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URBAN WEATHER GENERATOR – A NOVEL WORKFLOW FOR INTEGRATING URBAN HEAT ISLAND EFFECT WITHIN URBAN DESIGN PROCESS

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ABSTRACT

It is well known that local urban heat island (UHI) effects impact the urban environment from a public health standpoint and with regards to heating and cooling energy used by buildings. Unfortunately, neither urban planners and designers nor energy consultants currently have quantitative tools or methods at their disposal to incorporate this effect into the design of a neighborhood. This manuscript demonstrates the application of the earlier reported Urban Weather Generator (UWG) model (Bueno et al., 2012a, 2014) as a design tool to provide climate-specific advice for cityscape geometry and land use. UWG estimates local hourly urban canopy air temperature and humidity profiles from measurements at a nearby weather station based on neighborhood-scale energy balances. The morphed temperature output can be used to study the effect of localized UHI on building energy use profiles. To accomplish this, UWG was combined with a parametric simulation module that works either stand-alone or through the urban modeling interface (umi) (Reinhart et al., 2013) in Rhinoceros 3D. The newly proposed workflow is demonstrated through a case study of the MIT East Campus development in Cambridge, MA, USA, that includes the addition of 130,000 m^2 of laboratory space and residences to an existing urban condition. IPCC climate change predictions (Nakicenovic & Swart, 2000) are coupled with UHI to capture local and global heating on the site to promote thermally comfortable and energy-efficient development at each planning phase.

INTRODUCTION

Since 2007 more than half of the human population is living in cities and urban densities are projected to further increase in all major areas except Europe until 2050, with most pronounced increases in Asia and Africa (United Nations, 2004). As cities grow larger and densify, tall buildings fill the open spaces, forming ever-narrower urban canyons while concrete and asphalt surfaces replace natural terrains. These modifications lead to warmer nighttime temperatures in cities than in rural areas, a phenomenon known as urban heat island effect (UHI). UHI tends to be most intense near city centers and has a diurnal pattern, reaching minima in the later afternoon and maxima at night (Oke, 1987). The UHI influences outdoor thermal comfort conditions as well as heating and cooling loads for buildings (Gorsevski et al., 1998). This behavior is observed in numerous field studies around the world, including Nanjing, China (Huang et al., 2008), London, U.K. (Kolokotroni et al., 2012), and for a variety of climate regions (Crawley, 2008). The UHI is logarithmically proportional to population size (Oke, 1987) and is accelerated with the current trend in urban population growth.

Current urban design and planning processes (Besserud and Hussey, 2011) remain rather linear and usually begins with the layout of a street grid and land use patterns without considerations of the resulting changes in microclimatic conditions. Architects and enginers then work on individual building schemes with limited regards for the larger system. This neglect can partially be explained by a lack of planning tools that would support such larger considerations. Notable attempts to model microclimatic conditions include SUNtool (Robinson, 2011), which is based on mass, momentum, and energy conservation equations, and ENVI-MET (2010), which is a 3D model that simulates the surface-plant-air interactions in urban environment. Both of these tools require a graphical user interface (GUI) separate from 3D modelling interfaces used by designers to model massing designs. This presents a limitation for an integrated architectural design with energy considerations, especially when users need to modify or even simplify their building geometries to comply with the energy or UHI simulation platform. In a recent survey of energy modelers and architects by Samuelson et al. (2012), 23 out of 62 participants (37%) answered that the results of energy simulations “rarely” or “occasionally” had impact on design decisions even in AEC (Architecture, Engineering, and Construction) firms which employ in-house energy modelers. This is a direct result of this delayed use of tools within the design process, and therefore it is crucial that we create a tool within the current design platform to encourage early integration of energy and thermal comfort concepts with massing design.

In this manuscript, we propose a new urban design tool with UHI considerations and its implications for thermal comfort and energy. A significant simplification of the user interface for designers is justified via sensitivity analysis of simulation inputs. The new workflow using the tool is demonstrated via a case study in Cambridge, MA, USA.

UWG WORKFLOW

The UHI intensity is a function of how buildings are clustered together in a city, which is why we propose an intervention in the urban design process when the urban canyon forms take shape. The tool is developed as a stand-alone tool and a plug-in for a 3D modeling interface Rhinoceros ("Rhino") (2014) that is widely used by design practitioners and students around the world. Using UWG, designers can develop and evaluate their massing for UHI through a single platform in Rhino. Given the simulation results, they can modify their massing model and repeat these steps as demonstrated in the case study discussed below.

SIMULATION ENGINE & PLATFORM

Urban Weather Generator

Bueno (2012a) developed UWG using a building energy model based on Town Energy Balance scheme (Bueno et al., 2012b) and energy balances applied to control volumes in the urban canopy and boundary layers. UWG calculates the hourly values of urban air temperature and humidity based on reference weather data typically measured outside a city. It requires an EnergyPlus weather (epw) file (2013) and an Extensible Markup Language (xml) file describing the urban and rural site characteristics.

The recent evaluation in Singapore (Bueno et al., 2014) showed a range of land uses, morphological parameters and building usages that the model is able to simulate. It shows satisfactory performance for all weather conditions and for different reference sites. UWG's performance is comparable to a more computationally expensive mesoscale atmospheric model and its relatively fast algorithm makes it appropriate for iterative design tool applications. The simplification and assumptions of the model prevent it from capturing very site-specific microclimate effects, yet it is still robust enough to produce plausible values across urban morphology and vegetation parameters based on validations in three different sites.

umi

Urban Modeling Interface (umi) (version 02.0039; Reinhart, et al, 2013) was developed to streamline the workflow from formal design conceptualization through energy simulation within a single design platform. It is a plug-in tool for Rhino for simulating urban-scale operational energy, walkability, and daylighting. umi's custom toolbar guides the necessary user inputs, requiring minimum training to start using the tool. The energy component uses EnergyPlus (2013) and approximates individual building massings into a discrete number of representative shoebox models to reduce the simulation time (Dogan & Reinhart, 2013). UWG is developed for umi to take advantage of its existing energy component and to complement other aspects of environmental performance simulations.

UWG ARCHITECTURE

User Interface Capabilities

The UI schematically drawn in Figure 1 helps to create the xml input file required by the UWG, run up to six parametric simulations, and evaluate results. A tab-based organization is used in the UI to guide simulation steps and makes clear the hierarchy of information, representing each branch in Figure 1.

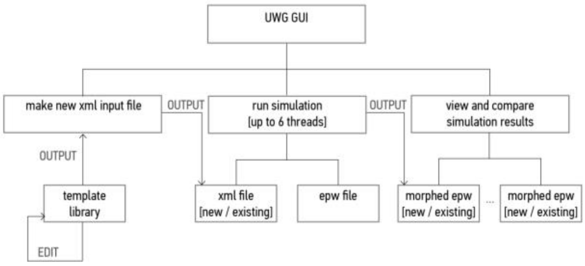
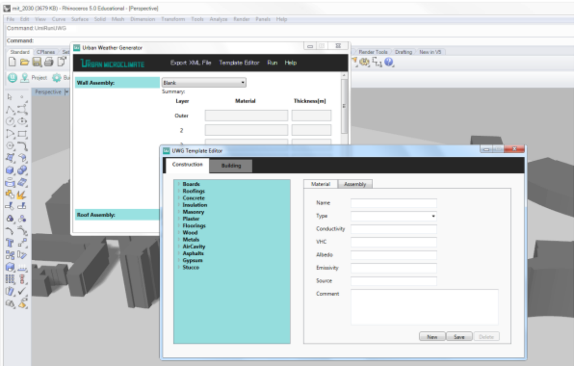


Figure 1 UWG is organized by users' goals

The process of creating the xml file is further broken down into four different parts: (1) building construction; (2) internal loads from occupants, equipment, and lighting; (3) geometric parameters and anthropogenic heat defining the urban space; and (4) information concerning the measurement of the weather data at the rural site. The template library is included to facilitate quick parametric simulations using different building construction, schedules, etc. The UI takes in multiple building templates and weighs their effects on the urban climate by the distribution of building types.

The Rhino version shares a similar UI as the stand-alone version (Figure 2). It takes advantage of Rhino and umi's functions to automatically extract site coverage ratio, façade-to-site ratio, average building height (weighted by building footprint), characteristic length ($\sqrt{\text{site area}}$), as well as average window-to-wall ratio and U-value (weighted by facade area) to further reduce user inputs and the extra step previously required to manually calculate or use Grasshopper definition provided above to obtain these parameters.



Command: UmiRunUWG

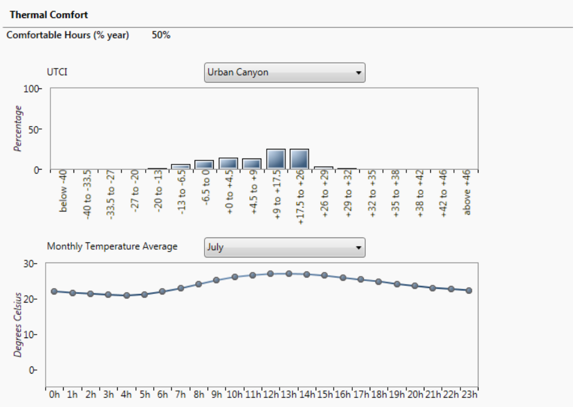
Wall Assembly: Blank

Figure 2 UWG's GUI is invoked inside Rhino by typing "UmiRunUWG" while running an umi project

Results Viewer: Evaluation Metrics

UWG compares up to six simulation runs (Figure 3) based on the UHI (dry bulb temperature change), thermal comfort metric Universal Thermal Climate Index (UTCI) (Bröde et al., 2010), and EnergyPlus energy use estimations (umi version). The monthly diurnal dry-bulb temperatures are used to analyze how UHI shifts the diurnal temperatures for heating and cooling seasons. The heating effect is evaluated based on the temperature difference between the urban and rural reference sites, by comparing the average dry bulb temperatures for each hour in a month.

For calculation of UTCI, the morphed air temperature and relative humidity from UWG are used. The average wind speed in the urban site (city centers with at least 50% of buildings higher than 25m) is about a quarter of the wind velocity measured at the reference site (ASHRAE Handbook of Fundamentals, 2013). The MRT is estimated from radiant temperatures for the sky, wall, and road calculated within UWG. The view factors (ASHRAE Handbook of Fundamentals, 2013) are calculated for a person standing on the sidewalk (middle of the sidewalk with a width of 1.53m (U.S. Department of Transportation Federal Highway Administration, 2014)) as well as in the middle of the canyon (i.e. for campus planning and parks). We use an algorithm developed by Cannistraro et al. (1992) to fit Fänger (1982)'s view factor graphs for horizontal and vertical rectangular surfaces for a standing person at 1.1m. The calculated values conform to those using Fänger's method. We expand the UTCI bins (Bröde et al., 2010) to 18 bins because UHI and climate change are approximately 2˚C – 5.4˚C and the standard UTCI bin sizes are too large.



Thermal Comfort

Comfortable Hours (% year) 50%

Figure 3 Results viewer for the stand-alone version compares annual UTCI (on the sidewalk and in the center of the urban canyon.) and monthly air temperatures

SENSITIVITY ANALYSIS

As UWG requires over 50 parameters, sensitivity analysis is performed to identify the most important parameters and reduce the number of user inputs. The goal of the sensitivity analysis is two-fold: (1) test significance of parameters that are of high interest to urban designers and planners, such as massing and land use, as well as (2) ensure that the inputs that are not readily available (i.e. meteorological parameters) can be approximated by existing measurements.

An earlier study for Toulouse and Basel (mild climates) (Bueno et al., 2012a) showed that site coverage ratio (= total building footprint/ site area), façade-to-site ratio (= total façade area/ site area), and vegetation are the most sensitive parameters for UHI. Additional studies for Punggol, Singapore (tropical, residential district) and Boston Financial District, MA (cold, commercial and densest district in Boston) are conducted to determine the most effective design strategies for each climate. If a parameter does not seem to be significant across all investigated climates, it can be given a default value for the GUI. On the other hand, if a parameter is relevant in even one climate, it should be considered relevant and thus be a required input. The Boston parametric study is documented here. Readers are referred to Nakano (2015) for Singapore study setup and results.

Setup and Metrics

Each parameter is changed one at a time and its simulation result is evaluated against the base case for its impact on temperature and energy use. The base case is the urban epw file generated using actual values for the Boston Financial District. Urban morphology data is extracted from geographic information system (ESRI, 2014) data using Grasshopper (Davidson, 2015) (our definition available at http://urbanmicroclimate.scripts.mit.edu). The anthropogenic heat input is estimated as the vehicular contribution of anthropogenic heat flux (Sailor, 2011) for compact high rise neighborhoods based on Stewart and Oke's Urban Classification (2012). The meteorological parameters such as boundary layer heights (500, 700 1000m for low, base, and high cases) are based on available data from Toulouse and Basel (Bueno et al., 2012a) as these measurements are not available for Boston. Building construction materials and schedules are obtained from the U.S. Department of Energy (US DOE)'s Commercial Reference Buildings (n.d.) for small office in Boston. We use "USA_MA_Boston-Logan.Intl.AP.725090_TMY3.epw" (US DOE, 2013) as the reference weather file. Rural vegetation and obstacle height are estimated from satellite images. Following weather morphing using UWG, energy implications are measured using EnergyPlus (2013).

Four metrics are compared against the urban base case to measure the UHI sensitivity: (a) temperature change of over 0.5K from the original for more than 0.5% of the 8760 hours in a year, (b) percent change in annual heating and cooling energy use, (c) percent change in winter (November – January) heating energy consumption, and (d) percent change in summer (June – August) cooling energy consumption. For energy metrics b – c, a pararameter is significant if the difference is greater than 2.0% compared to the base case. The cutoffs are set up to give stringent criteria to maeaure the parameter's relevance to UHI. If it

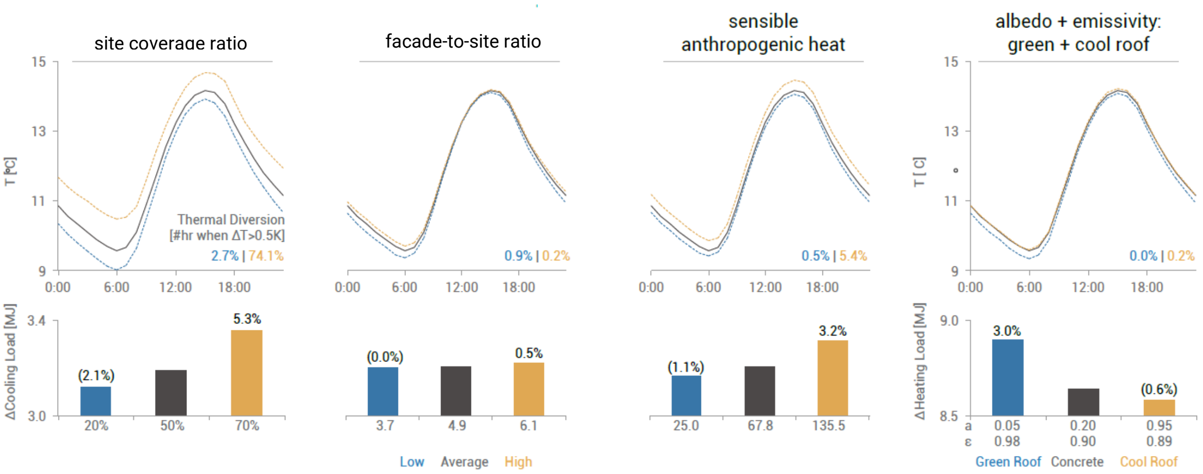


Figure 4 Site coverage ratio, façade-to-site ratio, anthropogenic heat, and roof materials are important for UHI in Boston

exceeds any metric for either low or high end of the sensitivity range, a parameter is significant.

Results

Site coverage ratio, façade-to-site ratio, anthropogenic heat, and roof materials are important for UHI in Boston (Figure 4) and Singapore, similar to the earlier studies in Toulouse and Basel. The site coverage ratio affects canyon width and it is the most important parameter for Boston and Punggol, Singapore, especially at night. The façade-to-site ratio describes the canyon height in the UWG model and thus solar radiation received by building façade. It is not significant for Punggol, perhaps because the variations were too small for the low and high ranges. The sensible anthropogenic heat comes mostly from traffic, and it affects the thermal comfort in the late afternoon and at night. The effects of using green and cool roofs are preliminarily tested via parametric studies for albedo and emissivity (values in Figure 4). In particular, green roofs affect the urban sensible heat flux into the urban boundary layer at night.

The consistency of results reduced required user inputs to the model by 46% without decreasing the simulation accuracy. The UI thus asks user inputs for these key parameters and vegetation (urban tree coverage) that is important for the European cities. Other user inputs include morphological parameters such as average urban building and rural obstacle heights (site-specific and easily obtainable) as well as building constructions and schedules (constants in the sensitivity analysis). Default values are assigned to parameters with small contributions to the UHI and they are moved to the Advanced Setting in the UI to facilitate quick simulation setup for even novice users. The advanced users who are familiar with urban heat flow and thermodynamics are able to change these values from the Advanced Setting expander or directly from the xml files to fine-tune their assumptions.

Authors found that the daytime boundary layer height has a small effect on the UHI. Compared to the base case, the thermal diversion (of greater than 0.5K) was only 0.1% and 0.0% of the year (metric a) and cooling load differed by 0.6% and 0.7% in the summer (metric d) for the low and high cases, respectively. The "reference height at which vertical profile of potential temperature is assumed uniform" seemed to affect the UHI for Boston. For cities with high wind velocities, advection can play a relevant role in the energy balance of the urban boundary layer. This represents a limitation for UWG and the parameter is left accessible in the UI via Advanced Setting.

CASE STUDY

Context and Design Schemes

The East Campus urban design study is part of the MIT 2030 initiative (MIT 2030 East Campus Urban Design Study, 2014) that aims to improve the MIT campus and Kendall Square to meet future academic and research needs. The vision is to create a gateway to Kendall Square to enhance connection and foster innovation between MIT and commercial partners. We propose an alternative to MIT's development plan by incorporating outdoor thermal comfort as one of the drivers for the urban design process. Similar to MIT's case, the goal is to strengthen the identity of the campus and create an inviting gateway to MIT from Kendall Square and subway station towards the waterfront through the open public space on the site.

Table 1 summarizes the two main schemes with parametric variations of the morphological parameters and insulations. The new Connection scheme aims to envelope the open space better. Shorter buildings at the gateway create a more welcoming arrival experience to the campus and create a sense of openness and connectivity to Kendall Square. This opening is also oriented towards the summer breeze direction for natural ventilation (not modeled as UWG does not currently consider it). The strategies focus on average building height, site coverage ratio, and façade-to-site ratio, which are known to affect the UHI based on the sensitivity analysis. Each simulation result guides the direction for the new alternative. The final alternative also explores the effect of using green roofs. The same Logan Airport weather file as the sensitivity analysis is used as the reference epw file.

In this paper, we present the summarized results. Nakano (2015) shows complete sets of results and setup for each case.

Table 1 Summary of the building characteristics for each alternative to the current campus and planned MIT design

	Avg bldg. height [m]	Avg site coverage ratio	Avg façade-to-site ratio
Current MIT campus	30.52	0.36	1.19
MIT's plan	34.26	0.48	2.52
Alt 1: MIT scheme - high rise	41.16	0.40	2.33
Alt 2: MIT scheme - low rise	29.41	0.53	2.43
Alt 3: MIT scheme - better insulation	30.52	0.36	1.19
Alt 4: Connection scheme	35.65	0.43	2.31
Alt 5: Connection scheme - low rise	34.61	0.47	2.31
Alt 6: Connection scheme - increased insulation and vegetation	34.61	0.47	2.31

Thermal Comfort Results

The diurnal UHI intensities are compared against the current campus in Figure 5. The minimum and maximum UHI intensities are -0.1K and 0.4K for the summer and 0.2K and 0.7K for the winter. The negative values indicate that there is urban cooling between the hours of 9am – 1pm in July for all cases. This is expected because much of the parking lot (concrete) is replaced by vegetation. Alternative 2 has the most cooling effect possibly because urban canyon height is short and thus heat can easily escape from the urban canyon. Based on the result from this simulation, the future schemes explore shorter urban canyon heights. This is exactly done for Alternatives 5 and 6, which are derivatives of Alternative 4. Each iteration (except for case 2) show improvements from the MIT case, which represents the current urban design process and does not account for the UHI.

Alternative 6 achieves urban cooling via shorter canyon heights as well as through cool roof and increased vegetation and shading on the streets. We also observe that urban cooling is greater for cases with higher levels of insulation (Alternatives 3 and 6) because the building construction is improved on average when new buildings with more insulation replace old buildings. Case 6 (cyan) has the least amount of urban heating in the summer from 3pm – 9pm and the third smallest increase in the winter. Boston has the highest dry bulb temperatures in July, so the effect of urban heating/cooling is more relevant in the summer months than in the winter. We select Alternative 6 as our best design for improving the thermal comfort. We note that the UI can visualize monthly results, but we show here the compiled July and December results for the purpose of the study. In Figure 6, we observe a small shift in annual UTCI.

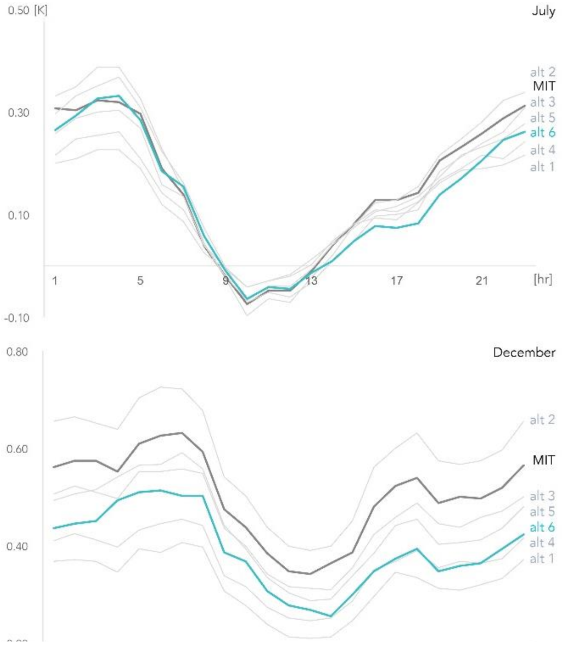


Figure 5 Comparison of UHI intensity against the current campus. MIT case in black and selected case 6 in cyan

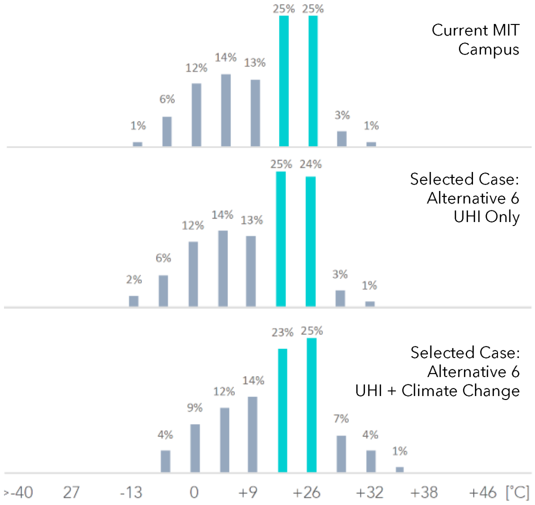


Figure 6 Annual UTCI histograms. No thermal stress between +9 < T < 26 C˚ (in cyan). Climate change and UHI are combined (bottom, discussed below)

Energy Performance Results

The energy demand values from umi are shown in Table 2. They are the normalized energy demand for heating and cooling loads for the new buildings representing a mix of 51.6% lab, 29.8% commercial, and 18.6% residential buildings. The estimations for each program are in line with energy consumption of the template buildings for 2008 – 2012 provided by the MIT Department of Facilities (Nakano, 2015).

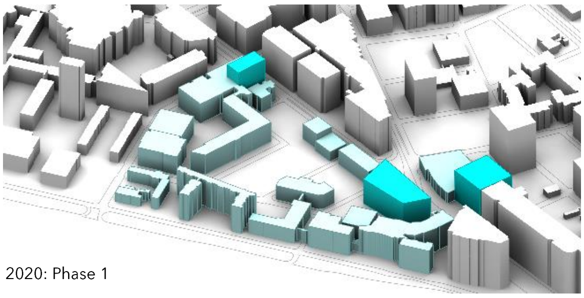
Table 2 Heating and cooling energy simulation results from umi for each scenario, in kWh/m^2

		Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6
Heating	429.32	415.65	359.33	369.61	427.46	408.98	407.85
Cooling	45.60	46.23	36.57	34.47	44.39	41.39	41.31
Total	474.92	461.88	395.89	404.08	471.84	450.38	449.16

The comparisons of the MIT design with each of the variations (alternatives 1 – 3) reveal the following effects of changing the urban design parameters. Alt 1 (MIT scheme with high rise) has lower cooling energy consumption than the MIT case possibly due to the increase in open green space. Alt 2 (MIT scheme with low rise) is the extreme case for minimizing the average building height. It has the lowest energy consumption for heating because buildings do not shade each other. Alt 3 (MIT design with increased insulation) improves the energy performance as expected. These observations show that shorter buildings, open space (to mitigate shading), and façade insulations are effective strategies for improving the energy performance. Alternatives 4 – 6 test the same strategies and see the reduction in energy consumption as insulation levels are increased and average building heights are reduced.

We note here that the insulation levels tested are for demonstrative purposes and should be refined further in the individual building design phase. Furthermore, energy consumption in turn affects the UHI, so we recommend continuing to use UWG in that stage to get a more accurate estimation of the UHI.

Based on the simulation results, we recommend Alternative 6 for improved thermal comfort particularly because urban heating is minimized during prolonged summer afternoons when cooling is most desired. Figure 7 shows the suggested phasing plan. The development of graduate housing space is prioritized in the first phase to meet student housing demand. The demolition of existing buildings and the conversion of parking lot space to green space happens during this stage as well. In phase 2, labs and commercial programs are built.


2020: Phase 1

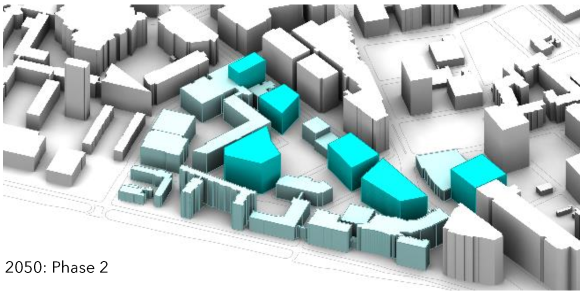

2050: Phase 2

Figure 7 Phasing plan for proposed alternative (Alt 6)

Application: UHI with Climate Change

Urban heating is the local and direct heating effect from urbanization. Here we discuss UHI in combination with the global heating effect – climate change – to holistically capture urban thermal comfort and energy consumption over time. Specifically we will evaluate the recommended Alternative 6 (Figure 7) at each phase to ensure a thermally comfortable campus throughout the urban development. We assume phase 1 is in 2020 and phase 2 in 2050. This evaluation also represents an application of how UWG can be used in conjunction with other tools towards a more holistic urban design process.

We utilize the climate change world weather file generator (CCWorldWeatherGen, 2008; Jentsch, James, Bourikas, & Bahaj, 2013) to morph an existing epw file for Intergovernmental Panel on Climate Change (IPCC) medium to high emissions scenario (A2) (Nakicenovic & Swart, 2000). The monthly average dry bulb temperatures in East Campus in 2020 and 2050 are shown in Figure 8. Compared to the current MIT campus in 2015, the annual average temperature increases are 0.9K by 2020 and 2.2K by 2050. The increases are most prominent for the summer and winter months.

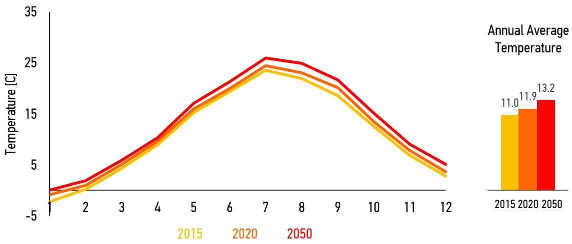


Figure 8 Monthly average temperature for East Campus using IPCC-A2 scenario

We use the morphed weather file from CCWorldWeatherGen in the UWG simulation to incorporate both climate change and UHI. Figure 9 breaks out the contributions of UHI and climate change on urban average monthly dry bulb temperature profiles from 2015 base (Boston Logan Airport reference site) to the current East Campus (UHI only) then to 2020 and 2050. Compared to the East Campus today, 1˚C increase in urban heating is predicted by 2020 and 2 – 3˚C increase by 2050. The average annual temperature is projected to increase from 11.3˚C to 13.5˚C between 2015 and 2050 in the East Campus when UHI and climate change are considered. The predicted maximum and minimum monthly average temperatures on our site in 2050 are 26.1˚C and 0.5˚C, respectively.

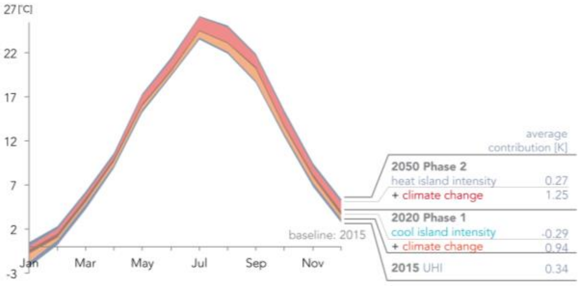


Figure 9 Changes in urban dry bulb temperatures from 2015 (Logan Airport) through 2050

In addition, we observe from Figure 9 that the average contribution of UHI is about a tenth of that from the climate change. The urban cooling in 2020 is most likely from the increase in open space (i.e. the urban canyon is wider and less heat is trapped) as some existing buildings are removed. In other words, the climate change is mitigated via a local change in the site morphology.

There is an upward shift in the UTCI histogram as seen in Figure 6. The hours above "no thermal stress" increase from 5% to 12% in 2050 compared to the current campus in 2015. The hourly count of the thermally comfortable hours (i.e. no heat stress) decreases by 2% by 2050.

This case study demonstrated the methodology to improve thermal comfort and energy performance of an urban development through a change in the urban morphology. Other aspects of environmental performance such as daylighting, mobility, and embodied energy should be considered for a complete evaluation of the performative urban design.

CONCLUSION

This manuscript introduced the new workflow for an urban design process with thermal comfort and energy considerations. The stand-alone and Rhino-integrated versions are created for different types of users, namely energy consultants and urban designers, respectively, to promote early integration of the urban heating considerations in the urban design process. The sensitivity analysis allowed us to identify the key parameters for UHI: site coverage ratio, façade-to-site ratio, and sensible anthropogenic heat, which are planned during the masterplanning phase of the urban design process. As a result, the UI is simplified and users can quickly set up, run, and compare their simulations. The case study for the MIT East Campus demonstrated how the tool can be used to design a thermally comfortable and energy efficient campus through an iterative design process focused on improving these key parameters.

Current limitations pertain to the simulation engines and the UI. The UWG's algorithm only morphs the dry bulb temperatures and relative humidity. In the calculation of UTCI, the urban wind velocity is an estimation of that of the undisturbed wind approaching a building in the urban site and does not capture the turbulence inside the street canyon. The impact of natural ventilation and window shading system is not yet included in the UWG algorithm. In addition, the energy simulation uses "shoebox" representation of zoning (Dogan & Reinhart, 2013) in the umi version of the tool. The results provide sensible results based on the author's experience, and it is in the process of being validated for modeling neighborhood-scale simulations. Furthermore, UI design is an iterative process that can be improved with additions of new features and further user testing. So far, two versions have been released and tested with twelve potential users. Currently the template editors for umi and UWG use different data structures. Sharing of the building template libraries would increase the tool efficiency and promote faster simulation setup.

Nonetheless, with this tool urban designers can articulate their designs with microclimatic conditions and parametrically test built densities and vegetation for masterplanning within their familiar workflow. Urban planners can advocate zoning regulations for building height and land use as well as policies for traffic intensity and cool and green roofs with energy and thermal implications. Finally, when used in conjunction with energy simulation tools, urban energy consumption predictions are improved compared to our current practice of using weather files from rural weather stations that do not reflect the microclimatic conditions of the urban sites. The initial version of UWG is available for download free-of-charge at http://urbanmicroclimate.scripts.mit.edu and will also be available in the next release of umi at http://urbanmodellinginterface.ning.com.

GLOSSARY OF TERMS

façade-to-site ratio = ratio of the vertical surface area (walls) to the urban plan area. Formally called vertical to horizontal urban area ratio in Bueno et al. (2012a)

site coverage ratio = ratio that describes how close buildings are built (building footprint/ site area). This is similar to lot coverage ratio in the New York Department of City Planning (2011) and is renamed from horizontal building density (Bueno et al., 2012a) to be aligned with existing zoning terms that are familiar to urban designers

ACKNOWLEDGMENT

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