A Novel Approach for Investigating Canopy Heat Island Effects on Building Energy Performance: A Case Study of Center City of Philadelphia, PA

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Keywords: Urban Heat Islands, Building Energy Performance, Weather Data, Local Climate Zones, Urban Weather Generator

Because of the urban heat island (UHI) effect, an urban agglomeration is typically warmer than its surrounding rural area. Today, UHI effects are a global concern and have been observed in cities regardless of their locations and size. These effects threaten the health and productivity of the urban population, moreover, they alter buildings energy performance. The negative impacts of UHI on human welfare have been confirmed broadly during the past decades by several studies. However, the effects of increased temperatures on the energy consumption of buildings still need a comprehensive investigation. Moreover, considering the UHI effects at the early stages of the design process is still not pervasive due to the lack of straightforward and convenient methodologies to include these effects in the estimation process of buildings' energy consumption. To fill the mentioned gaps, a novel methodology of coupling the Local Climate Zones (LCZs) classification system and the Urban Weather Generator (UWG) model is proposed in this study to evaluate the UHI impacts on the energy consumption of various building typologies positioned in different climate zones. The methodology is applied to the most populated area of city of Philadelphia, Center City, and modified Typical Meteorological Year (mTMY) data comprising the canopy heat islands effect in the scale of an urban block or a neighborhood are produced in the format of .epw. The initial results of this study show an average of 2.7 °C temperature difference between existing local climate zones of Center City and reference TMY3 weather data recorded at Philadelphia International Airport during three sequential summer days. The generated weather data then were incorporated into an Urban Building Energy Model (UBEM) to simulate the spatiotemporal differentiation of energy demand for cooling and heating end-uses at each building typology under two scenarios of weather data i.e. mTMY and TMY3 data.

INTRODUCTION

It has been projected that 68% of the global population will be living in cities by 2050 due to a rapid urbanization caused by the gradual shift in the residence of the human population from rural to urban areas.[1] This upstream urbanization has been recognized as an extreme example of land use/cover change that affects climate and hydrological cycles.[2] One of the most documented phenomena of urban climate change caused by urbanization is known as the "urban heat island" (UHI), which conventionally refers to the difference between the urban temperature and corresponding rural or suburban areas.[3] The UHI is one of the most evident anthropogenic interventions on climate, causing higher temperature inside the urban canopy layer (UCL) and threatening the health and productivity of the urban population. The negative impacts of UHI on human welfare have been broadly confirmed during the past decades by several studies.[4,5,6,7]

Moreover, the UHI affects building energy performance through changes of heating and cooling loads. Building energy performance is influenced by ambient temperature, while buildings themselves are one of the principals for changes to their surrounding temperature through their heat and CO_2 emissions into the atmosphere.[8] The results from a series of computational studies on prototype office buildings in 15 climate zones in the U.S. show an average of 17.25% increase in building cooling energy use and an average of 17.04% decrease in building heating energy use.[9] Santamouris & Georgakis[10] proved that heat islands cause a significant reduction (to about 25%) of the coefficient of performance values (COP) of the air conditioning systems for the central area of Athens, Greece. The reduced COP value leads to an increase in the size of the installed systems which in turn intensify peak electricity problems and energy consumption for cooling. Kolokotroni et al.[11] investigated the London Heat Island on energy used for heating and cooling load of a typical air-conditioned office building positioned at 24 different locations within the London Heat Island. Comparing the cooling and heating load of a typical air-conditioned office building, the study found that the urban cooling load is up to 25% higher than the rural load over the year while the annual heating load is reduced by 22%.

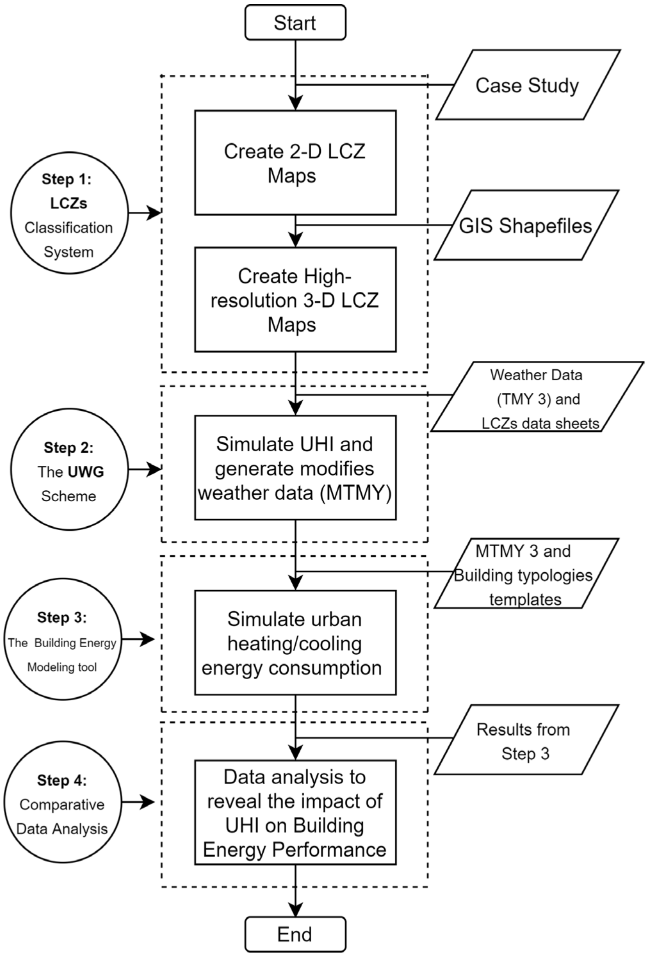

Figure 1. Proposed workflow for the study of UHI impacts on the energy consumption of building typologies located in different climate zones.

PROBLEM STATEMENT

Although the results of the mentioned studies and many more were able to provide an overview of the potential impacts of the UHI on building performance, their approaches in collecting the temperature variation inside the UCL have caused several limitations.

The conventional methods used in the past studies are requiring high computational cost, needing vast efforts on real weather data collection, and in many cases, they only focus on the energy performance of one particular building typology under the UHI effects. Moreover, considering the UHI effects at the early stages of the design process is still not pervasive due to the lack of straightforward and convenient methodologies to include these effects in the estimation process of buildings' energy consumption. Notably, the daily, seasonal, and spatial impacts of the phenomenon on various building typologies need to be studied inclusively. The lack of broad investigation in this realm is more evident when it comes to simulating these impacts on the energy performance of new and existing building typologies, building stocks with characteristic energy-related properties, located in different climate zones. Investigation of the potential UHI effects on a particular building type is essential to clarify the extent of these impacts and provide decision advice regarding the improvement of building energy performance.

Today, building energy simulation is of considerable benefit for architects, engineers, and urban planners. To simulate the energy performance of new constructions and major renovations, standard meteorological databases known as Typical Meteorological Year (TMY) weather data that is weather input files recorded at stations located in open areas, are usually being used in building energy simulation tools. Although TMYs, TMY3[12] in particular, might be the most commonly used weather data for building energy simulation, they are typically recorded at an airport where there are no nearby obstructs and consequently the effects of UHI are not included in this type of weather data. To fill this gap, the Urban Weather Generator (UWG) methodology was introduced by Bueno[8] and developed by Bueno.[13] The UWG model transfers meteorological information from a weather station located in an open area to a particular urban location and it incorporates the built environment impacts on original weather data. The UWG uses EnergyPlus; a building energy model[14], and the Town Energy Balance model.[15] The model calculates the hourly values of urban air temperature and humidity based on rural weather data measured outside a city. The result is a weather file with modified temperatures in the urban canyon. The original version of the model is available in beta, and an architect-friendly and open-source interface of the UWG was recently released by the Ladybug tools team[16] called Dragonfly.

Although the UWG can be mentioned as the most comprehensive canopy/energy model to estimate the UHI, there are still questions remaining regarding the scale of model application. Such as what is the best description of an urban area in a city or region? Or, how does this urban boundary differ from one to another city? Moreover, the model needs a vast amount if inputs for urban characteristics and properties which may not be easily adaptable. The common ground between the UWG and all other mentioned approaches used to measure or model the UHI intensity is called ΔTu-r. It means that the UHI intensity is the temperature difference between urban and rural (ΔTu-r) at standard screen height, inside the urban canopy layer.[17]

Thus, to have the most accurate measurement or simulation of the UHI intensity inside any urban canopy, it is first required to distinguish urban areas inside a city for their physical structure, surface properties, and thermal condition, and second to measure or simulate the UHI intensity inside the canopy level of each area separately. In order to categorize landscapes based on a typical range of values for surface cover, urban structure, fabrics (radiative and thermal properties of

Pennsylvania

City of Philadelphia, PA

Center City, Philadelphia, PA

Figure 2. Location map of the study area, Base maps: Pennsylvania Spatial Data Access (PASDA).

construction materials), and anthropogenic heat flux, the Local Climate Zones (LCZ) classification system was introduced in 2012.[17] The LCZ classification scheme consists of 10 built and 7 land cover types, and each of the 17 basic types is associated with typical value ranges for a set of key urban parameters. The reliability and validity of the system were demonstrated in several studies done in cities from various climatic zones, e.g., Singapore[18]; Colombo, Sri Lanka[19]; Presidente Prudente, Brazil[20]; Phoenix, U.S.[21]; Dublin, Ireland[22], and in Harare metropolitan city, Zimbabwe.[23] So far, the LCZ classification system has only been used by studies that measured the UHI through collecting the real data for temperature and humidity inside the cities, but its efficacy in the UHI simulation processes remained unexplored.

METHODOLOGY

To address the mentioned challenges, this study proposes a novel approach, that couples the UWG model with the LCZ classification system. The combination of the UWG tool with LCZs classification approach will provide a reliable methodology to estimate the UHI intensity at a scale of an LCZ, which is equal to a neighborhood or even an urban block without the need to understanding detailed and profound site meteorology and metadata collection. The entire workflow has been depicted in Figure 1.

In this study, an advanced and parametric workflow using a Grasshopper 3-D, the Meerkat plug-in, and GIS shapefiles is suggested to integrate urban datasets for LCZs map generation. These tools can support maps update in close to real-time because it is possible to import contemporaneous GIS data. The workflow is useful for any location for which GIS data are available and can classify urban areas to LCZs only by using urban morphological parameters retrieved from city GIS (.shp) files.

CASE STUDY

In order to discuss the workflow in more details, the densest and most populated area of Philadelphia, Centre City, was chosen as a study area. Center City is bounded by South Street to the south, the Delaware River to the east, the Schuylkill River to the west, and Vine Street to the north. It comprises 7,900,00 square meters (84,927,326 square feet) and has grown so much over the last 15 years that it now ranks second only to Midtown Manhattan when it comes to people living in the heart of a city.[24] (Figure 2)

The workflow was applied in four steps to - estimate the UHI intensity in an existing urban area, on the one hand- and to explore how these temperature differences will affect building energy performance of different building typologies in the area, on the other hand.

Step 1: 2-D LCZs Map and 3-D LCZs Model

In the first step, to estimate the urban heat island intensity in Center City, the area was first classified based on LCZs dataset sheets. The GIS shapefiles were used to confirm the values of geometric and surface cover properties of each local climate zones and to calculate the value of determining factors of each LCZ class. Figure 3 shows the Standard LCZ classes and LCZ subclasses observed in the area. The 3-D model of the built environment with detail of the near-building environment is required: 1- to provide a more accurate understanding of climate zones properties like building surface fraction, mean

Figure 3. Potential local climate zones in Center city of Philadelphia, PA

building height and aspect ratio (H/W), 2- to be incorporated into the Urban Weather Generator (UWG) to calculate hourly values of urban air temperature and humidity,

To create the 3-D model, Grasshopper 3-D and Meerkat (both Rhinoceros based plug-ins) were employed.[25] The GIS shapefile for the City of Philadelphia buildings (building footprints, elevation, and parcel) and trees canopy was obtained from Pennsylvania Spatial Data Access, Pennsylvania's official public access open geospatial data portal. The 3-D making workflow is useful for any location for which GIS data are available. Moreover, the land uses of the area were analyzed, and the existing function of buildings in the model was assigned to all the existing building of the area (Figure 4).

Step 2: Running Uwg Model to Estimate Urban Canopy Temperature at Each LCZ

In this step, the 3-D model of each LCZ was incorporated separately into the UWG model.

Table 1. Inputs for the UWG model and their adoption methods.

Input	Method adopted
Sky View Factor	LCZ dataset sheets/3D model
Aspect ratio (H/W)	LCZdataset sheets/3-D Model
Building Surface Fraction (BSF)	From LCZ dataset sheets and GIS shapefiles/3-D Model
Impervious Surface fraction (ISF)	LCZ dataset sheets/3D model
Pervious surface fraction (PSF)	LCZ dataset sheets/3D model
Height of Roughness Elements (HRE)	LCZ dataset sheets/3D model
Surface admittance	LCZ dataset sheets/3D model
Albedo	LCZ dataset sheets/3D model
Anthropogenic heat flux	LCZ dataset sheets/3D model

In this study, the version of the UWG plug-in for Rhinoceros called Dragonfly was used. Although the list of input required for the UWG to quantify the most accurate UHI intensity is broad and some of them like anthropogenic heat can be derived from neither the GIS shapefiles nor the TMY data, the LCZs dataset sheets default values of each LCZ will provide an accurate estimation for each zone properties such as surface albedo and anthropogenic heat flux. Table 1 shows the entire sources of input used in the UWG model. Furthermore, Table 2 concludes the properties of each potential LCZ observed in Center City of Philadelphia.

Typical Meteorological Year (TMY 3) recorded at Philadelphia International Airport was used as the reference weather data and hourly dry-bulb temperature inside the .epw file as the reference temperature to estimate the UHI intensity. The UWG model was then run for each LCZ seperately. Each LCZ works as a separated thermal island from adjacent LCZs and consequently has its own weather characteristics. And, the hourly UHI intensity was assumed as the difference between the LCZ temperature and the reference temperature (TMY3). The hourly canopy temperature has a characteristic regime that is most apparent over dry surfaces, on calm, clear nights.[26] To compare the results with the reference weather data, the canopy temperature at a same time (10 pm) in three consecutive days of June with clear sky cover and low wind speed are illustrated in figure 5.

Note that the UHI simulations were run for a calendar year inside each LCZ and the results were produced in .epw format that can be fed into a building energy Model for further investigation of the UHI impacts on buildings energy performance.

Figure 4. The final 3-D model of Centre City, Philadelphia including building functions

Step 3: Simulating Buildings Energy Consumption for Heating and Cooling

To evaluate the impact of the UHI on building energy performance, the prototype building models from the latest version of ASHRAE Standard 90.1 were used and the simulations for each building prototype were run under two scenarios of weather data i.e. with and without the UHI impacts.

Table 2. Properties of LCZs observed in Center city of Philadelphia, PA

	Properties				
	Average Building Height	Site Coverage Ratio	Facade to Site Ratio	Tree Coverage Ratio	Grass Civerage Ratio
LCZ1 Compact High-rise	99	0.64	3.6	0.06	0.01
LCZ12 Comapct High-rise with Compact mid-rise	50	0.68	3.9	0.1	0.07
LCZ2 Compact Mid-rise	20	0.68	1.84	0.19	0.01
LCZ24 Compact Mid-rise with Open High-rise	41	0.71	2.1	0.12	0.03
LCZ5 Open Mid-rise with Open High-rise	28	0.52	0.85	0.05	0.02
LCZ54 Open Mid-rise with Open High-rise	35	0.57	1.11	0.12	0.03
LCZ8 Large Low-rise with Open Medium-rise	17	0.69	0.39	0.05	0.02

The simulations were run in EnergyPlus for one calendar year and only for the prototypes that were found inside each LCZ.

Step 4: Data Analysis to Reveal the UHI Impacts on Building Energy Performance

The results of this study can be explained in two phases i.e. results from the UWG model and the results from the BEM model.

The highest temperature differentiation was recorded in LCZ 1-Compact High-rise, where buildings are very densely spaced with more heights and less tree/grass coverage (Figure 5). Although the lowest temperature differentiation was estimated at LCZ 9- Sparsely Built on June 22, the differentiation of the other two days and the average is still higher than the reference temperatures, which might question the accuracy level of the UWG when the number of buildings is deficient. Overall, results for the local climate zones where the effect of buildings on thermal conditions inside the canopy level is prominent reflects the expected outcome as decreasing average building height and façade to site ratio causes lower temperature differentiation from LCZ 1 to LCZ 8.

The energy performance of all studied building prototypes (ASHRAE Standard 90.1-2019-New Constructions) show different behavior under the two scenarios of weather data. By accounting the UHI-induced temperature, cooling end uses increased, heating end uses decreased, and total energy demand decreased in almost all prototypes except of Large Hotels in LCZ1 and Large Offices in LCZ2. In this particular location (Philadelphia) and climate zone (Mixed-Humid, 4A), the UHI impacts resuslted in decrearase of overall buildings energy consumption, however, the amount of decerease

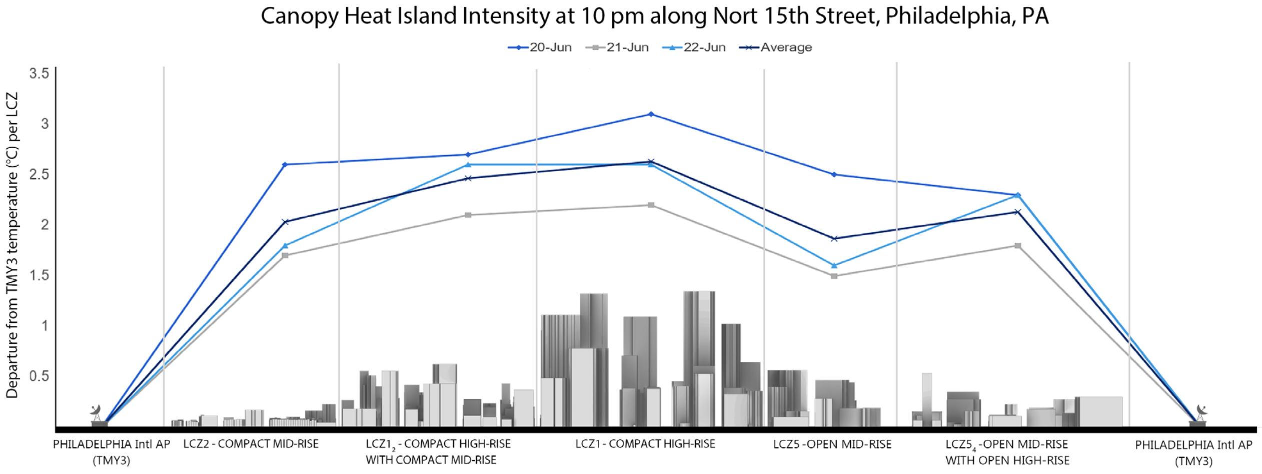

Figure 5. Departure from typical Dry bulb temperature estimated at 10 pm along North 15th Street inside each LCZ.

vary between different building typologies. The significant decrease of heating loads estimated in these prototypes caused the total amount of energy decrease.

In LCZ1, the heating demand showed a decrease in a range of maximum 13% in mid-rise apartments and minimum of 6.5% in large hotels. On the other hand, the cooling demand increased by a maximum of 11.5% in high-rise apartments and a minimum of 1% in large offices. Also, the maximum decrease in total energy demand was recorded at restaurant sit-down by 6% while the total energy demand increased by 0.3% in large hotels of LCZ1. Although the UHI intensity was estimated lower in LCZ2 compared to LCZ1, there are still significant changes in energy performance of buildings located in this zone. Accordingly, small Offices show 13% decrease in heating demand under the UHI impacts while retail strip malls show only 4% decrease. On the other hand, the maximum increase in cooling end uses belonged to restaurant sit-down prototype by 7% and the minimum was for large offices by 1.9%. large offices show a marginal increase of 0.05% in total energy demand while restaurant sit-down shows 4% savings in total energy demand.

CONCLUSION AND FUTURE WORKS

Under the UHI impacts, each building prototype showed a different treatment from the other prototypes. However, only one climate zone and a number of LCZs that found inside Center City of Philadelphia, PA was explored in this study. The study will continue to consider the UHI impact on building energy performance of other cities from different climate zones located across the U.S using the proposed workflow. Moreover, only prototypes for new construction were explored in this study and it is necessary to investigate other building prototype like existing buildings constructed in or after 1980 ("post-1980") and existing buildings constructed before 1980 ("pre-1980").

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the Hamer Center for Community Design, a research arm of Stuckeman School, and the Department of Architecture at the Pennsylvania State University. Also, the authors would like to thank Drs. Gerald Mills, Gregory Pavlak, and Loukas Kalisperis for their valuable insights.

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