly 9000 Mtoe in 2011. Over the last 40 years, carbon dioxide emissions have doubled (International Energy Agency, 2013a). The rapidly growing world energy expenditure not only causes supply difficulties and depletion of fossil energy resources, but also significantly influences the human living environment by triggering climate deterioration locally (e.g. Urban Heat Island (UHI) effects) and worldwide (e.g. global warming).

The mean global temperature has increased by 0.6 degree Celsius during the 20th century (Alcoforado & Andrade, 2008). However, a worldwide increase of as much as 5.8 degrees Celsius is expected to occur by the end of the 21st century (Smithson, 2002). Urban areas are the major source of carbon dioxide emissions contributing to greenhouse gases that exacerbate global climate and environmental change. Warming has been found at more significant levels over the land than over the ocean, and more intense in the northern hemisphere where 90% of people live (Smithson, 2002). Referred to as a significantly warmer metropolitan area than its surrounding rural areas, the heat effects by the UHI add discomfort to urban residents and increase the air-conditioning load substantially, especially in summer (Giannopoulou et al., 2011; Rizwan, Dennis, & Liu, 2008). Warmer cities have been frequently associated with global warming although they may not necessarily have a direct relationship (Alcoforado & Andrade, 2008). The intensity of UHI could result from a function of urban morphology, urban building physical characteristics, waste heat release, as well as, regional climate factors (McCarthy, Best, & Betts, 2010). However, it is also the result of the dense construction surfaces that absorb solar radiation more than natural surfaces, and the anthropic heat flux due to the cooling and heating of buildings (Rizwan et al., 2008).

Buildings and the built environment are major contributors to the trends of both the rising energy consumption and deteriorating urban micro-environment. 32% of total final energy consumption and nearly 40% of primary energy consumption are attributed to buildings (International Energy Agency, 2013b). In the United States, nearly half (47.5%) of all energy produced and three quarters of electricity is consumed by the building sector every year (U.S. Department of Energy, 2011). The ongoing and emerging industrial developments and urbanization in fast developing countries and underdeveloped regions will also intensify energy usage and cause supply difficulties (Madlener & Sunak, 2011). According to a recent report by the United Nations, population in urban areas is projected to increase by 72% from 3.6 million (2011) to 6.3 million (2050) in the next 40 years (UNDESA, 2011). As a result, the energy and environmental issues attributable to urban buildings will become more challenging to the built environment itself and to society. Therefore, how to achieve a more sustainable built environment has become a grand challenge for engineers, building researchers, urban planners, and policy makers.

3.3 Background and Research Objectives

3.3.1 Tighter and More Complex Urban Inter-Building Relationships Impacting Energy Use

In the presence of rapid urbanization, the relationship between building density and urban form has attracted wide interest, as it is expected that tighter and more complex building geometries will be more prevalent in urban areas in the following decades. Urban morphology, characterized by building density, size, height, orientation, and layout, could cause considerable variations in the local environment and microclimates. Mathematical and geometrical analyses have been conducted to study the issue concerning building height, plot ratio, orientation, solar obstruction, etc., and early research generated insightful discoveries that urban microclimates and buildings are inextricably interwoven (de La Flor & Domınguez, 2004; Krüger et al., 2010; Yao & Steemers, 2013). It is difficult to predict one building's energy performance accurately without considering the close proximity of other buildings and the energy implication that could result.

To understand the complex interactions that cause urban thermal-energy dynamics within spatially-proximal building networks, the concept of the Inter-Building Effect (IBE) has been introduced and further investigated over the last several years (Han et al., 2015b; Pisello et al., 2014, 2012). Research has demonstrated that the interrelationship between buildings within building networks results in substantial inaccuracies (up to 42% in summer, and up to 22% in winter) of energy consumption predictions for space heating, space cooling, and lighting (Pisello et al., 2014, 2012). The research also demonstrates that, irrespective of the climatological context, the energy performance of one building can be meaningfully impacted by surrounding buildings through mutual reflection and mutual shading, the two primary components that make up the IBE.

In order to better understand and explore successful urban planning and building designs that could affect the IBE, researchers disaggregated and quantified the shading effect and reflection effect separately from the IBE (Han et al., 2015b). The more nuanced analysis found shading to contribute to increased heating loads while reflection increased cooling energy required for spatially-proximal buildings. The monthly analysis of several weather profiles of multiple U.S. metropolitan cities under different climate zones revealed that the contribution of reflection and shading varies on a month-to-month basis as the impact of IBE is closely related to geographical locations and climatic conditions. However, limited research has sought solutions to mitigate negative thermal-energy inter-building relationships. Building energy performance in tropical cities with longer summers, longer daylight time and higher demand for cooling energy would benefit from mitigated reflection effect all year round. Therefore, directional reflective building envelopes have been investigated to help lessen mutually reflected solar radiation and mitigate Urban Heat Island effects within urban canyons in warmer areas (Han et al., 2015b). General solutions to address such negative effects within building networks are still largely unrealized, especially for the temperate areas where shading and reflection impact IBE differently depending on the season, or even over the course of a day.

3.3.2 The Potential of Thermal Storage Techniques within Building Networks

Energy consumption can be reduced by improving the thermal performance of the enclosures. Increasing the building envelope thermal resistance has been implemented as a common practice, but is subject to limitations of wall thickness and high costs. Improving thermal storage capacity was later introduced as an alternate solution. With the important characteristic to store and release heat within a certain temperature range, the use of phase change materials (PCMs) can significantly shorten overheated hours and shift peak electricity loads (Belmonte et al., 2015; Zhou et al., 2012).

As a result, PCMs could work as a suitable and promising solution for not only increasing indoor thermal comfort but also reducing the energy consumption of buildings.

Conventional building materials usually have sensible heat storage effects such that the heat is stored or released accompanied with temperature changes in the storage media. In contrast, PCMs have greater heat storage capacities with latent heat storage, where the heat is stored or released as heat of fusion/solidification during the phase change process of the storage with a small variation of PCM volume. They can be divided into different subcategories based on their chemical composition, such as organic compounds, inorganic compounds and eutectics (Zhou et al., 2012). Each material has its typical range of melting temperature and its range of melting enthalpy which could be employed for the thermal comfort context. PCMs have attracted attention by building researchers in the recent past, and several recent papers (Baetens et al., 2010; Nkwetta & Haghighat, 2014; Pomianowski, Heiselberg, & Zhang, 2013; Zhou et al., 2012) reviewed the state-of-the-art on knowledge of PCMs today specifically for building applications, including PCM selection, PCM thermal stability, impregnation of PCMs into construction materials (such as wallboards, walls, floors and ceilings), and evaluation and calibration for PCM numerical simulation. In the building application, the PCMs with phase change temperature 18 to 30 degree Celsius are preferred to meet the thermal comfort needs of building occupants (Zhou et al., 2012). Previous exploration demonstrated that PCMs have different benefits depending on quantity, types, locations, and climates. Despite the various advantages of PCM applications in buildings, the commercial implication of PCMs is yet to be fully explored. This is owing to the fact that most available information is limited to miniature models or prototype laboratory tests (Pomianowski et al., 2013).The gap between current PCM research and practical applications has also been identified due to a lack of realistic case studies and research (Pomianowski et al., 2013). Moreover, nearly all of the previous studies are discussed within the context of stand-alone buildings.

In this paper, we seek to evaluate the application of PCMs from the perspective of inter-building relationships that extend beyond a stand-alone building scenario and to explore the impact of PCM technology in a dense urban building environment. By implementing advanced numerical analysis approaches, this research aims to fill the literature gap by examining whether PCM-embedded building envelopes could serve as a possible solution to mitigate the negative thermal-energy impact of IBE through parametric analysis.

3.4 Methodology

To understand and quantify the impact of PCMs to inter-building thermal-energy performance, we conducted our research using the following methodology. Building upon early research on PCMs application for stand-alone buildings, we firstly develop several hypotheses using inter-building effect modeling techniques to examine building network scenarios. We then introduce how we design and model different simulation sets in the dynamic simulation environment. Parametric analyses were conducted to further investigate and evaluate PCM-embedded envelopes by comparing PCM locations in building envelopes, PCM types, and climatological conditions.

3.4.1 Hypotheses Development and Research Initiatives

PCM technology has been studied in building applications in many different ways with resulting positive effects on thermal comfort and energy implications (Baetens et al., 2010; Zhou et al., 2012). Therefore, we propose Hypothesis 1 in the inter-building context.

Hypothesis 1. PCM-embedded building envelopes lead to reductions in cooling and heating energy in an urban context where buildings are in close proximity.

Location of PCM layers is critical for wall performance in terms of controlling heat transfer capabilities (Jin, Medina, & Zhang, 2013; Jin, Zhang, Xu, & Zhang, 2014). Through a dynamic wall simulator, PCM layers at varying distances from the interior gypsum layer have been studied experimentally through differential scanning calorimeter tests and cooling experiments (Jin et al., 2013). The results showed that the most optimal location for PCM layers should be within the first insulation layer (Jin et al., 2013). With that, we propose Hypothesis 1a to further verify Hypothesis 1 in the simulated inter-building environment.

Hypothesis 1a. PCM-embedded building envelopes lead to higher reductions in cooling and heating energy when the PCMs are embedded in the inner layers in an urban context where buildings are in close proximity.

PCM technology has been suggested to be more efficient when applied to roof areas for single buildings (Zhou et al., 2012). In the inter-building scenario, mutual reflection and mutual shading of neighboring buildings could cause significant thermal-energy impact (Han et al., 2015b; Pisello et al., 2012). Thus, vertical building envelopes (i.e. exterior walls) can also play an important role on energy saving by creating an enclosed PCM space. Therefore, we propose Hypothesis 2.

Hypothesis 2. Both PCM-embedded roofs and PCM-embedded building walls have positive influences on energy savings in an urban context where buildings are in close proximity.

In addition, since different PCMs have their own material properties and temperature-enthalpy profiles, the effectiveness of PCMs are largely dependent on melting temperature ranges and local weather conditions. A number of PCM types and climatological data are used in this numerical analysis for a more comprehensive study.

3.4.2 Simulating the IBE in a Dynamic Environment

Over the last several decades, dynamic building simulation has developed rapidly by building researchers for front-end designs and more sustainable building lifecycles. Simulation tools offer powerful functionalities and best practices to predict and improve building energy performance. EnergyPlus (Crawley et al., 2001; US Department of Energy, 2010), an energy analysis and thermal load simulation engine developed and distributed by U.S. Department of Energy, has become a popular building energy performance simulation tool owing to its sophisticated and validated functions. It was also utilized for previous IBE research for dynamic building analyses.

Early IBE simulation efforts were conducted based on a realistic physical urban block in the state of New York to study energy consumption of space cooling and space heating (Pisello et al., 2012). Later, IBE research was expanded to investigate the energy discrepancies in lighting and validated the IBE, e.g., mutual shading and mutual reflection, as an important effect to be modeled in situations where buildings are surrounded by other nearby buildings (Pisello et al., 2014). Real-world experimental work and empirical data were used to calibrate and verify the simulation work. An essential geometric element for shading and reflection in the EnergyPlus environment, the shading surface, was used extensively to achieve modeling objectives while avoiding excessive running times.

In this study, we modeled a nine-building block as a hypothetical building network as illustrated in Figure 3. The reference building is modeled as a three-story office building in the center of the building network with eight shading-surface buildings surround it. The morphology of each building within the building network is identical with a square shape of 10 meters per side. The distance between buildings was set to be 5.25 m (Height/Width ratio = 2) for both the East-West direction and the North–South direction. This baseline non-PCM building and modeling information (construction materials, temperature set-points, schedules for lighting, equipment, and occupants, etc.) were inherited from previously published IBE research (Han et al., 2015a, 2015b; Pisello et al., 2014, 2012) for the credibility of the numerical analysis. Some key parameters are listed as below. The opaque envelope of the reference building consists of four layers, external brickwork (0.10 m), XPS extruded polystyrene (0.080 m), light weight concrete block (0.010 m), and internal gypsum plasterboard (0.013 m), with a global thermal transmittance of 0.314 W/m^{2}k. The floor includes wooden flooring (0.020 m), mineral wool (0.15 m), floor structure (0.20 m), and external rendering (0.025 m), with a global thermal transmittance of 0.246 W/m^{2}k. The roof also consists of four layers with asphalt (0.010 m), mineral wool (0.15), air gap and roof structure (0.20 m), and plasterboard 0.015 (m), with a global thermal transmittance of 0.250 W/m^{2}k. The external windows are modeled as double clear glass panes (6-6 mm with 6 mm air). The diffuse solar reflectance of the exterior building envelopes and the ground are set to be 40% and 20%, respectively. The main working hour schedule is from 8am to 6pm during weekdays.

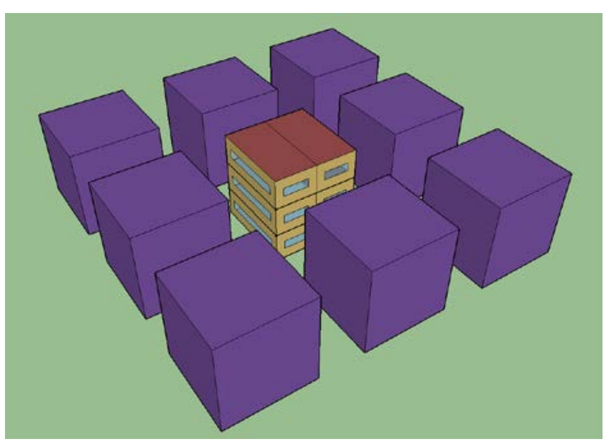

Figure 3: Hypothetical Nine-Building Network

3.4.3 Simulating the Impact of PCM-Embedded Building Envelopes in the Inter-Building Environment

Using a one-dimensional conduction finite difference algorithm, the ability to simulate PCMs has been developed and studied in EnergyPlus. (Alam, Jamil, Sanjayan, & Wilson, 2014; Sage-Lauck & Sailor, 2014; Tabares-Velasco, Christensen, & Bianchi, 2012). Particularly, Tabares-Velasco et al. developed a procedure to verify and validate the PCM model using an approach as dictated by ASHRAE Standard 140, and also provided several suggestions addressing the limitations of current Energy-Plus PCM models (Tabares-Velasco et al., 2012). In this study, building models with PCM layers were built referring to published data and validated experimental parameters (Pisello et al., 2014, 2012). A typical microencapsulated PCM type is used for this analysis (Tabares-Velasco et al., 2012) and is indicated as PCM type "P22". It has a conductivity of 0.18 W/m-k, density of 855 kg/m^3, specific heat of 2500 J/kg-K, and a melting temperature point around 21.6 degrees Celsius. In addition to PCM type "P22", the simulation effort was carried out using five commercial BioPCM materials (Alam et al., 2014). All BioPCMs have the same material properties of conductivity (0.2 W/m-k), density (235 kg/m^3), and specific heat (1970 J/kg-K), but different melting temperatures and temperature-enthalpy profiles. According to the melting temperature range from 21 to 29 degrees Celsius, the BioPCMs are indicated as "Q21", "Q23", "Q25", "Q27", and "Q29", respectively. Different PCM layers were embedded within the volume of the building envelopes inherited from previously published IBE models. The thickness of PCM layers was set to 0.021 meter for all cases as one control parameter. The temperature-enthalpy profiles of all six tested PCMs are illustrated in Figure 4 (Alam et al., 2014; Tabares-Velasco et al., 2012). The latent heat of individual PCM types was thus reflected. To avoid simulation errors, the time step of the simulation was set to three minutes as suggested by the program developers (US Department of Energy, 2010). Monthly and annual simulation outputs were reported.

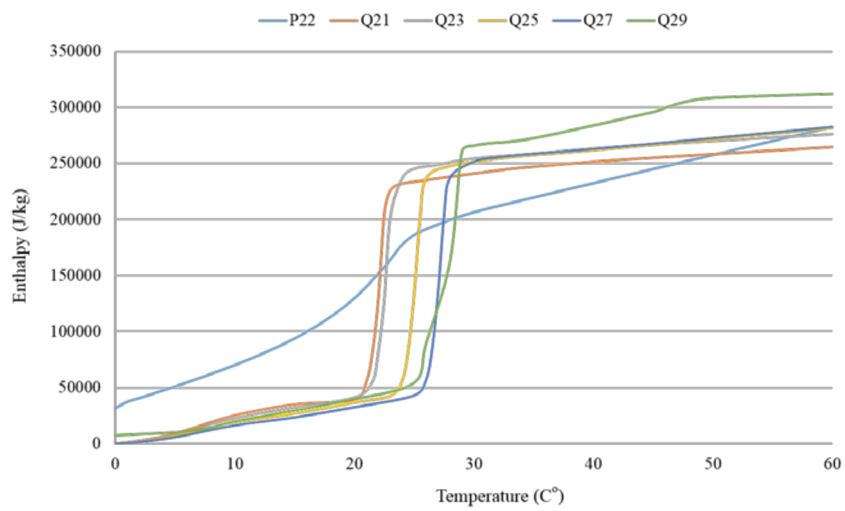

Figure 4: Temperature-Enthalpy Profiles of Six Different PCM Types (Alam et al., 2014; Tabares-Velasco et al., 2012).

Previous IBE research has found that the impact of IBE vary by climatological context (Han et al., 2015b; Pisello et al., 2012). To investigate the impact of PCM building envelopes to the IBE, four typical U.S. cities from different climate zones—Washington, D.C., Minneapolis, MN, Los Angeles, CA and Miami, FL—were selected for this study. Minneapolis, MN and Miami, FL represent extreme climate conditions as the coldest and the hottest metropolitan city in the United States. Los Angeles, CA represents a subtropical Mediterranean climate while Washington, D.C. has distinctive and roughly equal-length seasons as a typical temperate city. Under the weather profile of each city, the impact of PCMs was tested through a comparative study by setting the building envelopes of the control building as either conventional or PCM-embedded, by examining different locations of PCM layers, and by testing different types of PCMs. The energy performance of the reference building was monitored and reported over the course of the simulation period.

3.5 Analysis and Results

3.5.1 Case Study 1: The Impact of PCM Layer Location within the Volume of the Walls on Inter-Building Thermal-Energy Performance

The first case study was designed to test the impact of PCMs on IBE in general, as well as to test the effectiveness of PCMs at varying locations within the volume of the building envelopes. A typical PCM type, "P22", is first used for this analysis. Annual results of control building energy consumption including space heating, space cooling, and total primary energy consumption are contained in Tables 8–11 for Washington, D.C., Minneapolis, MN, Los Angeles, CA, and Miami, FL, respectively. The left columns of these tables indicate the simulation types: "NoPCM" stands for the pure IBE situation as baseline values; "PCM OuterLayer" represents the results when the PCM layer is placed next to external brick-work; similarly, "PCM MidLayer" and "PCM InnerLayer" denotes the outcomes when the PCM layer is embedded in the middle layer of the envelope volume and closer to the internal plasterboard, respectively. In the rows of "PCM OuterLayer", "PCM MidLayer" and "PCM InnerLayer", variation percentages were also calculated according to the baseline IBE values "NoPCM". A "+" is designated to indicate an increase in energy usage while a "−" means that saving would occur for that particular situation, indicating less energy is being used. For instance, the "−13.7%" in Table 8 indicates a reduction of 13.7% for primary cooling energy consumption required for the reference building within the building network when the PCM layer is placed close to internal plasterboard.

Table 8: Reference Building's Energy Consumption with Different PCM Layer Locations within Building Envelopes in Washington, D.C.

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	18362.9		7782.9		26145.9	
PCM_OuterLayer	18043.6	-1.7%	7502.3	-3.6%	25545.9	-2.3%
PCM_MidLayer	17719.5	-3.5%	7168.7	-7.9%	24888.2	-4.8%
PCM_InnerLayer	17596.3	-4.2%	6716.2	-13.7%	24312.5	-7.0%

Table 9: Reference Building's Energy Consumption with Different PCM Layer Locations within Building Envelopes in Minneapolis, MN

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	33959.6		5787.3		39746.9	
PCM_OuterLayer	33602.0	-1.1%	5549.4	-4.1%	39151.4	-1.5%
PCM_MidLayer	33283.0	-2.0%	5299.2	-8.4%	38582.3	-2.9%
PCM_InnerLayer	33217.1	-2.2%	4941.1	-14.6%	38158.3	-4.0%

Table 10: Reference Building's Energy Consumption with Different PCM Layer Locations within Building Envelopes in Los Angeles, CA

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	3078.9		7321.5		10400.4	
PCM_OuterLayer	2868.7	-6.8%	6874.0	-6.1%	9742.7	-6.3%
PCM_MidLayer	2777.4	-9.8%	6670.9	-8.9%	9448.3	-9.2%
PCM_InnerLayer	2655.9	-13.7%	5978.6	-18.3%	8634.5	-17.0%

Table 11: Reference Building's Energy Consumption with Different PCM Layer Locations within Building Envelopes in Miami, FL

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	377.0		20062.6		20439.6	
PCM_OuterLayer	283.2	-24.9%	19704.5	-1.8%	19987.7	-2.2%
PCM_MidLayer	240.9	-36.1%	19522.2	-2.7%	19763.2	-3.3%
PCM_InnerLayer	192.7	-48.9%	19119.7	-4.7%	19312.5	-5.5%

Note: Absolute values of heating energy consumption are too small and excluded from the percentage variation discussion.

Our first observation from Tables 8–11 is the variation percent-ages are all negative. It indicates that PCM-embedded building envelopes lead to energy conservation in all three studied categories (space heating consumption, space cooling consumption, and total HVAC energy consumption) and all three simulation types ("PCM OuterLayer", "PCM MidLayer", and "PCM InnerLayer") under a dense urban IBE environment despite different heating-cooling load patterns of the four studied cities. The reference building in Los Angeles, CA showed the greatest improvement in heating consumption (−13.7%), cooling consumption (−18.3%), and total energy consumption (−17.0%), but had the least energy variations in Minneapolis, MN and Miami, FL which represent the extreme climatological conditions. We also noticed that there is a clear trend and indication in each table that inner PCM layers resulted in more effective thermal storage capability as greater energy reductions occurred. Taking Los Angeles, CA again as an example, the reference building would achieve 17.0% of energy conservation when the PCM layer is embedded to the inner layer of the building envelope, but could only improve by as little as 6.3% when embedding PCMs near the outer layers.

The effectiveness of latent thermal store capability are very dependent on the PCM types, indoor thermostat and local weather condition. We are interested in exploring the influences and proper selections of different PCMs in the inter-building settings. In addition to PCM type “P21”, the annual simulation was carried out using five BioPCM materials with different melting temperature ranges, indicated as “PCM Q21”, “PCM Q23”, “PCM Q25”, “PCM Q27”, and “PCM Q29”, respectively. The simulation results of six different types of PCMs embedded in the inner layer of a building envelope across four different weather inputs are reported in Tables 12–15.

Table 12: Reference Building’s Energy Consumption with Different PCM Materials in Washington, D.C.

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	18362.9		7782.9		26145.9	
PCM_P22	17596.3	-4.2%	6716.2	-13.7%	24312.5	-7.0%
PCM_Q21	17848.8	-2.8%	6964.2	-10.5%	24813.0	-5.1%
PCM_Q23	17921.9	-2.4%	6977.8	-10.3%	24899.7	-4.8%
PCM_Q25	18147.5	-1.2%	7253.6	-6.8%	25401.1	-2.8%
PCM_Q27	18172.4	-1.0%	7470.5	-4.0%	25642.9	-1.9%
PCM_Q29	18152.5	-1.1%	7389.0	-5.1%	25541.4	-2.3%

Table 13: Reference Building's Energy Consumption with Different PCM Materials in Minneapolis, MN

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	33959.6		5787.3		39746.9	
PCM_P22	33217.1	-2.2%	4941.1	-14.6%	38158.3	-4.0%
PCM_Q21	33412.0	-1.6%	5117.2	-11.6%	38529.2	-3.1%
PCM_Q23	33482.2	-1.4%	5125.4	-11.4%	38607.6	-2.9%
PCM_Q25	33669.1	-0.9%	5365.4	-7.3%	39034.5	-1.8%
PCM_Q27	33690.3	-0.8%	5553.0	-4.0%	39243.4	-1.3%
PCM_Q29	33674.4	-0.8%	5483.0	-5.3%	39157.4	-1.5%

Table 14: Reference Building's Energy Consumption with Different PCM Materials in Los Angeles, CA

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	3078.9		7321.5		10400.4	
PCM_P22	2655.9	-13.7%	5978.6	-18.3%	8634.5	-17.0%
PCM_Q21	2676.7	-13.1%	6100.5	-16.7%	8777.2	-15.6%
PCM_Q23	2743.4	-10.9%	6083.2	-16.9%	8826.6	-15.1%
PCM_Q25	2987.0	-3.0%	6654.5	-9.1%	9641.4	-7.3%
PCM_Q27	3016.4	-2.0%	6990.8	-4.5%	10007.3	-3.8%
PCM_Q29	2988.0	-3.0%	6843.7	-6.5%	9831.7	-5.5%

Table 15: Reference Building's Energy Consumption with Different PCM Materials in Miami, FL

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	377.0		20062.6		20439.6	
PCM_P22	192.7	-48.9%	19119.7	-4.7%	19312.5	-5.5%
PCM_Q21	198.8	-47.3%	19516.9	-2.7%	19715.7	-3.5%
PCM_Q23	226.4	-39.9%	19402.0	-3.3%	19628.4	-4.0%
PCM_Q25	340.9	-9.6%	19334.7	-3.6%	19675.6	-3.7%
PCM_Q27	357.0	-5.3%	19578.7	-2.4%	19935.7	-2.5%
PCM_Q29	348.6	-7.5%	19488.1	-2.9%	19836.7	-2.9%

The reductions of the reference building's total energy consumption are also plotted in Figure 5. Tables 12–15 indicate that different selection of PCM layers lead to varying building thermal-energy performance, and the reference building in our inter-building settings achieves the best performance with type "PCM P22". Among all BioPCMs, "PCM Q21" and "PCM Q23" demonstrate significantly better performance compared to the other three in Washington, D.C., Minneapolis, MN, and Los Angeles, CA. However in Miami, FL, selections of PCMs did not result in much difference due to its long hot summer and short moderate winter.

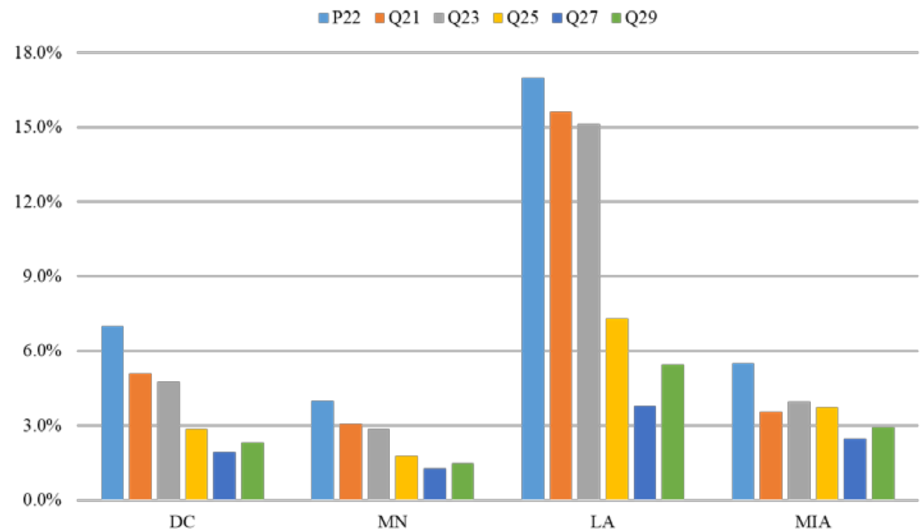

Figure 5: Reductions of Reference Building's Total Energy Consumption by Six Different PCM Types

3.5.2 Case Study 2: The Impact of Location of PCMs of Building Envelopes on Inter-Building Thermal-Energy Performance

In order to understand the influences and energy implications by PCM roofs and PCM walls separately within an inter-building environment, we then designed and simulated how the reference building's energy performance would change due to the PCM locations in the building envelopes in Case Study 2. The results of the reference building's space heating, space cooling, and total primary energy are reported in Tables 16–19 for our cross-regional analysis. Similarly, "NoPCM" stands for the baseline value as noPCM technology is implemented in the building network models. "PCM RoofOnly" and "PCM WallOnly" indicate the cases that PCMs are only applied to roof areas and exterior wall areas, respectively, and the "PCM Entire" denotes the case that PCM layers covered the entire building envelope. For all analyses of this case study, PCM type and the location of PCM layers within the envelope volume are set as control parameters.

PCM type “P22” is used and the PCM layers are embedded as inner layers toward the most effective situation. The interpretation of symbols (“+” and “−”) stay the same as the previous case.

Table 16: Reference Building’s Energy Consumption with Different PCM Layer Locations in Washington, D.C.

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	18362.9		7782.9		26145.9	
PCM_RoofOnly	17924.2	-2.4%	7012.9	-9.9%	24937.2	-4.6%
PCM_WallOnly	17815.5	-3.0%	7155.3	-8.1%	24970.8	-4.5%
PCM_Entire	17596.3	-4.2%	6716.2	-13.7%	24312.5	-7.0%

Table 17: Reference Building’s Energy Consumption with Different PCM Layer Locations in Minneapolis, MN

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	33959.6		5787.3		39746.9	
PCM_RoofOnly	33597.2	-1.1%	5186.5	-10.4%	38783.6	-2.4%
PCM_WallOnly	33416.6	-1.6%	5261.7	-9.1%	38678.3	-2.7%
PCM_Entire	33217.1	-2.2%	4941.1	-14.6%	38158.3	-4.0%

Table 18: Reference Building's Energy Consumption with Different PCM Layer Locations in Los Angeles, CA

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	3078.9		7321.5		10400.4	
PCM_RoofOnly	2802.8	-9.0%	6348.0	-13.3%	9150.8	-12.0%
PCM_WallOnly	2715.7	-11.8%	6463.3	-11.7%	9179.0	-11.7%
PCM_Entire	2655.9	-13.7%	5978.6	-18.3%	8634.5	-17.0%

Table 19: Reference Building's Energy Consumption with Different PCM Layer Locations in Miami, FL

Simulation Type	Heating (kWh)		Cooling (kWh)		Total (kWh)	
NoPCM	377.0		20062.6		20439.6	
PCM_RoofOnly	281.3	-25.4%	19379.4	-3.4%	19660.7	-3.8%
PCM_WallOnly	195.8	-48.0%	19471.0	-2.9%	19666.8	-3.8%
PCM_Entire	192.7	-48.9%	19119.7	-4.7%	19312.5	-5.5%

The numbers in Tables 16–19 are consistent with our previous results and further support that Los Angeles, CA and Washington, D.C. benefit the most from PCM-embedded building layers. Here again we observe that every simulated case leads to a reduction in energy consumption. It is interesting to note that PCM roofs and PCM vertical walls bring similar energy improvement to the reference building. The variation percentages of total energy consumption of "PCM RoofOnly" and "PCM WallOnly" are almost identical in the simulated four cities ("−4.6%" and "−4.5%" in Washington, D.C.,"−2.4%" and "−2.7%" in Minneapolis, MN, "−12.0%" and "−11.7%"in Los

Angeles, CA, "−3.8%" and "−3.8%" in Miami, FL). However, a combination of PCM-embedded roofs and PCM-embedded walls could result in about 50% more energy reduction. This could be due to a more stable indoor thermal performance of an enclosed area. In the inter-building urban settings, the PCM-embedded roof could be favorable to deal with direct sunlight and solar radiation, while PCM-embedded vertical building envelopes could be more effective with offsetting the thermal-energy perturbation by mutual shading and mutual reflection of spatial proximal buildings.

3.6 Discussion

Due to economic booms, urban sprawl and population migration, buildings and densification of the urban built environment have contributed significantly to and will continue to exacerbate global energy and environmental concerns. A great deal of research effort has focused on reducing building energy consumption and achieving a more sustainable built environment (Berardi, 2013; Parrish, Singh, & Chien, 2015). To treat buildings as stand-alone entities would ignore the neighboring buildings within their building networks that may substantially perturb the thermal-energy performance and the local micro-climate. Recent research (Pisello et al., 2014, 2012) has demonstrated that one building's energy performance and supply prediction can be greatly influenced by its nearby microenvironment creating IBE within spatially-proximal building networks. In order to understand the complex IBE and further seek solutions to mitigate the negative impact within urban building networks, researchers have studied the mutual shading and mutual reflection through a nuanced disaggregate analysis (Han et al., 2015a). Although the research found shading to contribute to increased heating and lighting loads while reflection increased cooling energy required for spatially-proximal buildings, the contribution of reflection and shading varied on a month-to-month basis. Tropical cities with longer summers, longer daylight time and more demand for cooling energy would benefit when reflection effect is mitigated all year around. Directional reflective building envelopes have been shown to mitigation UHI effects and improve energy consumption by lessening the mutual reflection within urban building canopies, especially for tropical cities (Han et al., 2015b; Rossi, Pisello, Nicolini, Filipponi, & Palombo, 2014). However, we still lack strategies to promote sustainable and energy-responsive buildings in the context of a dense building network. The research presented in this paper contributes to the exploration of solutions to mitigate the negative impact by the IBE in dense urban settings.

With the capabilities to shift and decrease peak loads, PCMs have been considered as a promising building application to both improve human indoor living comfort and reduce building energy consumption without a substantial increase in the weight of the construction material. Previous empirical and numerical studies demonstrate that PCMs have different benefits depending on quantity and types of PCM selection, locations of implementation and climates, but mostly discussed from the perspective of stand-alone buildings (Nkwetta & Haghighat, 2014; Sage-Lauck & Sailor, 2014; Tabares-Velasco et al., 2012; Zhou et al., 2012). This paper contributes a systematic approach to examine and expand the use of PCM technology from a single building analysis to a more realistic inter-building environment. To test our Hypotheses 1 and 1a, we first introduced a systematic approach to test the reference building's energy performance while the PCMs are embedded in the inner layer, middle layer, and outer layer of the volume of the building envelopes, respectively. We found the application of PCM-embedded building envelopes to contribute to decreasing loads in both heating and cooling despite the four different and distinct climatic conditions. The total primary energy consumption for HVAC was reduced by up to 17%.

This is due to the fact that PCMs raise the building inertia to solar light which initiates mutual shading and mutual reflection of IBE, and may help to minimize negative mutual influences between buildings that lead to increases in energy consumption in urban environments. Consistent with a previous empirical study (Jin et al., 2013), we found better performance for inner layer PCM placement in all four tested cities. This is due to the fact that the PCM was in the partially-melted state before cooling and was able to release latent heat during cooling processes, which results in the best performance of PCM envelopes (Jin et al., 2014). Thus, we found support for our Hypotheses 1 and 1a. The intensity of IBE and the performance of PCMs have been discussed in previous research to be highly dependent on the local climatological conditions. In our analysis, one temperate city, Washington, DC and one subtropical city, Los Angeles, CA, were shown to be more effective when PCM-embedded layers are applied to the inter-building context owing to larger temperature variation over the course of each simulation day and larger temperature fluctuation over the course of the simulation year comparing to extreme conditions. Thus, our research supports the finding that IBE results and PCM impact are dependent on local conditions.

The roof area of a building is exposed to sun over the course of daylight hours and absorbs more solar radiation compared to the other areas of a building, and thus has become a critical area for building applications to improve energy consumption. For instance, green roofs (Goussous, Siam, & Alzoubi, 2015; Niachou, Papakonstantinou, Santamouris, Tsangrassoulis, & Mihalakakou, 2001) and cool roofs (Pisello & Cotana, 2014; Romeo & Zinzi, 2013) have been widely studied to mitigate UHI effects. Previous PCM research also suggest the placement of PCM layers on roofs to be more efficient in single building cases (Zhou et al., 2012). To expand our understanding of PCM application in the inter-building scenario, we tested the impact of a PCM-embedded roof scenario, a PCM-embedded wall scenario, and a combined PCM-embedded envelope (wall and roof) scenario, respectively, for a comparative analysis. The results revealed that vertical building envelopes and roofs are nearly equally important in improving the reference building's thermal energy performance. However, embedding PCMs in both the roof and the wall over the entire building envelope would improve energy savings by about 50% depending on the simulated city. It accomplishes this by creating a more thermally stable enclosed indoor area. This outcome is found consistently in all the four simulated urban cities. Thus, we found support for our Hypothesis 2 as PCM-embedded building walls and roofs have positive influences on energy saving.

To examine the sensitivity of these findings based on the type of PCM utilized, we tested six types of PCMs with different melting ranges and temperature-enthalpy profiles in our simulated inter-building urban setting. We found that the reference building's energy performance varies when different PCMs were used. However, in all PCM types simulated and for all four climatological contexts we found PCMs to result in reductions in energy consumption. This suggests that the introduction of PCMs is an effective strategy for reducing energy consumption of buildings in urban settings but that the appropriate selection of PCM type used to achieve better thermal performance depends on the local weather conditions.

Motivated to explore strategies to reduce the negative energy and environmental implications of inter-building effects in cities, this research was initiated to examine and quantify the impact of PCM-embedded building envelopes on thermal-energy dynamics within an inter-building environment. It provided us with a more explicit understanding of the dynamic response of PCM technology to inter-building relationships. The simulation results demonstrate that PCM-embedded building envelopes could serve as possible solutions to mitigate unfavorable thermal-energy IBE outcomes, and the parametric analysis also suggests more effective practices to take advantage of the latent heat capacity in a more realistic inter-building environment. A human-based check was conducted to ensure the accuracy of the dynamic simulation input and output in executing the dynamic simulation. No exceptional results, warning, or error messages were observed over the course of the simulation. Nevertheless, the modeling and simulation efforts also have several limitations. The hypothetical building network model we inherited for this study contains only nine buildings with identical morphology. The purpose of this limited urban setting is to not only to keep the research scope reasonable, but also sufficient enough to examine our hypotheses and research questions. It is possible that a more complicated outcome due to larger urban scale may exist and, if so, was neglected in the research. Future research should address the limitations to understand the impact of PCMs from a larger scale analysis, incorporate empirical studies using thermal sensing technology that could calibrate simulation analysis, as well as seek out other measures that could be used to mitigate the negative IBE impacts.

3.7 Conclusions

We investigated the potential of PCM technology within an inter-building micro-environment to reduce the negative impact on energy use that can result in spatially proximal building networks. We developed and demonstrated a systematic approach to examine the impact of PCM-embedded building envelopes in an inter-building context. This research built upon and extended previous IBE modeling approaches that studied energy predictions in a dense urban building network. A hypothetic building network was modeled in the dynamic EnergyPlus simulation environment under the climatological contexts of four typical cities in the United States. The energy consumption of the reference building demonstrated considerable improvement and consistent reductions across our simulated contexts, although the magnitude of reductions was dependent on local climatological conditions. The placement location of PCM-embedded layers was found to be especially important in order to make full use of the thermal storage capacity of PCMs. We also studied and discussed better practices for more effective PCM application in the inter-building environment through parametric analysis. This research expands our understanding of the use of PCMs from a stand-alone building scenario to a dense urban inter-building environment. The results suggest PCM-embedded building envelopes as possible solutions to mitigate negative inter-building influences and improve energy efficiency within urban building networks, especially in temperate cities. Urbanization is exacerbating energy and environmental challenges created by the tighter spatial building interrelationships in cities. Therefore, future research is critically needed to develop strategies—like the PCM-embedded envelop strategies presented in this paper—to reduce the intensity of Inter-Building Effects and achieve comfortable, energy efficient and sustainable cities.

3.8 Acknowledgements

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CHAPTER 4: ASSOCIATING NATURAL AND BUILT ENVIRONMENT SYSTEMS - A FRAMEWORK FOR UNDERSTANDING BIO-INSPIRED APPLICATIONS IN THE BUILT ENVIRONMENT FROM A LEVELS-OF-ORGANIZATION PERSPECTIVE[3]

4.1 Abstract

Rapid urban development has prompted severe global deterioration by excessively exploiting natural resources and encroaching on nature. Climate change has been identified as one of the most severe challenges humanity has ever faced. The built environment—the center of human activities and social civilization—not only contributes to climatological changes locally and worldwide, but also has to adapt to the consequences of such environmental impacts. Therefore, how to build a sustainable and resilient built environment has become an overarching goal of professionals and researchers in the architecture, engineering, and construction (AEC) fields. Bio-inspiration as a design approach is emerging as a strategy to improve the functioning of the built environment. Natural systems are often more efficient and robust due to their time-tested structures and mechanisms. In this paper, we introduce a framework that draws parallels between natural systems and the built environment through a levels-of-organization perspective. We categorize a number of current bio-inspired applications in the AEC fields based on the levels-of-organization framework and argue that most have focused on relatively low levels of organization, i.e. materials and building (sub-) components. However, higher-level examinations and systematic cross-level synergies may result in greater impacts on the sustainability and resilience of the built environment. Inspired from a self-regulating phenomenon of plant density that results from intra- and inter-specific competition for limited resources, an approach to determine optimal urban building

[3] This journal-length manuscript was co-authored with Prof. John E. Taylor, Prof. Michael J. Garvin and Prof. Ignacio T. Moore, and will be submitted to a peer-reviewed journal.

network design is introduced and discussed as an example for how this framework can support cross-level assessment. This research contributes a unique and holistic framework that strengthens our understanding of the associations between the fields of biology and AEC. This framework may help promote sustained and resilient urban growth that better integrates natural and built environment systems at and across levels of organization.

Keywords: *Bio-inspiration; Built environment; Climate change; Levels-of-organization; Self-regulation; Urban system*

4.2 Challenges in Building a Sustainable and Resilient Built Environment

Over the last several decades, rapid development in urban areas, both densification and sprawl, has triggered severe natural deterioration, such as biodiversity loss and depletion of non-renewable resources. Cities occupy merely 2% of the earth's surfaces, but represent the highest concentration of human activities and resource consumption (Pacione, 2009). Today, more than half of all human beings live in urban areas, and urban inhabitants are responsible for 75% of the world's energy use (Madlener & Sunak, 2011). According to a recent report from the United Nations, urban population is predicted to increase by 72 percent in the next 40 years (2010-2050) (UNDESA, 2011). Ongoing and upcoming industrial developments and urbanization in fast developing countries and underdeveloped regions will not only intensify current challenges on energy and resource supply, but also substantially influence the human living environment by amplifying Urban Heat Island effects, air pollution, and/or water contamination locally as well as global warming and climate change that have worldwide impacts (Madlener & Sunak, 2011).

As a result of urban development, climate change is arguably the most influential impact to the globe, and has been repeatedly identified as one of the most severe challenges humanity has ever faced (Gill, Handley, Ennos, & Pauleit, 2007; Taylor Buck, 2015). Currently, cities and the urban dwellers contribute to 80% of greenhouse gas (GHG) emissions that exacerbate global climate and environmental change (Feng et al., 2015). Consequently, a worldwide increase of as much as 5.8 degrees Celsius is expected to occur by the end of the 21st century (Smithson, 2002). A recent study also confirmed the devastating impacts of climatological change on biodiversity loss (Garcia, Cabeza, Rahbek, & Araujo, 2014). Although the mitigation of GHG emissions has been urgently required by the Intergovernmental Panel on Climate Change (IPCC, 2007), global GHG emissions are still increasing despite the initiation of many climate protocols and policies and a variety of activities that promote "green" development (Olivier, Peters, & Janssens-Maenhout, 2012).

The concept of sustainability was first introduced as an holistic understanding to reduce ecological footprints and resource needs in urban development (Fiksel, 2006). Over years, researchers strived to design net-zero buildings or similar facilities with neutral or minimal environmental impact in terms of energy use, carbon emission, waste, etc. (Robert & Kummert, 2012). However, the built environment—the center of human activities and social civilization—not only initiates climate changes locally and worldwide, but also has to adapt to the consequences of such environmental impacts. As a result, urban resilience has emerged as another important parallel concept given the current and potential impacts of global climate change (Leichenko, 2011). Robust urban building-infrastructure systems are needed to counter the increasingly volatile climate and the serious subsequent hazards in urban regions. Thus, how to build a sustainable and resilient urban environment has become an overarching goal of engineers, architects, building researchers, policy makers, and urban planners.

Modern buildings often have to fulfill complex and sometimes contradictory responsibilities during their life cycles. Early urban development approaches generally aimed to overcome or encroach upon nature rather than embrace it (Taylor Buck, 2015). High density and vertical development have become the norm in urban districts driven by economic factors and the limitation of urban land (Chau, Wong, Yau, & Yeung, 2007). Such urban expansion have proven to exert negative impacts on the well-being of urban inhabitants (Gullone, 2000). Not until recently have efforts increased to reconnect landscapes and the built environment to enhance livability of quality of life (Beatley & Newman, 2013). Ecological demands have emerged as a driving force in the new development of building technologies that promote sustainability efforts (Knippers & Speck, 2012). Biophilic cities have set great examples by increasing the urban vegetation and biodiversity while fulfilling the social and economic need in populated urban regions (Beatley & Newman, 2013). People are beginning to realize the importance of knowledge transfer from biology and ecology into architectural and engineering design. Thus, analogies and metaphors from nature have become important paths for us to construct and maintain a more sustainable and adaptable built environment.

4.3 Biological Inspiration in the Built Environment

Natural system has been refined by evolution for over 3.8 billion years through trials and errors (Bhushan, 2009). Biological inspiration is one of the oldest design practices in civilization (Pacheco-Torgal, Labrincha, Diamanti, Yu, & Lee, 2015). Going back thousands of years when ancient Chinese first tried to make artificial silk, designers and creators started to draw inspirations from biological strategies for alternative solutions (Helms, Vattam, & Goel, 2009). Although the early “abstractions” from nature mostly focused on the appearances and patterns of natural species, aspects of natural functions and mechanisms were also replicated in human designs. One classic example is the evolution of the invention of man-made airplane: Leonardo da Vinci, the great polymath of the 14^{th} century, conceptualized the early designs of flying machines by studying how birds fly; the Wright brothers, who later built and flew the world’s first successful airplane in 1903, also spent a great deal of time observing how birds lift themselves and make turns during flight.

The term “biomimetics” was first coined by Otto Schmitt in the 1950s when he proposed it as a research methodology of using an engineering/physics approach to biological sciences and a biological approach to engineering tasks during his doctoral research (Bhushan, 2009; Schmitt, 1969). Even though the biological side could cover all fields and different scales of biological research from Zoology to Botany, from Physiology to Biochemistry, and from Microbiology to Ecology, early development of biomimetics was rather sporadic and slow (Pacheco-Torgal et al., 2015). It did not draw significant attention from researchers across different disciplines until Janine Benyus popularized the concept of biomimicry in the late 1990s (Benyus, 1997). Since then, biomimicry has generally re-emerged as an applied science that derives inspiration for solutions to human problems through the study of natural designs, processes and systems (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006).

Due to the novelty of biomimetic methods and their interdisciplinary characteristics, biomimicry has been considered as a major innovative way in pursuing design solutions and solving human-induced tasks (Bar-Cohen, 2006; Weissburg, Tovey, & Yen, 2010). It also becomes a leading paradigm for the development of new technologies that can potentially lead to significant scientific, societal and economic impact (Lepora, Verschure, & Prescott, 2013). Biomimetic designs have been successfully implemented across a great number of disciplines, such as materials science

(Aizenberg & Fratzl, 2009; Heuer et al., 1992), optics (Y. Li, Zhang, & Yang, 2010), mechanical engineering (Reap, Baumeister, & Bras, 2005; Spolenak, Gorb, & Arzt, 2005), robotics (Clark et al., 2001; Laschi, Mazzolai, Mattoli, Cianchetti, & Dario, 2009), architecture (Gruber, 2008; John et al., 2005), fluid dynamics (Saha & Celata, 2011), and computer science (Ratnieks, 2008), among others, especially with the recent rise of cross-discipline collaboration. Over the last few decades, the extent of biomimicry research has developed to an unprecedented level. According to a survey of the United States Patent and Trademark Office, a dramatic increase in the percentage of biomimicry-related patents relative to the total number of U.S. patents published has occurred, from less than 1% in 1990 up to 7% in 2005 (Bonser, 2006). A recent study also demonstrated that this new research paradigm has expanded rapidly from less than 100 publications per year in the 1990s to several thousand research articles that are published annually in the first decade of the 21st century (Lepora et al., 2013).

Two multidisciplinary approaches have been developed and widely accepted to utilize biomimicry in other disciplines like engineering, including a "top-down" problem-based approach and a "bottom-up" solution-based approach (Bhushan, 2009; Yurtkuran, Kırlı, & Taneli, 2013). The solution-based process is often used when biological knowledge influences human design, which could potentially lead towards highly innovative solutions and technologies. However, biological research must be conducted to identify a specific trait at certain biological level (e.g. organism or ecosystem) before it can be translated into a design that responds to a human problem. Unlike the "biology influencing design" approach, the problem-based approach allows designers to first identify problems and then examine ways natural organisms have solved similar issues, foregoing any in-depth biological research. By comparison, the "top-down" approach is generally faster and more straightforward, but the innovativeness of solutions is limited as it is most likely only applicable to certain human difficulties. BioTRIZ was recently introduced as a methodology to facilitate the transferring of ideas and analogues from biology to engineering using design principles as a database of inventive solutions (Vincent et al., 2006; Vincent & Mann, 2002). Although, the initial Theory of Inventive Problems Solving (TRIZ) did not include biological principles, they are incorporated in the BioTRIZ database to foster the biomimetic field (Vincent et al., 2006).

Certainly, not all solutions resulting from inspiration from natural evolution will be perfect, or suitable for the human context; however, natural systems are often more sustainable and resilient due to their time-tested patterns compared to man-made systems, especially at a time when professionals and researchers in the AEC fields need to solve more urgent and problematic tasks related to environmental impact and climate change. Over the course of evolution, biological organisms have successfully adapted their characteristics through selection and interaction within their micro-environments to meet constantly changing environmental conditions. While researchers have been exploring means to build a sustainable and resilient urban built environment in a variety of ways from engineering or architecture perspectives, it is possible that answers may be available in nature. The transfer of ideas and analogues from nature also brings many new insights into the AEC fields to architect bio-inspired structures and high-performance materials (Gruber, 2008; John et al., 2005). While the majority of these have focused on singular issues, potential applications discussed relating to the built environment include reduction of embodied energy in construction products, less materials use, improvement of resource efficiency, novel designs and technologies, and minimizing maintenance requirements (Zari, 2010). From a hierarchical perspective, Benyus elaborated that the emulation of natural strategies in the built environment engages three level of mimicry: form, process and ecosystem (Benyus, 1997). This differentiates biomimicry from similar concepts of biophilia, biomorphism and ecological design, that focus on the affiliation with natural systems (Wilson, 1984), aesthetic properties of natural shapes and patterns (Kuhlmann, 2011), and integrated ecological processes that minimize environmental damage (Cowan & Van Der Ryn, 1996), respectively. Through a classification of natural systems, Knippers and Speck summarized four main natural design principles that can be used for architectural applications: heterogeneity, anisotropy, hierarchy, and multi-functionality (Knippers & Speck, 2012). Gruber used life sciences terminology, including order, propagation, growth, processing of energy, reaction to the environment, to investigate and interpret the relation between the fields of biology and architecture (Gruber, 2008). Most recently, Zari elaborated a categorization framework that explain the mimicry of an organism, an organism’s behavior or an entire ecosystem in terms of its form, material, construction method, process strategies and function (Zari, 2010).

Among all the important characteristics and different point-of-views in bio-inspired studies, interdependency is perhaps one of the most important features in natural systems that is shared by built environment systems. No plants or animals live in an environment interacting only with their own species. Quite oppositely, they interact and co-evolve with each other over time. Similarly, urban infrastructure systems are characterized by their interdependency. A small infrastructure failure may result in dysfunction of a region. Nature thrives when three characteristics—effectiveness, efficiency, and multi-functionality—are intricately tied in a mutualism state by different natural species (Chen, Ross, & Klotz, 2015). Accordingly, by adopting these three characteristics, smart, coordinated and balanced urban systems would seemingly be attainable. Nevertheless, the literature suggests that employing biological principles across systems in the built environment remains relatively unexplored; most bio-inspired research has examined singular and independent issues. In this paper, we propose a framework that draws parallels between natural systems and the built environment through a levels-of-organization perspective to examine interdependencies across levels/systems that are often neglected. By categorizing a number of current bio-inspired applications, this study aims to holistically understand the current status of this interdisciplinary approach in the AEC fields and give suggestions for future exploration that lead to co-evolution and association between natural and built environment systems.

4.4 Levels of Organization Conceptualization and Categorization

Living things are diverse and complex. Self-organization, defined as the formation of complex patterned structures from units of less complexity without external interactions, is a key characteristic for all processes in nature (Camazine, 2003). Natural systems self-organize to be able to function well in their environments and systems. Because of this, biologists have classified hierarchically biological structures and systems, and introduced the levels-of-organization concept using a reductionistic approach, which ranges from the smallest atoms and molecules and sub-cellular level, to the largest units in the world, biome and biosphere (Lobo, 2008). Each level of organization is larger than the next. Following certain types of assembly, a group of entities at lower levels can constitute higher-level organizations. Similar to the natural environment, the built environment is dynamic, highly interdependent and structured hierarchically, and it needs to be organized to function efficient and effectively. In the following table (Table 20), a levels-of-organization framework for the built environment is presented, inspired from the various levels of organization that exist in nature. Nature's definitions and examples are tabulated, followed by the analogous comparison in the built environment at each level along with a rationale for each classification. For instance, a tissue is defined as an ensemble of similar lower-level cells that carry out a specific function in biology. Different types of tissues collectively can constitute a structural unit as a higher-level organ. Analogously, building sub-components, e.g. a layer of a wall, can be considered as a "tissue" in the rank of built environment systems. They are made of lower-level building materials, or "cells", while several different wall layers (tissues) make up walls of certain types at the "organ" level. Specific examples and explanations are discussed and elaborated in the table.

Table 20: A levels-of-Organization Framework for the Built Environment

Level of Organization	Nature	Built Environment
Atom	Basic unit of matter	Same: basic unit of matter
Molecule	Neutral group of two or more atoms, chemically bonded	Basic element of building materials
Cell	Basic biological unit of all organisms	Basic element of structure or system such as ductile iron, copper
Tissue	Ensemble of similar cells with specific purpose	Ensemble of structural elements such as wood-studs or particle boards
Organ	Collection of tissues joined in a structural unit to provide a function such as heart	Component of a system such as a wall, pump or fixture
Organ System	Group of organs that work together towards a similar goal such as the circulatory system	Specific sub-system such as electrical circuits, plumbing loops, or pavement
Organism	Individual living thing	Individual constructed unit such as building or highway
Population	Organisms of same group/species living in same geographical area	Similar constructed units such as commercial buildings
Community	Various populations or species living and interacting in same geographic area	Various constructed units in the same geographic area such as neighborhoods
Ecosystem	Communities of living organisms and nonliving things	Communities of constructed units, living and nonliving things such as a city
Biosphere	Global sum of all ecosystems	Similar

From Table 20, our first observation is natural and built environment systems have several hierarchical similarities. They have the same subatomic particles, similar concepts at the sub-cellular level as the smallest level of organization, and share our living planet at the highest level. It is worth noting that an ecosystem, by definition is a community of living organisms in conjunction with the nonliving components of their environment as a system, includes the impact of the built environment to nature. Biotic (natural systems) can be affected by the abiotic (built environment systems), and vice versa. This reflects an interweaving relationship between the natural and built environments. In the following paragraphs, we discuss a number of current bio-inspired practices in the AEC fields by categorizing them from the lowest rank, i.e. materials, to higher levels in urban neighborhoods. Current developments on the study of ecosystem biomimetics is also discussed at the end of this section.

The materials science field, at the "cell" level, has been generally considered one of the areas where biomimetics is likely to have the most impact and is currently an area of significant focus by researchers across different disciplines (Fratzl, 2007; Pacheco-Torgal et al., 2015; Wegst et al., 2014). Nature provides a wide range of materials that exhibit remarkable engineering performance and different functionalities for us to choose and learn from, such as tough spider silk and lightweight but strong bamboo (Barthelat, 2007). The processes used by living organisms to synthesize biomaterials are quite different from those used by us to produce the wide range of materials that support modern societies. Unlike the techniques for making traditional artificial materials, natural materials are often built in extremely efficient ways with minimal amounts of base components and at ambient temperature (Wegst et al., 2014). The secret has been revealed as highly organized and complex characteristics of biological materials, e.g. hierarchical structuring, to achieve specific combination of stiffness, toughness, and strength (Barthelat, 2007). With the potential to produce high performance building materials with multi-functionality and higher adaptability, biomimetic materials research is becoming enormously promising in the AEC fields. Over the last several decades, researchers have been striving to duplicate natural material properties into artificial man-made materials that are multifunctional, lightweight, benign, and recyclable (Pacheco-Torgal et al., 2015). By determining the features that control the performance of natural materials and structuring and assembling key elements through bio-inspired processes, e.g. layer-by-layer assembly, it creates numerous opportunities for deriving new strategies to create innovative bio-based materials. The most impressive features of biosynthesis are self-assembly, biomineralization, water-based chemistry, and resource efficiency. Bio-inspired materials have the potential to revolutionize the way infrastructures and buildings are constructed. Current applications include natural replications of mechanical resistance, optical properties, self-cleaning, and thermal storage (Pacheco-Torgal et al., 2015). Bio-inspired cement has been invented by mimicking the crystallographic nature and biosynthetic procedure through a skeletal formation process. More innovative bio-based materials with growth (adaptive) and self-healing abilities are continuing to be explored (Fratzl, 2007; Pacheco-Torgal et al., 2015).

To a level higher in built environment systems, "tissues" are defined as partial building components and are made up of the same type of building materials with specialized properties. Current bio-inspired applications at this level mainly focus on external coatings/surfaces and kinetic connections. Bio-inspired computer algorithms can be also profiled in this category referring to nerve tissues that are able to transfer signals in governing the communication network. However, the boundary between "cells" and "tissues" in built environment systems can be quite vague. For example, antireflective coatings or self-cleaning surfaces at the "tissue" level generally represent similar materials properties of antireflective materials and self-thinning materials at the “cell” level, but recent study on multifunctional bio-inspired sol-gel coatings for architectural glasses could exhibit both material characteristics (Cannavale et al., 2010). The self-cleaning coating is perhaps the most discussed example and a well-developed bio-inspired solution in the AEC fields. It was originally inspired from several natural surfaces, the most well-known is the lotus leaf (Barthlott & Neinhuis, 1997), that shows a tremendous hydrophobic and self-cleaning effect. By mimicking the microstructure of leaf surfaces, self-cleaning coatings display a high level of water and dirt-repellency and a high resistance to the soiling and growth of mold and thus have a wide range of possible applications from window glass to cement. Bio-inspired self-cleaning surfaces could reduce the maintenance effort and improve overall building life cycle performance. Similarly, antireflective properties have been discovered on insect eyes, insect wings and leaves of plants in understory forest to reduce reflection, improve night vision, and capture more light (Y. Li et al., 2010). Antireflective surfaces are replicated based on biomimetic nanopillared arrays (Y. Li et al., 2010); one of the applications in the AEC fields is to improve the efficiency of solar panels since antireflective surfaces have the ability to suppress reflection and improve transmission of light, which are crucial for the performance of optical and electro-optical devices. High elasticity of plant structures is the basis of many plants’ movement and also allows for reversible deformations (Poppinga et al., 2010). Nastic plants are typical examples that have been observed. Through functional-morphological analyses of nastic plant movements, kinetic and deployable movable building structures can be designed based on viscoelastic deformation to improve the mechanical performance.

An “organ” is a basic building component in the level-of-organization framework, and several “organs” with similar functions work together to form “organ systems”, or comparably, specific sub-systems (within a building), such as a structural system, envelope system, or HVAC system.

Although the prevalence of building research in these areas is quite high, bio-inspired applications at these two levels are limited to building facades (Reichert, Menges, & Correa, 2015), solar shadings (Fiorito et al., 2016), and building envelope systems (Loonen, 2015; Webb, Hertzsch, & Green, 2011). Building envelopes not only protect building occupants against inclement influences from outside, but provide connections between indoor spaces and outdoor areas. Similarly, skin is a key component in thermoregulation and acts as the heat transfer interface to the external thermal environment and can respond to a range of ambient conditions. Researchers have drawn inspiration from the skins of plants and animals to design sustainable enclosure systems (Webb, Aye, & Green, 2013; Webb et al., 2011). In a recent study by Webb, a combination of external fur, bioheat transfer and internal surface evaporation is considered in a model of a commercial office building facades for temperature and heat-transferring analysis (Webb et al., 2011). The translation of natural characteristics provide flexible, adaptive solutions for façade design that provide occupant thermal comfort while minimizing energy consumption. Bio-inspired sensors are another example categorized at this level (Lenau, Cheong, & Shu, 2008). Biological systems have the capability of densely distributed sensing and monitors of changes in temperature, deformation, flow, pressure, and damage. Recent development of artificial sensors has focused on analogies from chemoreceptors (Lenau et al., 2008). Most sensors in building applications are simple and single-functional, and are yet to achieve the level of monitoring and feedback where our building can approach sustainable solutions. Bio-inspired multifunctional sensors can contribute to improve the effectiveness and efficiency of building automation systems and building management systems (Pacheco-Torgal et al., 2015).

Buildings or infrastructures are the basic elements in the built environment. Each individual is characterized as an “organism” in the levels-of-organization framework. Trees/plants have been discussed as role models for buildings, which can generate food and oxygen, sequester carbon dioxide, distill water, acquire solar energy, create micro-climates, and self-replicate (Alston, 2015). Of all the buildings that inspired from nature, the Eastgate building in Harare, Zimbabwe is the most frequently mentioned example (Turner & Soar, 2008). Termite mounds exhibit remarkable thermal performance to support as many as two million termites living in. The temperature regulation in the mounds is achieved through careful orientation, spatial organization and techniques of passive ventilation. Inspired by how the mounds are built, the Eastgate building was designed to have a relatively thermally stable interior environment with minimal mechanical cooling, and is considered to be a highly successful building in terms of energy efficiency and GHG emissions reduction. In addition to buildings, bridges are another form of infrastructure in the AEC fields that nature can offer enormous potential for inspiration. Hu et al. reviewed 15 bridges project built from last 20 years with a variety level of levels of inspiration from nature, and summarizes five main aspects in nature that may inspire the development of future bridge systems: geometry, structure, kinetic mechanism, energy efficiency, and intelligence (Hu, Feng, & Dai, 2013). They found that despite being aware of bio-inspired ideas, bridge designers and engineers are not capable of finding proper resources or collaborators that could revolutionize their design. As a result, most bio-inspired bridges today are still within the low-level of inspiration which could result in awkward shapes rather than efficient structures (Hu et al., 2013).

The inter-relationship between buildings of similar type and morphology, between buildings of different form, height and functionality, and between buildings with their surrounding micro-environment are categorized into “population”, “community”, and “ecosystem” levels, respectively. Mutual interaction between buildings within a building network has been studied through a bio-inspired perspective (Han et al., 2015b). Research has shown that bio-inspired retro-reflective building envelopes can improve buildings' thermal-energy performance by mitigating the negative mutual reflection and the lessening of reflected solar radiation in spatially proximal buildings, and that this in turn could lead to reduced Urban Heat Island effect (Han et al., 2015b). The original idea was inspired from peculiar reflectivity of a temperate flower petals that exhibit a cool effect to escape the "micro-greenhouse effect", a similar heat island effect in floral world. Likewise, antireflection is another optical property displayed by natural species. Its application on glass-clad skyscrapers in densely populated areas can mitigate hazardous reflectivity issues for neighboring buildings and passing traffic and pedestrians (Pacheco-Torgal et al., 2015). Current ecosystem-based biomimicry studies investigated how ecosystems are capable of adapting to constant changing and optimizing resource use, and identified two ways to mimic ecosystems including mimicking ecosystem functions and mimicking ecosystem processes (Garcia-Holguera, Clark, Sprecher, & Gaskin, 2016; Taylor Buck, 2015; Zari, 2014). Emulating the interrelated complexity of the parts of an ecosystem to achieve more efficient, effective and holistic building design, Garcia et al. introduced a theoretical basis and initial development of an ecomimetic design method (Garcia et al., 2014). Zari also examined the processes of ecosystems and presented an integrated set of natural principles that can guild sustainable and architectural and urban design (Zari, 2014). A thoroughly investigating of ecosystem biomimetics can offer insights on how the built environment could function more like a system other than a set of independent building entities.

4.5 A Cross-Level Optimal Model on Urban Building Designs from a Bio-Inspired Self-Regulating Perspective

From the levels-of-organization framework for the built environment presented in previous section, the IBE research that considers inter-relationships between buildings should be better categorized at the "population" and/or "community" levels depending on building geometry and functionality. Plants have been discussed as role models for buildings. How plants regulate their density level may also provide inspiration in searching for optimal building networks. In this section, I presented and discussed an approach to determine an optimal status of the IBE as an example for how this approach can help develop ideas as well as support cross-level assessment.

4.5.1 High-Density Urban Building Networks

Building density plays an important role in shaping urban forms and causes variation to the local micro-environment (Yao & Steemers, 2013). The concept of urban density is complex and rather subjective representing different notions in different countries, across different cultures, and to different people (Ng, 2010). High-density cities appear to be very efficient in a number of ways, especially in urban land use and development, infrastructure and transportation sharing and access, environmental preservation, and even some social benefits (Jabareen, 2006). Conversely, unsuccessful overcrowding may result in very little open space and a congested cityscape. High-density construction and building operations also require more energy use and deteriorate the local micro-environment. Recent research has demonstrated that the interrelationship between buildings and their close proximity within building networks, namely the Inter-Building Effect (IBE), results in substantial thermal-energy deviations and environmental impacts to surroundings (Han et al., 2015a; Pisello et al., 2014, 2012). Such influence could easily escalate in denser urban settings.

Despite the diverse and controversial opinions, high-density development has consequently become a topic of increasing interest worldwide owing to the tremendous pressure on urban development exerted by rapid urbanization and population migration (Ng, 2010; Rode, Keim, Robazza, Viejo, & Schofield, 2014), and is generally considered more sustainable more sustainable, efficient, and economical compared to extensive urban sprawl (Ng, 2010). The number of cities and megacities continues to rise, yet the IBEs are expect to be amplified under high-density urban environments owing to the negative impacts of compactness on natural light, solar gain, and ventilation. This challenges the optimal determination of urban morphology due to limitations in urban spaces and resources, and complicates the task of achieving energy efficiency in cities. Fire regulations and natural light duration are normally the key issues in governing the height and spacing of buildings (Ng, 2010; Rode et al., 2014). In reality, site areas are limited and become even scarcer in cities. Largely driven by economic factors, the relaxation of building height restrictions creates the norm of "vertical skyline" in newer urban districts (Chau et al., 2007). However, it is clear that increasing density is not a panacea and urban developments that overemphasize high density in a simple quantitative way could give rise to serious environmental deterioration and social ramifications. How to design density-optimal building networks and plan density-optimal cities have challenged urban planners and building researchers, especially as cheap and plentiful fossil resources are depleting. In order to avoid the negative impact of high-density buildings and the substantial IBEs induced by high-density building networks, appropriate density control and planning have become crucial. Innovative design and planning perspectives are needed to aid the process of searching for the most optimal building networks and ideal density level in urban cities.

4.5.2 Inspiration from Plants' Self-Regulating and Coexistence

When an individual plant is encountering increased population density with limited resources during its life, the effect of increasing density will not only decrease the growth rate but also increase the mortality rate (Lonsdale, 1990). Such a phenomenon often occurs in a group of undisturbed even-aged plant stands. Only a limited number of plants can coexist within a certain living area given the resource constraints in space, sunlight, water, and nutrients. As a result, plants become fewer and fewer progressively, or "thinner", as the average plant size increases over the course of plants' growth. Such plant self-regulation has been studied empirically by plotting the average weight of individual plants over density within a plant stand, and a "-3/2 self-thinning rule" has become widely accepted among ecologists (Zeide, 1987). In competing for the limited resources from the surrounding environment, winning individual plants would occupy more space and take up more nutrients and water and losers die. As a result, nature-selected optimal levels of plant clusters are reached over time due to intra-specific competition (Lonsdale, 1990).

However, natural species do not live in a world where they only interact with other members of their own species. They must interact with the environment and each other in functioning as an ecosystem. Inter-specific competition has been described as the ability of an individual of one species to inhibit the survival or growth of individuals from other species for similar but limited resources, when demand is greater than supply, under the same spatial and temporal condition (Goldberg & Barton, 1992). Although the classical competition theory revealed that two species that have the same resource requirement should not coexist (Schoener, 1974), researchers found different natural species being able to coexist in the same ecosystems despite their physical similarities (Bengtsson, Fagerström, & Rydin, 1994). The concept of resource partitioning was introduced to explain such coexistences (Bengtsson et al., 1994). It is helpful for different species to coexist with slightly different ecological niches. Particularly in the plant kingdom, the species compete for space above and below ground, in order to obtain necessary solar light, water, and soil nutrients for them to grow and sustain. Spatial and temporal niches are defined and classified within the context of interspecific competition and species coexistence in plant ecology (Schoener, 1974).

4.5.3 Cross-Level Optimal Urban Building Network Designs

Natural species regulate their own density for reproductive advantages, as well as share resources with others in order to live, grow, and thrive in one ecosystem. The balance point between competition and coexistence makes their own unique but ideal living environment. Although building networks and plant clusters share a number of similarities in terms of functionalities and morphologies, current urban building development fails to consider resource requirements and environmental impact caused by IBEs among spatially-proximal building networks, especially when clusters of tall and high-density buildings have invaded urban areas and are in competition for a limited quantity of land. To avoid the occurrence of dysfunctional urban building systems, a bio-inspired perspective for optimal urban building network planning and development with minimal negative impact on energy and environment may provide a promising design approach.

In deciding an optimal urban density that considers energy use and environmental assessment, a large number of inputs should be taken into account. They are best categorized by complexity and levels of impact. The levels-of-organization framework can be employed, and the parameters can be classified into three levels, building level, building network level, and urban ecosystem level. Example parameters are tabulated in Table 21. All the building attributes that contribute to the building thermal-energy performance should be considered at the individual building level, such as characteristics of building envelopes and HVAC systems. At the building network level, parameters like building coordinates, building orientations, and vertical obstruction angles determine the spatial relationships between individual buildings within the network. The information of the building site, such as plot ratio and site coverage, also contributes to the understanding of building distribution and planning within the studied area. Additionally, embodied energy and operation costs are often ignored by building designers and urban planners. At a broader level, those life cycle parameters need to be taken into account coupling with other urban ecosystem level parameters, such as vegetation cover ratio and access to mass transit systems.

Table 21: Example Parameters of the Multi-Variant Optimization Framework

Levels of Organization	No.	Parameter
Individual Building Level	A_1	Building geometry
	A_2	Thermal mass
	A_3	HVAC efficiency
	A_4	Window-wall ratio
	A_5	Lighting
	A_n	…
Building Network Level	B_1	Coordinate
	B_2	Orientation
	B_3	Vertical obstruction angle
	B_4	Plot ratio
	B_5	Site coverage
	B_n	…
Urban Ecosystem and Building Life-cycle Level	C_1	Embodied energy
	C_2	Building operation equivalent
	C_3	Access to mass transit system
	C_4	Vegetation cover ratio
	C_5	Climatic condition
	C_n	…

With the governed parameters determined, optimization approaches, e.g. a multi-variant optimization method, can be then employed to search for optimal density levels or urban designs with the favorable energy and environmental performance across different scales. There is certainly no universal or unified solutions for a design of a built environment system, especially when different parameters are taken into consideration, and regional characteristics and climatological conditions would lead to different outcomes. The cross-level optimal approach can surely help urban designers to evaluate the building/urban behavior hierarchically and systematically. The model can also be simplified or be more comprehensive to consider both spatial and temporal effect to achieve mixed-use buildings and infrastructures and multi-functional land development.

4.6 Conclusions and Implications

Over millions of years, nature has developed materials, algorithms, structures, mechanisms, and many other benefits that work for organisms individually and as a system (Bar-Cohen, 2006). Unlike sprawling urban development that degrades the environment, evolution in nature selects highly efficient, effective and multi-functional biological creatures, and failed solutions become extinct. Human have always made efforts to imitate nature as a living library. It is reasonable to consider mimicking biological methods, processes and systems an easier way to solve the problems we are struggling with today. The application of bio-inspiration has become an innovative problem solving approach (Bar-Cohen, 2006). Although we have a tradition of looking to nature for inspirations in the AEC fields and the superposition of biological paradigms has already delivered new insights and solutions to the built environment system (John et al., 2005; Pacheco-Torgal et al., 2015), bio-inspired AEC applications are not as numerous and popular as for other disciplines. Conferred as an ontology that can support the design and planning of cities' urban infrastructure (Taylor Buck, 2015), biomimicry is worth exploring to evolve towards achieving a sustained and resilient built environment.

A levels-of-organization framework for biomimicry was presented in this study to understand the structural hierarchies and similarities between natural and built environment systems. By categorizing a number of characteristic applications in the AEC fields, we found that most research effort has been focused on relatively lower levels of organization, such as materials and building (sub-) components. In order to have a greater impact in terms of improving the sustainability and resilience of the increasingly denser urban built environment, higher-level examinations and systematic cross-level synergies are needed. To further elaborate this level-of-organization framework, a model to determine optimal urban building network design was introduced and discussed as an example for how our framework can support cross-level assessment. The bio-inspired model for urban building development was inspired by the intra- and inter- specific competition phenomenon from nature (Goldberg & Barton, 1992; Lonsdale, 1990). By considering energy use and environmental sustainability assessment and more at different levels, the designers can understand and take advantage of the interdependencies between urban building-infrastructures with in a community for net-zero building network design. Going forward, life cycle assessment and industry ecology should also be considered in determining local optimal configurations of individual buildings and build networks. Achieving a high-level synthesis of interactions among the many infrastructure systems and processes will become increasingly important to sustainable building network development and smart growth as clusters of dense urban settings grow due to rapid urbanization and population migration in the coming decades.

Although many biological structures and mechanisms seem to be good examples for the AEC fields given the similarities natural and built environment systems have, this promising inter-disciplinary paradigm challenges researchers and educators in several ways. Not all natural solutions are well suited for human applications. In fact, all solutions require a deep understanding before the knowledge and terminology can be successfully translated to a different discipline (Vincent et al., 2006). On the other hand, barriers and difficulties have been found to transfer concepts and motivations of biomimicry into engineering curriculum (Santulli & Langella, 2011). The level-of-organization framework elaborated in this study would help deal with these challenges by understanding the close connections between natural and built environment systems, examining their interdependencies, and seeking solutions at and cross levels. Nature provides an immense database of designs that can inspire creative thoughts and provide possible solutions to human complications. The discussion of this cross-level organizational comparison clarifies the similarity and strengthens the understanding of association between the fields of biology and the AEC fields. Taking this into account, an innovative development will inevitably take the direction to a more sustainable and resilient urban systems.

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CHAPTER 5: CONCLUSIONS AND CONTRIBUTIONS

Over the last decades, a great deal of research effort has focused on reducing building energy consumption in order to achieve a more sustainable built environment. The majority of this research considers buildings as stand-alone entities without considering the neighboring buildings within their building networks that may substantially influence thermal-energy performance. The concept of IBE was introduced and discussed within spatially-proximal building networks, but was largely considered as a monolithic effect across building networks (Pisello et al., 2012). Motivated by and building upon previous IBE approaches that studied energy consumption predictions in dense urban building networks, my doctoral research strove to explore, mitigate and optimize the complex mutual influences of the IBE through numerical and empirical analyses for a sustainable and resilient urban built environment.

This research first built upon prior IBE research and building network models (Han et al., 2015b; Pisello et al., 2014, 2012) to contribute a systematic approach to deepen our understanding of the IBE in a dynamic simulation environment by disaggregating the separate and distinct impact from reflection and shading for a more nuanced analysis (Han et al., 2015a). Through cross-regional analysis of a hypothetical building network, I found shading to contribute to increased heating and lighting energy consumption while reflection increased cooling energy required for spatially-proximal buildings. I also identified a consistent trend that shading has a relatively larger contributing to IBE. Larger variations of the energy impact were observed in warmer climatic cities when shading and reflection are disaggregated. The case study in Italy not only interpreted the IBE disaggregation analysis with respect to urban morphology characterization in a realistic urban setting, but also investigated the impact of increasing urban density level. The results demonstrated different and more complicated building energy behavior and the shading effect showed more dominant in denser urban blocks. Those key trends and characteristics due to the influence of mutual shading and mutual reflection identified in this research could help in the search to minimize mutual influences between buildings that lead to increases in energy consumption in urban environments.

By investigating the potential of PCM technology within an inter-building micro-environment to reduce the negative impact on energy use, this research also contributes to the exploration of solutions to mitigate the negative impact by the IBE in dense urban settings. PCMs have been considered as a promising building application to both improve human indoor living comfort and reduce building energy consumption, but are mostly discussed from the perspective of stand-alone buildings (Baetens et al., 2010; Han & Taylor, 2016; Zhou et al., 2012). Under different weather profile of each simulated city, the impact of PCMs was tested through a comparative study by setting the building envelopes of the control building as either conventional or PCM-embedded, by examining different locations of PCM layers, and by testing different types of PCMs. Consistent with a previous empirical study (Jin et al., 2013), I found better performance for inner layer PCM placement and the analysis revealed that vertical building envelopes and roofs are equally important in improving the reference building's thermal-energy performance. Embedding PCMs in both the roof and the wall over the entire building envelope would add 50% improvement by creating a more thermally stable enclosed indoor area. Overall, the results suggest PCM-embedded building envelopes as possible solutions to mitigate negative inter-building influences and improve energy efficiency within urban building networks, especially in temperate cities (Han & Taylor, 2016).

Dense urban settings not only lead to massive energy and resource consumption, but also exert competition for the use of space and facilities (Ng, 2010). How to determine and reach an optimal density level thus become critical in modern urban designs. Since natural systems and built environment systems are both dynamic, highly interdependent and structured hierarchically, a levels-of-organization framework for the built environment was presented inspired from the various levels of organization that exist in nature. Plants have been discussed as role models for buildings. How plants regulate their density level may also provide inspiration in searching for optimal building networks. Last but not least, this research contributes to determine optimal urban building network designs through a bio-inspired endeavor. Inspired by the intra- and inter- specific competition phenomenon from nature (Goldberg & Barton, 1992; Lonsdale, 1990), a model to determine an optimal status of the IBE was discussed an example for how the levels-of-organization framework can help develop ideas and support cross-level assessment. This holistic levels-of-organization framework strengthens our understanding of the similarities and associations between the fields of biology and AEC, and will help promote sustainable and resilient urban growth that better integrates natural and built environment systems at and across levels of organization.

CHAPTER 6: FUTURE WORK

In an effort to reduce the negative impact of buildings on energy use, health, and the environment, my research interests lie at the intersection of an holistic understanding of sustainable building networks and methodologies to reduce energy consumption at the inter-building level. The goal of my doctoral research is to advance our understanding of urban building networks thermal-energy dynamics to achieve sustainable energy conservation in the built environment. Considering buildings as networks rather than as stand-alone entities highlights the inextricably linked and interwoven relationship between urban micro-climates and buildings. With this approach, I strove to explore, mitigate, and optimize the mutual influences of the IBE in dense urban settings through numerical analyses over the last several years. Moving forward, I plan to expand this building network thermal-energy dynamics through multiscale analysis—at the building scale, inter-building scale, and urban regional scale—to achieve higher levels of sustained energy conservation in the built environment utilizing this levels-of-organization framework. Nature is an immense database of designs. Using bioinspiration as an innovative and interdisciplinary research paradigm, I will continue to explore synergies and associations between natural and built environment systems, leading to possible solutions to transform urban buildings through sustainable and resilient building network designs.

At the building scale, strategies for self-adaptive and responsive building retrofit are essentially important to promote energy savings. There is a particular need for this research because 87% of residential buildings and 74% of commercial buildings were built before the year 2000 when rigorous energy regulations were not yet established (U.S. Department of Energy, 2011). To develop an effective and efficient building energy management systems, research at building level needs to be expanded to focus on smart energy monitoring and building operation by integrating smart sensors, building management systems, building information models, and building energy models into building systems.

At the inter-building scale, by coupling and utilizing computational fluid dynamics analysis and micro-climate modeling tools, I plan to continue to build an understanding of the mutual interactions between networks of buildings, as well as to develop interventions to IBEs that favor the energy performance of buildings in different climatological conditions. Solar right and solar access need be evaluated and assessed especially for tall building networks. Empirical studies of scaled building network models using PCMs and retro-reflective materials will be examined at this level. The empirical results can be used to calibrate simulation models that could lead to larger scale analysis for urban thermal-energy management and prediction. Cost-effective analysis will also be conducted in this empirical study guiding practical applications of retrofitting old building networks or designing new urban building networks. In addition to my previous research that mainly focused on mitigating the negatively IBE impact, strategies to harvest on-site renewable energy, e.g. wind, can also be investigated at the inter-building level. By channeling and taking advantage of the IBE, this future research will contribute to the development of net-zero building networks by integrating sustainable building network design with suitable renewable energy harvesting that could offset on-site building energy usage.

Finally, at the urban and regional scales, I will implement the levels-of-organization framework to not only associate building thermal-energy research across different levels but also expand the IBE concept to resource sharing, temporal effect, social and economic impacts, and more in dense urban settings. By transforming my research findings from both the building and inter-building scales and considering human factors, my future research will adopt an holistic view of energy, environmental, economic and social problems to achieve ecologically sustainable and resilient urban systems.

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