A Bio-Inspired Solution
to Mitigate Urban Heat Island Effects

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ABSTRACT

Over the last decade, rapidly growing world energy consumption is leading to supply difficulties, exhaustion of fossil energy resources, and global environmental deterioration. More than one-third of energy expenditure is attributable to buildings. Urbanization is intensifying these trends with tighter spatial interrelationships among buildings. This is escalating building energy consumption due to the mutual impact of buildings on each other and, as a result, exacerbating Urban Heat Island (UHI) effects. I sought solutions to this significant engineering issue from nature, and discovered a similar heat island effect in flowers, namely the “micro-greenhouse effect”. However, a special cooling effect has been observed in a peculiar temperate flower—Galanthus nivalis—which generates cooler intrafloral temperatures. In this research, I studied the special retro-reflectance of the flower petals, which has been suggested as a possible contributor to this cooling effect, and implemented a bio-inspired retro-reflective pattern for building envelopes. I conducted cross-regional energy simulation of building networks in a dynamic simulation environment in order to examine its thermal-energy impact. I found that building surface temperatures dropped considerably when neighboring buildings were retrofitted with my bio-inspired retro-reflective façade. I concluded that my bio-inspired retro-reflective pattern for building envelopes; (1) lessens the reflected heat of solar radiation in spatially-proximal buildings leading to reduced UHI, and (2) reduces the energy required for cooling and, therefore, energy consumption. The research has further implications and contributions on building design, urban planning, development of retro-reflective technology, and environmental conservation.

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1. INTRODUCTION

Over the last decade, rapidly growing world energy expenditure has raised attention and generated concerns. According to the 2013 Key World Energy Statistic [1], 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, CO_2 emissions have doubled. Intensified energy consumption not only causes supply difficulties and exhaustion of fossil energy resources, but also significantly influences the human living environment, triggering global environmental deterioration, including ozone layer depletion, global warming, climate changes, etc. [2]. Contributing to these frightening trends, 32% of total final energy consumption and nearly 40% of primary energy consumption are attributable to buildings [3]. In the United States, nearly half (47.6%) of all energy produced, and three-quarters of electricity is consumed by the building sector every year [4]. Thus, how to achieve a more sustainable built environment has become a major task for engineers, building researchers and energy policy makers.

Urbanization is challenging the efforts to achieve a more sustained built environment and has become a central topic in fast-developing countries over the last several decades [5]. A recent United Nations Report indicated that a significant shift in population from rural areas to urban areas would occur and cause pressure on energy, resources and the environment [6]. Population in urban areas is projected to increase by 72%, from 3.6 billion in 2011 to 6.3 billion in 2050. As a result, it is reasonable to expect the morphology of urban areas to involve much tighter spatial interrelationship among buildings that may exacerbate urban environmental issues.

The existence of an urban heat island (UHI) effect has been documented for over a century [7]. UHI refers to a significantly warmer metropolitan area than its surrounding rural area attributed to human activities. Although such urban heat climates can be considered as a mild offset for some temperate, cold, or high-latitude cites in winter [8], the heat effect would be further intensified in summer days, adding discomfort and increasing the air-conditioning load. Previous research on UHI suggests that this phenomenon is essentially produced by the dense construction surfaces that absorb solar radiation more than natural surfaces, and the anthropic heat flux due to the cooling and heating of the buildings [9, 10]. Thus, urbanization would most likely exaggerate the UHI effect, which will not only influence the health and welfare of urban inhabitants, but also exacerbate global energy concerns. Researchers have argued that such consequence is already occurring [5]. Energy usage in China has been growing dramatically along with the economic boom and population migration in urban areas over the last decade, and China replaced the United States as the largest energy consumer in 2010 [11]. Although measures have been taken to mitigate existing UHI effects [9, 12-15], such as increasing urban thermal mass, expanding evaporative surfaces and vegetation covers, choosing high albedo urban paving and roofs for both their active and passive effects etc., the results are not as encouraging as anticipated.

Urban geometry also plays a particular role in establishing building/urban behaviors. It is difficult to predict building energy performance accurately because simulation tools do not consider the close proximity of other buildings in the urban environment and energy implications that could result. 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 (up to 42% in summer, and up to 22% in winter) for heating and cooling [16, 17]. The research also demonstrates that the energy performance of one building can be significantly impacted by surrounding buildings through mutual reflection and mutual shading. Therefore, in order to deal with denser urban building morphology owing to urbanization, we need more research that examines inter-building relationships from the perspective of heat re-radiation in order to mitigate heat flux under a building canopy. Hence, the objective of this research is to explore solutions for reducing Inter-Building Effects that contribute to UHI effects.

2. THEORETICAL BACKGROUND

While researchers have been researching solutions for reducing energy consumption in the built environment from engineering or architecture perspectives, it is possible that answers may lay hidden in nature. Nature, through a long period of trial and error, may have already solved many of the problems we are struggling with today. Some of the time-tested patterns and solutions in nature may be able to be implemented in the context of the built environment. Thus, it is appropriate to examine examples of how resource constrained problems have been solved by other living organisms or ecosystems under similar conditions. In doing so, we may find solutions that achieve maximal energy performance with minimal resources.

Biomimicry was introduced as an applied science that derives inspiration for solutions to human problems through the study of natural designs, processes and systems [18, 19]. Although widespread and practical application of biomimicry as an architectural design method remains largely unrealized, several biomimicry solutions have already been successfully implemented in building systems [20, 21]. Two approaches have been developed to utilize biomimicry in engineering and architecture, including a problem-based approach and a solution-based approach [22-24]. The solution-based approach is often used when biological knowledge influences human design, which tends to result in novel technologies or systems to arrive at a solution. However, biological research must be conducted to identify a specific trait in an 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 firstly identify problems and then examine ways natural organisms have solved similar issues without an in-depth biological understanding.

I was motivated to find a bio-inspired solution for the UHI that occurs in dense urban settings, and discovered several similarities between building systems and botanical systems, in particular flowers. A building envelope is similar to flower petals; the inter-building area enclosed by building envelopes in close proximity is akin to the intrafloral area encircled by petals; building occupants interact in and among buildings, while pollinators forage inside flowers, etc. Since building occupants are the consumers of energy in buildings [25], I firstly chose to examine how flowers attract and interact with their pollinators. Other than visible characteristics such as being bright, colorful and iridescent, flowers use thermal properties inside the petals to attract pollinators [26], as warmer intrafloral temperatures are essential to floral reproductive success, as well as pollinators' energy efficiency [27, 28]. Some biologists even suggest that pollinators forage for heat rather than food (nectar), while colors and iridescence are only used as cues to visit back to the same flowers [26, 29].

In order to attain elevated temperature as heat rewards to attract pollinators, flowers have evolved different self-thermoregulation capabilities. Many species use heliotropism to increase intrafloral temperature by tracking the sun during daytime [30], others through optical properties of their flower petal [31]. 80% of angiosperms, the most advanced species in the plant kingdom, have conical-shape epidermal cells in the petals, which not only absorb incident light more efficiently, but also act as light-traps for light reflected from both sides [31]. Because flowers typically have warmer intrafloral temperatures than ambient temperature, this phenomenon is also called the "micro-greenhouse effect" by botanists [32]. Similar to the UHI effects of building systems, the floral environment exhibits a heat island effect, but unlike flowers and pollinators who derive benefits from warmer air, the UHI is generally considered a negative phenomenon to be mitigated in cities. Biologists later found that flowers and their pollinators could not afford to invest in warming due to physiological reasons. Research has demonstrated an upper limit temperature for pollinators using an Australian native bee as a model [33], at which temperature point bees choose their target flower and nectar despite the heat rewards.

Researchers have also discovered several cooling mechanisms, such as evaporation at the expense of water and self-shading by their tepals [34], which have also been evolved in flowers under extreme temperatures and locations. I identified one flower in particular with an adapted cooling mechanism. The snowdrop (Galanthus nivalis) is a bell-shaped "hanging flower" with white oblong flowers of about 2-4 cm in length bending to the ground. Research has shown that hanging flowers seem to be capable of collecting energy with significantly warmer intrafloral temperatures since the hung flowers act as traps for rising warm air from the ground [35]. However, a recent study about temperature distribution in light-colored flowers found that the snowdrop flower exhibits a peculiar cooling effect [36]. Infrared cameras were used to detect the exact radiative temperature of the petal surface with high resolution without interfering with either the measured objects or their micro-environment. The measurement showed a uniform temperature which is 2.7 degrees Celsius lower than ambient. Another phenological study in Central Europe also disclosed tendencies toward earlier flowering of Galanthus nivalis [37]. Although no theory yet exists to fully explain the snowdrop's cooling mechanism [36, 38], the special reflective property of the flower petals has been suggested as a possible contributor (Fig. 1).

Figure 1: Retro-reflectant flower petals of Galanthus nivalis

Reflective phenomena are generally classified into three types: specular reflection, diffuse reflection, and retroreflection (Fig. 2). Most building and city envelopes are made of diffuse materials, which means an incident beam is reflected back at many different angles rather than one angle as the case of specular reflection. Unlike specular and diffuse reflection, retroreflection is the phenomenon of light rays striking a surface and being redirected back to the light source. One typical example of retro-reflectance is the illuminated retro-reflectors installed on the back of bicycles for safety purposes to reflect car lights in the dark. The snowdrop flower may have retro-reflective-like microstructures in the petals and use them to reflect solar radiation out of its micro-floral environment in order to retain a cool intrafloral area. Although the visibility properties of retroreflective material has been well studied, the use of this technology is still limited to specific purposes, e.g. improving pavement markings and road signs for safety and illumination [39]. The thermal and heat-transferring characteristics of retro-reflection are still not clear.

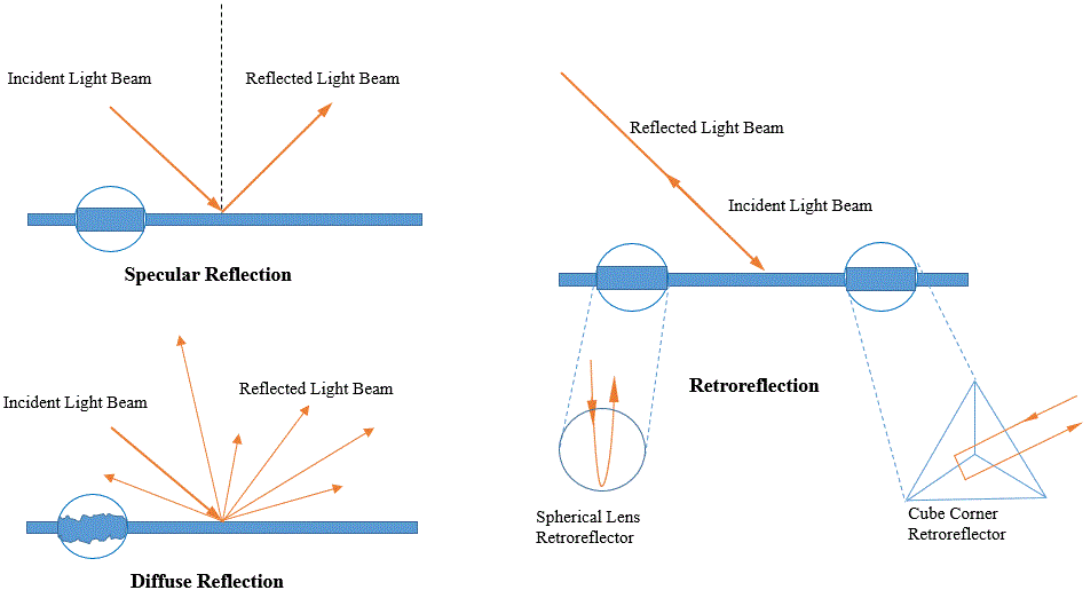


Figure 2: Reflective phenomena: diffuse reflection, specular reflection, and retroreflection. (Adapted from 3M Retroreflective Report 2012)

Retro-reflection is generally achieved through multiple reflections within the retro-reflector through subtle surface designs to direct light back toward the source [40]. Common retro-reflectors (Fig. 2) have either spherical lenses (tiny glass heads) or prismatic elements (cube corner) [39]. While sphere reflectors are better at returning the light somewhat off-axis from the source (improved visibility of road signs), the corner reflectors are more effective in sending the light back to the source over long distances. Moreover, corner reflectors have the property to reflect back toward the source a large portion of the energy incident upon their surfaces, and over an appreciable range of incident angles of the incoming ray. Recent studies have focused on experimental measurement of retro-reflectance and durability of retro-reflective specimens in miniature models [41-44]. Retro-reflectance of commercial retro-reflective samples were measured by subtracting the reflectance using the integrating sphere measurement from total reflectance deduced from the amount of temperature rise by irradiation [42]. The results confirmed the advantage of prism-array sheet samples that exhibited a total reflectance of 71.0% to 77.8%, with 23.5% to 29.5% retro-reflectance, more than two times better than that of beam-embedded sheets (~10%) in terms of retro-reflective property. These studies have led to an increased awareness that building thermal-energy behaviors could be impacted potentially by such reflective characteristics. Nevertheless, we lack research on how retro-reflective surface may impact the surface temperature and energy performance of buildings in dense urban settings. By implementing advanced numerical analysis approaches, this research aims to fill this literature gap by examining whether a retro-reflective building surface plays a role in forming and retaining a cooler intra-area among buildings located in close proximity.

3. METHODOLOGY

3.1 Hypotheses

To answer the research questions inspired by the peculiar thermal and reflective property of the snowdrop flower, two hypotheses were proposed as following,

Hypothesis 1: Retro-reflective building envelopes lead to lower surface temperatures in neighboring buildings where buildings are in close proximity;

Hypothesis 2: Retro-reflective building envelopes lead to reductions in the energy required for cooling in an urban context where buildings are in close proximity.

3.2 Retro-reflective Surface and Simulation Development

In order to meet the needs of increasing the sustainability and energy efficiency of buildings, building energy analysis and dynamic simulation have developed rapidly over the last decades, and have become powerful tools for predicting and improving building energy performance both for research and design purposes [45, 46]. The first step in my simulation effort was to identify a surface design that could be modeled in an energy simulation environment that enables retro-reflective property investigation. The current application of retro-reflectance is to embed micro-level optical retro-reflectors into material surfaces or plastic sheets to improve visibility. Thus, in order to attain similar and substantial retro-reflectance in energy simulation environment, I proposed a macro-scale retro-reflective surface design with an array retro-reflector pattern (Fig. 3). As mentioned above, cubic-corner retro-reflectors are more effective in sending the light back to the source over long distances over an appreciable range of incident angles of the incoming rays. Therefore, I designed my retro-reflective pattern façades such that each unit cell of the pattern was a cubic-corner retro-reflector consisting of three mutually perpendicular plane surfaces.

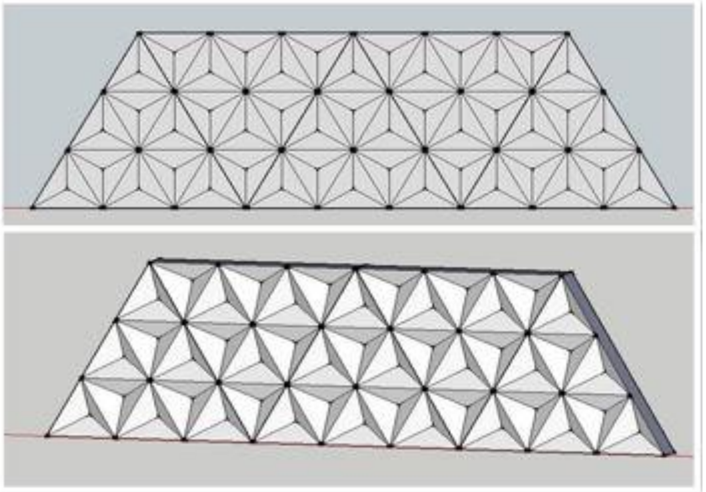


Figure 3: Macro-scale cubic-corner retroreflector array

EnergyPlus is an energy analysis and thermal load simulation engine distributed by the U.S. Department of Energy [46]. Over the last decade, EnergyPlus has become a popular research tool for energy performance simulation [16, 47, 48], and thus was chosen here for the dynamic analysis. To develop a complete and precise simulation utilizing EnergyPlus, detailed information is needed regarding envelope geometries, material and construction, schedules, internal gains, shading surfaces and the HVAC systems [49]. EnergyPlus uses three-dimensional coordinates to define thermal zones and urban geometries such as buildings and shading surfaces. As an essential geometric element of EnergyPlus for shading and reflection, shading surfaces can be considered as neighboring building façades or obstructions, such as building exterior walls, trees, mountains, etc. Shading surfaces can block direct solar radiation and diffuse sky radiation by casting shadows to surrounding buildings. Reflective parameters, glazed or unglazed, could be also assigned on shading surfaces to facilitate solar reflection. The effects of shading and reflection from surrounding obstructions and solar heat gains are accurately computed using detailed surface geometries and the ray-tracing method on receiving surfaces [49].

However, EnergyPlus itself has limited functionalities to facilitate geometric information inputs. When building envelopes with detailed surface patterns are simulated, EnergyPlus not only requires extensive input data and prohibitive running time, but also can result in error-prone analysis. In order to correctly model the geometry of a complex retro-reflective façade design, a graphical third-party application was used. OpenStudio was developed by the National Renewable Energy Laboratory (NREL) as a collection of software tools to support whole building energy modeling using EnergyPlus. Via the OpenStudio plug-in, detailed building envelopes can be visualized and built precisely in a SketchUp interface, while enabling geometric coordinate extraction for EnergyPlus input. For the authenticity of simulation results, information about construction materials, temperature set points, and schedules for lighting, equipment, and occupants were retained from a case study urban residential block [16].

EnergyPlus also has sophisticated functions to model HVAC (Heating, Ventilation and Air Conditioning) systems. Each system component, such as a fan, pump, or cooling coil, can be defined as an individual object, and be connected in loops as the actual HVAC networks of ductwork and piping. For the purpose of studying the HVAC energy consumption of reference buildings, the Ideal Loads Air System setting, an ideal status of HVAC model, was implemented for this study. The Ideal Loads Air System has the conception of "purchased air" which supplies unlimited hot or cold air at predefined temperature and humidity for heating and cooling. Numerical urban thermal information is essential in investigating the UHI phenomenon, but EnergyPlus does not simulate the effects of the urban morphology and environment on local air thermal behavior [49]. The reason is that for each simulation run, the meteorological information such as wind speed, wind direction, and air temperature are directly read from pre-defined weather files, such that we could not examine the UHI effects by directly measuring outdoor dry-bulb temperature in urban canyons. However, the amount of reflected heat in each direction could be estimated by monitoring variations of surface temperatures, which is a proxy for changes in urban thermal behavior.

In order to evaluate and quantify how the proposed retro-reflective property could impact thermal and energy assessments, two case studies were designed to represent the inter-building context. The proposed procedure began with a reference building with a neighboring testing surface in the first case study, followed by year-round simulation of a network of buildings subject to different climatological contexts in the second case study. For each case, a regular plane diffusive wall and a retro-reflective pattern diffusive wall were applied to building exterior façades for separate simulation runs. Based on the comparison of results, it is possible to measure the magnitude of thermal and energy behavior differences.

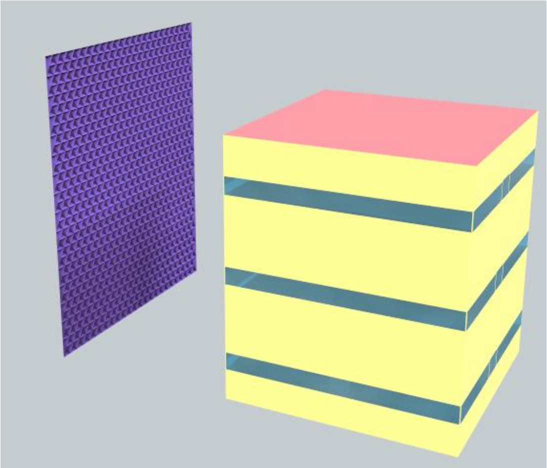


Figure 4: Case study 1: Reference building with testing surface

3.3 Case Study 1: Examining Surface Temperature

The first case study is illustrated in Figure 4, which consisted of a stand-alone reference building and a neighboring testing surface on the west side. The reference building (on the right) was modeled as a three-story building with a square shape of 10 meters per side, while the testing surface (on the left) was represented using a shading surface element in EnergyPlus. The testing surface acted as a neighboring building's exterior wall. Each floor was set as a thermal zone, the unit EnergyPlus uses for heat balance calculation. Construction and material information in terms of thickness, transmittance, thermal capacity and external reflectance were inherited from a previous IBE case study urban block [16]. The east façades of the reference building, opposing to the testing surface, worked as a control surface for the analysis and monitoring process. Figure 5 provides several examples of azimuths of the sun, how the shadows were cast, and how the solar beams were reflected over the course of the simulation. Since the testing surface faced toward the east, the re-directed solar reflection from the shading surface to control surface was analyzed primarily in the morning due to the projection of sunlight. The top and right parts of the testing surface were sunlit in early morning around 7 a.m.; later at 9 a.m., only the bottom part was not directly hit by solar beams; the entire surface was receiving and reflecting solar radiation two hours later. Since surface temperatures were influenced by the amount of solar radiation that was being received, this comparative analysis could be conducted correspondingly by studying the temperature variations of the control surface at different times to test the first hypothesis.

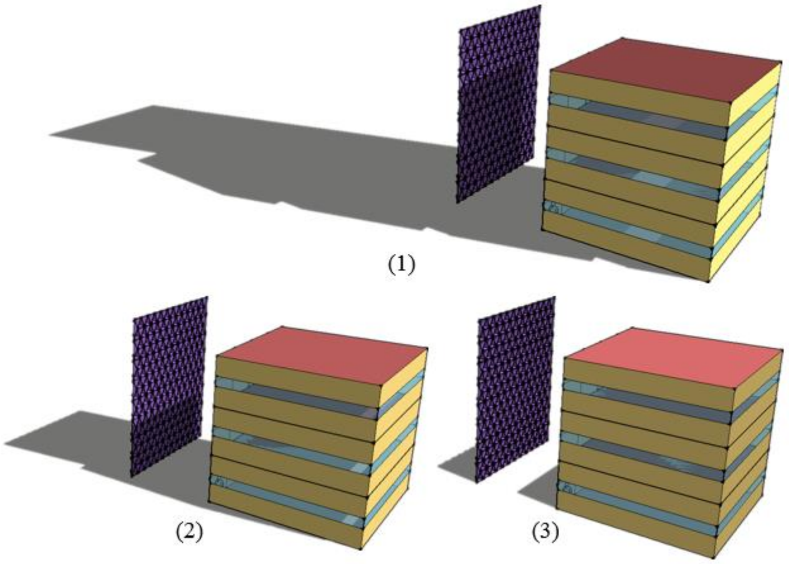


Figure 5: Shading and reflection visualization at (1) 7 a.m., (2) 9 a.m., and (3) 11 a.m. in Case Study 1

In addition to the analysis of temperature differences at specific times, all-day average temperature variations of the control surface were also conducted under two different climatological contexts, Minneapolis, Minnesota and Miami, Florida, as they are the coldest and hottest cities in the United States in terms of average annual temperatures representing two extreme climate conditions. Four typical seasonal dates, January 21st (typical winter day), April 21st (typical spring day), July 21st (typical summer day), and October 21st (typical fall day) were selected to calculate the average value of temperature variation of the control surface in Minneapolis and Miami, respectively. All-day average temperatures were calculated during the daytime (from sunrise to sunset) for each situation when the sunlight could impact the mutual interaction between neighboring buildings.

3.4 Case Study 2: Examining Primary Energy for Heating and Cooling in Realistic Urban Contexts

Unlike the first case study that focused on the examination of dynamic thermal impact of a retro-reflective façade, the second case scenario was aimed at understanding how the energy behavior of the HVAC systems of a building could be influenced when a retro-reflective surface was applied on building envelopes of an entire building network. To test that, I developed a nine-building block within the EnergyPlus modeling environment as shown in Figure 6. The control building was situated in the center of the block, surrounded by eight shading-surface buildings. The morphology of each building was the same for all buildings within the network. Only adjacent building envelopes that could potential influence control building were modelled using retro-reflective façades. In the EnergyPlus simulation environment, secondary reflections are not considered. In other words, solar radiation directed from the control building to the ambient would never return through secondary reflections of its neighboring obstructions in this numerical analysis environment. Thus, to reduce modeling and computational difficulties of thermal zones, the control building surface reflectance was set as 75%. This value was set based on a related study [42], which found that the reflectance in a prism-array retro-reflective sheet is around 71.0%~77.8%.

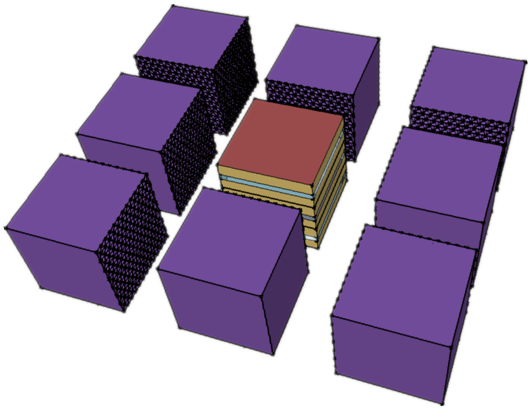


Figure 6: Case Study 2: A network of nine buildings with the control building in the middle of the block

In order to quantify and systematically analyze the retro-reflective effect especially in urban context, the building network simulation was carried out with respect to different real climate conditions. Eight populous cities were selected covering four U.S. census regions (Northeast, Midwest, South, West) and six climate zones [47, 50, 51]: West Region: Los Angeles, CA (zone 2) and San Francisco, CA (zone 3); Midwest Region: Chicago, IL (zone 5) and Minneapolis, MN (zone 6); Northeast Region: New York, NY (zone 4) and Boston, MA (zone 5); and South Region: Houston, TX (zone 2) and Miami, FL (zone 1). The selected cities are ranked within the top 50 cities in the United States. by population and are located in the top 20 metropolitan areas reported by the U.S. Census Bureau. They covered 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. Sixteen more simulations were run in the second case study for the cross-regional analysis. Monthly and annual energy consumption of each individual city were compared regarding heating energy, cooling energy, and total energy consumption of HVAC.

4. ANALYSIS AND RESULTS

4.1 Case Study 1: Impact on Surface Temperatures

In the first cast study, a 15-day period (June 1st – June 15th) was simulated for the initial investigation of the dynamic thermal comparing diffusive to retro-reflective surfaces. Weather data from Miami was input. As a warmer city, I expected it to yield more pronounced outcomes. The control surface of the reference building was broken down into three sections (top, middle, and bottom) and 24 parts for local thermal analysis as marked in Figure 7. The average temperature of each sub-surface was calculated, and the simulation result of the temperature difference is contained in Figure 8 at three different times in the morning (7 a.m., 9 a.m., and 11 a.m.) when solar light could be reflected to the control surface by the testing surface through mutual reflection. In Figure 8, the white histograms represented the temperatures of the control surface when a regular diffusive wall was used as the testing surface; while the solid black histogram bars registered the temperature of a control surface under the retro-reflective context. Although thermal distribution patterns vary in different scenarios, I observed in all instances that temperatures of the control surface dropped considerably.

Figure 7: Control surface breakdown in Case Study 1

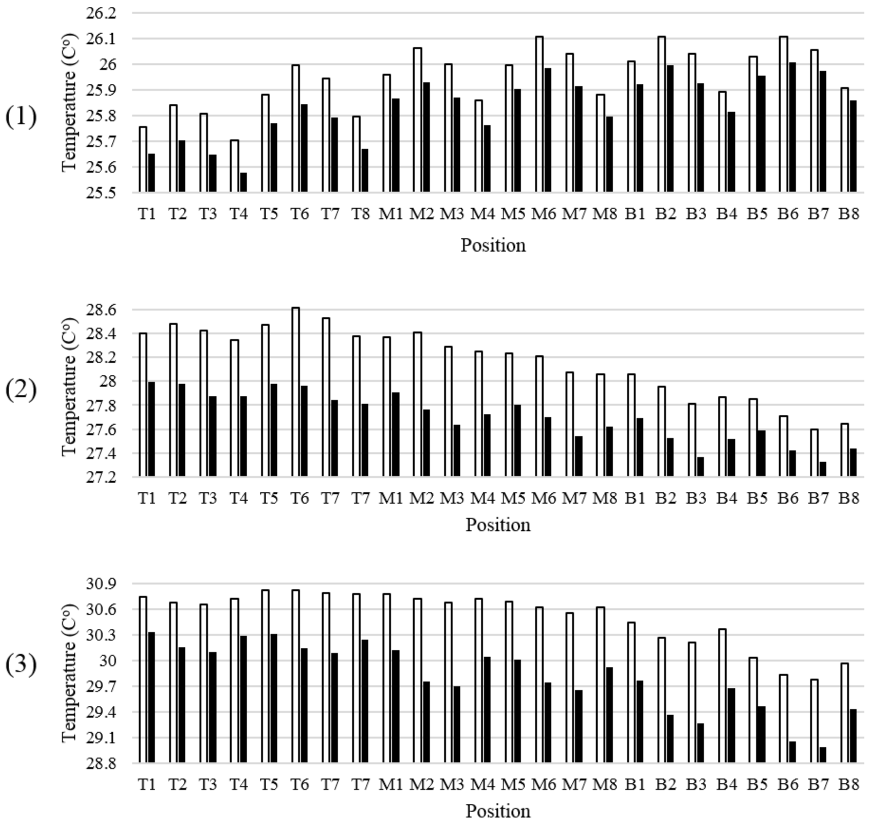
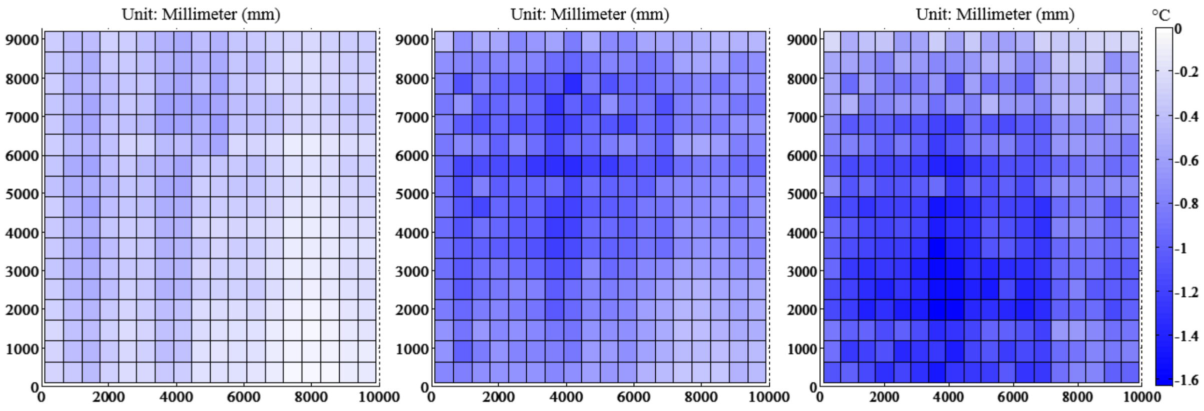


Figure 8: Control surface temperature variations at (1) 7 a.m., (2) 9 a.m., and (3) 11 a.m. (Solid black histograms stand for when retro-reflective pattern diffusive wall was used for the testing surface; Black outlined histograms represent that a regular diffusive wall was used for the testing surface)

In order to better understand this thermal phenomenon, the control building surface was further divided into 324 (18×18) area-equal sub-areas (data points) for higher resolution local comparison and better visualization. The graph in Figure 9 illustrates temperature difference distribution maps which indicate the impact of the retro-reflective property on the thermal behavior of building façades. The lighter parts in Figure 9 represent that no significant thermal variances occurred for different testing surfaces, while the darker blue parts represent that a considerable reduction of temperature occurs when the testing surface was retrofitted with a retro-reflective façade. At 7 a.m., there was little temperature difference at the bottom right part of the control surface, while the top left part started to exhibit a cooling effect. As the sun height rose and more solar beams reached the testing surface, the cool area expanded and moved downwards in the distribution map. This trend is due to the fact that the dynamic thermal behavior of the control building is closely related to the incident angle of solar beams, as the reflected light by the testing surfaces would heat the control surface. The average decrease in temperature of the entire surface was 0.43 degree Celsius, 0.85 degree Celsius, and 0.99 degree Celsius at 7 a.m., 9 a.m. and 11 a.m., respectively. The maximum temperature differences were up to 0.66 degree Celsius at 7 a.m., 1.39 degree Celsius at 9 a.m., and 1.64 degree Celsius at 11 a.m.



(1) (2) (3)

Figure 9: Temperature difference distribution of the control building surface between diffusive and retro-reflective testing façades

Table 1 shows the results of average temperature reductions of the control building surface during daytime at typical seasonal days in Miami and Minneapolis. In both of the two cites, summer days register the highest temperature reductions owing to the longer daylight time and the steeper sunlight angles while typical winter days result in the lowest simulated surface temperature reductions. This observation is further supported by closer inspection of the values for each separate location. Miami has a long summer and a mild winter such that the average reduction of the typical winter day does not differ substantially from the other seasonal days. On the other hand, Minneapolis is characterized by a long, cold winter and a hot, humid summer which is reflected by the more marked differences between winter and summer surface temperatures. It is worth noting that in this simulation I only considered one side of the reference building, the testing surface only played a significant role in roughly half of the daylight hours in affecting the control building surface. For this reason, the all-day average values in Table 1 are not as large as the results of specific times presented earlier in this section.

Table 1: Average temperature reductions of the control building surface during daytime at different typical seasonal days in Miami, FL and Minneapolis, MN (in degrees Celsius)

City	Typical Seasonal Day (Winter) January 21st	Typical Seasonal Day (Spring) April 21st	Typical Seasonal Day (Summer) July 21st	Typical Seasonal Day (Fall) October 21st
Miami	0.32	0.40	0.46	0.37
Minneapolis	0.12	0.40	0.42	0.22

4.2 Case Study 2: Impact on Primary Energy for Heating and Cooling

In order to describe the potential impact of the retro-reflective property on energy behavior, the second case study was carried out in the context of an urban block. Year-round simulation was first conducted under the climatological context of Miami, FL and Minneapolis, MN, the coldest and hottest cities in the United States in terms of average annual temperatures. The monthly simulated results are shown in Table 2 with respect to heating energy and cooling energy consumption by the HVAC systems of the control building. I observed a decrease in cooling loads under hot climates, however, heating consumption was detected to increase somewhat in cold seasons due to less re-directed solar radiation being absorbed by building exterior walls.

Table 2: Monthly HVAC energy consumption in Miami, FL and Minneapolis, MN

	Miami				Minneapolis			
Month	Heating Energy (J)	Cooling Energy (J)	Heating Energy with Retro-reflective Façades (J)	Cooling Energy with Retro-reflective Façades (J)	Heating Energy (J)	Cooling Energy (J)	Heating Energy with Retro-reflective Façades (J)	Cooling Energy with Retro-reflective Façades (J)
Jan.	1.64e4	5.11e9	2.16e5	4.81e9	1.77e10	0	1.79e10	0
Feb.	6.51e6	5.58e9	7.45e6	5.28e9	1.02e10	0	1.05e10	0
Mar.	0	7.41e9	0	6.98e9	5.08e9	8.01e7	5.37e9	6.22e7
Apr.	0	8.78e9	0	8.37e9	2.06e9	1.18e9	2.27e9	1.04e9
May	0	1.06e10	0	1.01e10	9.68e7	4.90e9	1.19e8	4.51e9
Jun.	0	1.10e10	0	1.06e10	1.37e6	7.23e9	1.92e6	6.76e9
Jul.	0	1.19e10	0	1.14e10	0	9.45e9	0	8.99e9
Aug.	0	1.18e10	0	1.14e10	0	7.35e9	0	6.91e9
Sep.	0	1.13e10	0	1.08e10	3.45e8	3.78e9	3.76e8	3.49e9
Oct.	0	1.02e10	0	9.79e9	1.52e9	3.25e8	1.63e9	2.74e8
Nov.	0	7.53e9	0	7.22e9	7.63e9	0	7.78e9	0
Dec.	0	5.22e9	0	4.94e9	1.46e10	0	1.47e10	0
Subtotal	6.53e6	1.06e11	7.67e6	1.02e11	5.93e10	3.43e10	6.06e10	3.20e10
Total	1.06e11		1.02e11		9.36e10		9.27e10	

I then expanded to a cross-regional energy analysis of eight cities. Table 3 includes the results of this analysis. Cooling energy and total energy reductions were calculated specifically in terms of both absolute values (in the unit of kilowatt-hour (kWh)) and relative percentage (%). For each category, the largest observed values are highlighted in bold. From the table we can observe that the cooling energy demand percentage varied from 36% in Minneapolis, MN to almost 100% in Miami, FL of total HVAC energy. As a whole, I found that the total energy consumption and cooling energy consumption were reduced by up to 8.2% and 9.8%, respectively, in different metropolitan areas.

Table 3: Cross-regional comparisons of HVAC energy performance of the control building

Control Building	West		Midwest		South		Northeast	
HVAC Performance	**LA**	**SF**	CHI	MN	**MIA**	**HOU**	BOS	NYC
Cooling Energy Percentage (%)	**99.4**	**93.3**	46.8	36.7	**99.9**	**96.9**	49.4	61.6
Reduced Cooling Energy (kWh)	**1129.2**	840.0	680.4	629.5	**1307.9**	**1068.0**	620.8	730.3
Reduced Cooling Energy (%)	**7.9**	**9.8**	6.5	6.6	4.4	4.9	**6.8**	6.2
Reduced Total Energy (kWh)	**1110.3**	752.8	370.4	259.5	**1307.5**	**1001.2**	302.1	457.0
Reduced Total Energy (%)	**7.7**	**8.2**	1.7	1.0	4.4	**4.4**	1.6	2.4

Los Angeles, CA, Miami, FL, and Houston, TX were the three cities that had the highest values for both cooling energy savings and total energy savings, where more than 96% of energy contributed to the cooling requirement. San Francisco, CA also had a much higher cooling demand (93%) compared to heating, achieving a 9.83% reduction in cooling consumption and 8.22% in total HVAC energy consumption. Although the other four cities from cooler climate zones in the Midwest and Northeast, did not match the improvements of the aforementioned four cities, we still observed reductions in energy consumption for each.

4. DISCUSSION

A great deal of research effort has focused on reducing energy consumption in the built environment due in part to the fact that nearly 40% of primary energy consumption are attributable to buildings and the fact that urban sprawl and the population migration are exacerbating energy concerns [3, 6]. Previous research has identified that building energy performance is influenced by Inter-Building Effects especially in buildings that are in close proximity to each other [16, 17], i.e. through shading and reflection, which also contribute UHI effects that have a negative impact on urban thermal-energy behavior. The research presented in this thesis contributes to this discussion through a bio-inspired endeavor [19, 22]. Driven by the advantages of nature's time-tested patterns and solutions that may be implemented in the context of the built environment, the authors identified a directional reflective phenomenon from retro-reflective flower petals which exhibit a cooling effect [25], and analyzed the thermal and heat-transferring characteristics under the building network context in a dynamic simulation environment.

This thesis contributes a perspective on how a retro-reflective building surface influences the thermal performance of neighboring building envelopes. Based on previous literature that retro-reflectors could direct the solar rays back to the source [39, 42], I expected that less solar radiation would reach the control surface opposing the retro-reflective façade. I designed a case study of a simple one-surface-one-building scenario to examine my first hypothesis. The construction materials and thermal characteristics remained the same to govern the comparative simulation, while the testing surface was modelled with either a diffusive wall or the retro-reflective array pattern. Temperatures were measured and monitored in the control surface. The results in Figure 8 and Table 1 reveal consistent trends of lower surface temperatures of the control building over the course of the simulation period when the testing surface was retrofitted with a retro-reflective façade. Thus I found support for my first hypothesis. Since identical diffusive solar radiation by the sky would reach the control surface under the same simulated weather environment, I am confident to conclude that less solar radiation has reached to the control building owing to the change of the surface design. Figure 9 illustrates how the retro-reflective façade contributes to cooling during the daytime. The cooler part shifts accordingly to the location and height of the sun, which improves the ability of the directional reflective building envelopes to shift the reflected solar radiation outside the urban canopy.

This thesis also contributes a systematic approach to examine retro-reflective building envelopes on building cooling and heating energy performance. Consistent with retro-reflective thermal characteristics in the first case study, less heated building surfaces were expected to lead to reduced cooling energy consumption. As an extension of the investigation of the Inter-Building Effect [16, 17], a second case study was developed as a network of buildings scenario incorporating different real climatological input and realistic local environmental conditions to explore my second hypothesis in terms of building energy behavior. I investigated eight populous cities covering all four Census Regions in the United States and the cross-regional results confirm reductions in building cooling energy over six major climate zones. This outcome is due to mitigated mutual reflection that can negatively impact cooling energy consumption in urban dense settings. However, mutual reflection could also be considered as a mild offset in winter to lessen the heating demand, which is reflected in the simulated results from northern areas which resulted in considerable cooling energy conservation but less HVAC energy savings. Taken as a whole I found support for Hypothesis 2 as energy use reductions were observed in all cities and all regions simulated. This second case study offers a better understanding of the reflection component of the Inter-Building Effect. It is also suggests that retro-reflective building envelopes might have more impact in warmer climatic cities that have longer daylight time and more demand for cooling energy.

The main contribution of this research is the exploration of the directional reflective property on urban thermal dynamics. Highly reflective materials have been studied for possible use as cool roof materials to mitigate UHI effects [52], but high albedo was not advisable on exterior walls because the reflected solar radiation from them would be absorbed by the surroundings. Computer-controlled building panels have also been implemented that could manipulate solar directions by rotating the angle of mirrors to reduce the cooling demanding [53]. However, the mechanical systems of movable panels are complicated to design and build, consume energy, and are costly and time-consuming to maintain. In contrast, retro-reflective building envelopes could enable similar functionality of directional reflection without having any moving parts, thus requiring little maintenance effort. Although current measures of retro-reflective techniques are limited to specific purposes [39], they have been well studied and widely used, which may facilitate implementation in the built environment. Since research already suggested that UHI effects are largely produced due to the fact that more solar radiation is absorbed by construction surfaces than natural surfaces [9, 10], the retro-reflective property could extend the conception of "cool roofs" to vertical urban envelopes [42, 54], i.e. "cool walls", in mitigating UHI effects. As a result, counterbalanced heat effects would foster a comfortable urban living environment reducing negatively impacted mutual reflection in urban areas, and mitigating cooling demands in the built environment.

The purpose of this research was to examine whether retro-reflectance contributes a cooling effect, potentially mitigating UHI effects. The result of the thermal and energy behavior of building networks in this research provide support that UHI effects may be mitigated.

Nevertheless, the modeling and simulation efforts also result in some limitations. The network of buildings modeled only included nine buildings for this preliminary study to keep the research scope reasonable but sufficiently detailed to examine the proposed question. It is possible that larger urban-scale phenomena of retro-reflective surfaces may exist and, if so, were neglected in this research. Given the IBE and UHI effects are likely to be more substantial in a central city area where tall buildings interacted with a spatially proximal building network, the simulated block size and morphology should also be considered in future research. Another limitation is within the simulation environment. Even though EnergyPlus provides a well-developed simulation platform for researchers, it does not support the calculations of secondary reflection which would minimally impact the results. As the simulation tools evolve, these secondary effects should be examined and quantified.

5. CONCLUSIONS

In this thesis, a method for evaluating the thermal and energy performance of urban building networks from a retro-reflective perspective was proposed and described. The initial idea was inspired by the snowdrop flower petal that enables it to escape a similar heat effect as UHI effects in floral world [36]. The research built upon previous approaches that studied the thermal and energy dynamics of inter-building relationships, utilizing the same urban block models to facilitate comparison [16, 17]. Two case studies were established and simulated in the EnergyPlus environment for thermal-energy building assessments. Temperature variations and the dynamic thermal behavior of the control surface in the reference building were first analyzed with a proposed cubic-corner retro-reflective design façade applied to its neighboring building's exterior envelope. The second case study then expanded to a nine building urban block for a systematic cross-regional analysis of building energy performance. The building block was studied in eight different populous metropolitan areas, covering all four census regions and six major climate zones in the United States. The findings of temperature difference distribution demonstrate that building surface temperatures dropped consistently and considerably when neighboring buildings were retrofitted with a retro-reflective façade surface. Moreover, the results revealed reductions of cooling energy consumption under the retro-reflective context for both total energy consumption and cooling energy consumption of HVAC, by up to 8.2% and 9.8% in different metropolitan areas. These thermal and energy behavior results could play an important role in mitigating UHI effects.. This will become increasingly important in the future as buildings in urban areas evolve into tighter spatial relationships triggered by population migration and urbanization.

APPENDIX A: Transfer Matrix of Cubic-Corner Retro-Reflector

Considering an arbitrary incoming ray as a vector $R_0 = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$ hitting to a cubic-corner retro-reflector consisting three mutually perpendicular plane surfaces. If the ray is sent to yz-plane, the x directional component is revered, so the transformation on the vector is $\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ y \\ z \end{pmatrix}$

Which gives us the transformation matrix $T_x = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

Similarly, y directional component and z directional component vector would be reversed when the ray is reflected off xz-plane and xy-plane, respectively, with the transformation matrix

$T_y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ and $T_z = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$.

Thus, emergent ray

$$R_0^{'} = T_x T_y T_z R_0 = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

$$= -\begin{pmatrix} x \\ y \\ z \end{pmatrix} = -R_0$$

With the transfer matrix of cubic-corner reflector $\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$

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