UMI - AN URBAN SIMULATION ENVIRONMENT FOR BUILDING ENERGY USE, DAYLIGHTING AND WALKABILITY

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ABSTRACT

One widely recognized opportunity to reduce global carbon emissions is to make urban neighborhoods more resource efficient. Significant effort has hence gone into developing computer-based design tools to ensure that individual buildings use less energy. While these tools are increasingly used in practice, they currently do not allow design teams to model groups of dozens or hundreds of buildings effectively, which is why a growing number of research teams are working on dedicated urban modeling tools. Many of these teams concentrate on isolated sustainable performance aspects such as operational building energy use or transportation; however, limited progress has been made on integrating multiple performance aspects into one tool and/or on penetrating urban design education and practice. In this paper a new Rhinoceros-based urban modeling design tool called umi is presented which allows users to carry out operational energy, daylighting and walkability evaluations of complete neighborhoods. The underlying simulation engines are EnergyPlus, Radiance/Daysim as well as a series of Grasshopper and Python scripts. Technical details of umi along with a case study of a mixed use development in Boston are documented.

INTRODUCTION

Sometime in 2007, for the first time in history, fifty percent of humans were living in urban areas (UN Population Fund, 2007). *Homo sapiens* became *homo urbanus* (Grimond 2007). Over the next two decades, the United Nations expects that we need to plan, design and build new homes for 1.7 billion people, "most of them among the poorest and most vulnerable". With buildings already accounting for some 40% of carbon emissions in many countries, the prospect of adding such titanic numbers to the built environment is worrisome. If we further add a 40% world-wide increase in transportation related carbon emissions (WBCSD 2004), any energy efficiency measures realized to date will be negated. There is an undeniable need for concepts and solutions that lead to more sustainable urban growth, concepts that work across a range of climates and cultures. Measures of success are relatively easy to define: A neighborhood needs to be economically and socially viable so that people want to live there and have low overall carbon emissions so that we can all sustain our lifestyle.

What role can the building performance simulation community play within this context? Over the past forty years we have made significant progress measuring, modeling, and manipulating heat and mass flows entering and leaving buildings to the point where current state-of-the-art simulation engines – if operated by qualified professionals – can predict annual future energy use of standard constructions within 10 percent. Prominent green building rating systems such as LEED rely on modern energy simulation engines for design and verification. Yet, despite these positive developments, energy modeling practice has to date only penetrated a fraction of new building construction. One recognized obstacle is a severe shortage of trained building simulationists. Professional organizations and universities are trying to address this issue (ASHRAE/IBPSA-USA/IESNA, 2012). Nevertheless, even if the number of energy modelers was to rise substantially over the coming years, there would remain many projects, especially in areas in which most urban growth will occur, that will not be able to afford an architect, let alone a building modeler. One way for building performance simulation programs to have a larger impact is to expand the urban performance simulation user group to urban planners and municipalities that may use the tools for generating higher level planning guidelines. For that to happen, tools are needed that effectively model multiple buildings. Interestingly, as one expands from individual to groups of buildings, weaknesses of existing simulation engines become more apparent such as difficulties to reliably model microclimatic effects including urban heat island and local wind conditions. Finally, as one's focus expands to the urban scale, operational energy use becomes but one concern with questions such as local transportation mode choices, access to daylight and outdoor comfort conditions equally competing for the designer's attention.

Based on these observations, the authors determined a need for a new generation of urban performance simulation tools that are able to efficiently model multiple buildings, approximate microclimatic effects and consider multiple sustainable performance metrics. This manuscript documents the development

such a tool. The tool, called *umi*, is an urban modeling design platform with capabilities to evaluate operational building energy use, sustainable transportation choices, daylighting and outdoor comfort at the neighborhood and city level. Operational energy and sustainable transportation were chosen since they constitute two dominant urban carbon emission factors. Daylighting and outdoor comfort are indicators for resident comfort and wellbeing. Focus users for umi are architects and planners working at urban level projects as well as municipalities interested in retrofitting their existing building stock. The objective of umi is to give users access to meaningful information that facilitates design interventions at the neighborhood, street and building scale.

Following a review of previous urban modeling efforts, the different simulation modules in umi are described, and example outputs are shown for a hypothetical mixed use development in Boston, MA, USA.

PREVIOUS EFFORTS

The concept of understanding cities better by modeling them is not new. The classic video game SimCity by Will Wright, arguably constituted the first successful effort to allow non-experts to model the effects of urban planning decisions on "citizens' happiness". Today's SimCity 4 environment allows players (among a plethora of other measures) to install electricity from wind and PV within their jurisdiction and as well as to implement public transportation, bike-only streets and energy-efficient building codes (Maxis 2013). To support their choice, players are provided with high quality 3D renderings and data visualizations. Another remarkable urban platform is ESRI's CityEngine, a commercial tool that generates detailed three dimensional urban scenes based on two dimensional geographic information system (GIS) databases (ESRI 2013). Intended users are urban planners and architects who may use the tool to communicate their designs as well as game developers. Holistic City Software offers CityCAD, a CAD environment for urban master planning. The aforementioned tools emphasize user experience and data reporting, but they currently offer only limited quantitative environmental building performance simulation analysis beyond direct shading studies.

There are long standing research and practice attempts to model larger scale urban performance measures such as land use combined with transportation. UrbanSim is a modeling environment used for this purpose that has been under active development for close to two decades and that has been applied to a number cities in the US and elsewhere (Waddell 2002, 2011).The focus user group in the US for these type of planning models are Metropolitan Planning Organizations, environmental organizations, real estate developers and community

shareholders. These models tend to go down to the urban zone or parcel level as the smallest unit.

As described by Swan and Ugursal (2009), there are generally two types of model categories used to model the energy use of parts or all of a country's or region's building stock: top down and bottom up. Top down methods treat a group of buildings as an energy sink and estimate future energy use as a function of macroeconomic variables. The underlying models are derived based on regression from historic data and can be used for short term demand planning. Top down models treat buildings as black boxes and cannot provide information on the environmental consequences of the adoption of new technologies or local interventions at the individual building level. They are hence less relevant for the focus of this manuscript. Bottom up models can rely on a set of archetypical or actual sample buildings that represent a segment of the building stock. These archetypes or samples may be modeled using building performance simulations and – based on the number of building pertaining to each type – the effect of for example retrofitting measures made to an archetype can be extrapolated to the overall building stock. Bottom up models can hence be used to support energy policy decisions and large scale energy demand assessments. A fundamental difference of these models compared to umi is that bottom up models treat all buildings of the same type as identical for statistical purposes. Umi, being architectural and urban design focused, is particularly interested in resolving differences in energy use of buildings due to local urban microclimatic conditions such as self-shading and urban heat island effects. On the other hand, there is a strong link between bottom up models and urban design tools since the archetype buildings used by the former provide crucial building construction information such as typical building assemblies and infiltration rates for a given building type and region. In the US, a useful set of archetypical buildings is the DOE Commercial Building Benchmark Models (Torcellini *et al.* 2008).

The research most closely related to umi is the development of SUNtool by Robinson and colleagues initially in the UK and later in Switzerland (Robinson *et al.*, 2007). SUNtool is an urban modeling platform that consists of a series of XML based input and output files, an integrated solver as well as a JAVA based GUI that handles data input and results visualization. The solver includes integrated custom modules for modeling microclimatic effects, transient heat flow, plants and equipment as well as occupant presence and behavior. As of May 2013, the individual modules within SUNtool have been rigorously documented in various publications and internal versions of the software have been applied in Greece and Switzerland. But, the software itself has not been publicly released.

For the *Young Cities* project, Huber and Nytsch-Geusen proposed an interesting coupled thermal building and district energy plant model (2011). The model simulates individual buildings in EnergyPlus (US-DOE 2013) and couples the resulting loads with a Modelica (2011) based plant model. The coupling was realized using LBNL's Building Control Virtual Test Bed (Wetter 2011). As pointed out by Huber and Nytsch-Geusen, a key advantage of generating individual building models in EnergyPlus is that the simulations can be easily parallelized. They applied their model to a new 35 ha development in Iran using Autodesk Ecotect to model the buildings.

Yet another, mainly Germany focused solar urban design tool is GSOL (Goretzki 2013). The tool calculates heating demand of buildings in a given neighborhood using a simple heat balance algorithm. It then repeats the calculation – assuming that all building are unshaded – and reports potential optimization strategies to maximize the use of solar energy. It has been used in close to 200 German communities and is focused on heating dominated climates.

UMI ARCHITECTURE

General Approach

The basic approach of umi is similar to SUNtool and the Young Cities Project in that it is grounded in first principal building performance simulation modeling. It uses the WINDOWS based NURBS modeler Rhinoceros (McNeel 2013a) as its CAD modeling platform, EnergyPlus for thermal building-by-building simulations, Daysim for daylight simulations and custom Python scripts for walkability evaluations. A fundamental difference between umi's and Young Cities's approach compared to SUNtool is that instead of relying on an altogether new, fully integrated urban simulation model an effort has been made to base the tool on existing simulation engines that have longstanding active development teams. An obvious advantage of this approach is that umi directly benefits from past

and future developments by others and may draw users from existing communities that are already familiar with EnergyPlus and Daysim. On the flip side, additional effort has to be made to meaningfully couple and process the simulation results from the different modules. Of particular importance for the authors was for umi to introduce urban designers and architects to building performance simulations within a familiar modeling environment and to thus allow them to combine urban environmental performance assessments with computational design approaches such as parametric modeling and optimization. Umi hence includes components for Rhinoceros' visual scripting environment Grasshopper (McNeel 2013b). Rhinoceros and Grasshopper are widely used in leading architecture and urban design schools and practices worldwide where they tend to be applied for schematic design and design development.

umi Workflow

Umi consists of an intuitive four button workflow within Rhinoceros (Figure 1). For daylighting and transportation there are additional expert toolsets available in Grasshopper.
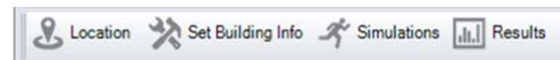

Figure 1: Umi workflow in Rhinoceros

Going from left to right users initially select a site location plus other site conditions including the amenity template that is used for walkability evaluations (see below). Umi users are then provided with an intuitive layering structure in Rhinoceros to build massing models of a city or neighborhood that consist of building envelopes, trees, shading objects, other infrastructure, and streets (Figure 2). Buildings, trees and all kinds of shading objects are represented as closed polysurfaces. Windows and accompanying static shading devices can either be automatically generated based on window-to-wall ratios or custom modeled in arbitrary detail. As required by EnergyPlus, windows must be fully embedded into their surrounding walls. Streets and walking paths are

Figure 2: Umi model of a mixed use development in Boston, MA, USA
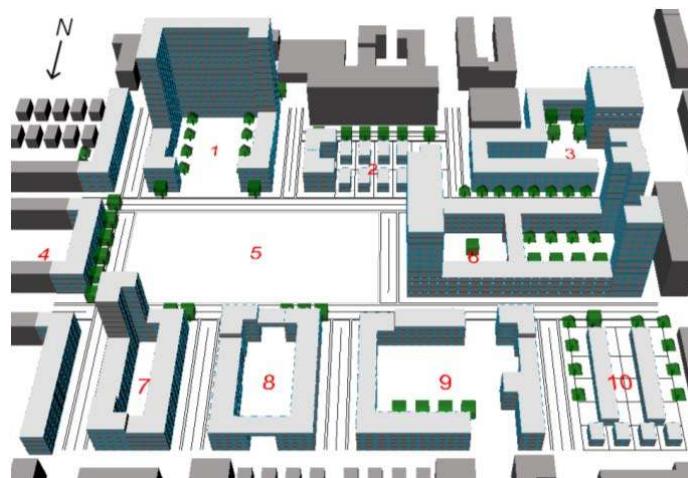
1 Landmark building with explicit mixed land-use
2 Residential block and single family housing units
3 Irregular courtyard composition with massive block
4 Row houses (in a straight line)
5 Park
6 Massing composition
7 Narrow courtyard complex with a relative hi-rise
8 Explicit mixed land use with wider courtyard
9 Widest courtyard with low-rise arrangement
10 Single family houses in row and individual units

modeled as a network of lines. Parks are modeled as surfaces or curves. Once the geometry has been modeled, each building is associated with a customizable template of material definitions and schedules, plant types as well an amenity type using the 'Set Building Info' button (Figure 1). The various simulation models are invoked via 'Simulations,' and results are loaded back into Rhinoceros using a Python based viewer (see below).

Urban Microclimate and Climate Change

To consider the urban heat island effect umi users are directed towards the Urban Weather Generator (UWG) a combined Urban Boundary Layer and Urban Canopy model that was developed by Bueno, Norford , Hidalgo and Pigeon (2013). UWG converts an EnergyPlus epw weather file for a rural weather station into a nearby urban center accounting for hourly urban heat island effects. The model uses a variety of geographic and urban fabric specific input parameters such as building topology, construction type and vegetation. Street, Reinhart Norford and Ochsendorf (2013) showed that UWG – in its current form – may only be used with caution as the conversion only yields reliable results in Boston if the rural station is located windward of the city and is not situated nearby any large bodies of water.

Umi-Energy

As explained above, umi generates EnergyPlus files for each building and runs individual annual simulations either in sequence or parallel depending on the number of process threads available. Multi-zone EnergyPlus models are generated in two steps. The building volume, as defined by the building envelope, is initially broken into different levels. Core and envelope zones are then auto-generated by umi with all envelope zones having a depth that corresponds to twice the floor-to-floor-height. All zones are assigned the same construction types, schedules and infiltration rates specified in the building's template. Interior zone boundaries on the same level are modeled as air surfaces. In order to model mixed-use buildings, adjacent and intersecting

building blocks may be combined into a larger structure. Adjacent surfaces between different building blocks are modeled as adiabatic surfaces. Umi currently reports HVAC energy use based on EnergyPlus' ideal air loads system combined with user-defined coefficients of performance. However, more complex HVAC systems supported by EnergyPlus could easily be implemented going forward. During each individual building simulation, neighboring objects are modeled as shading objects. As mentioned before, energy simulation results can be mapped back into the Rhinoceros scene (Figure 3) and combined with aggregate analysis and visualizations of building performance. As an example, Figure 4 shows aggregate hourly load curves for electricity gas and associated carbon emissions using mean conversion factors from ASHRAE 189.1 (2010) for the neighborhood from Figure 2.There are some pronounced heating demand peaks in January and early December which could be potentially mitigated via architectural interventions and lead to substantial equipment savings if the neighborhood were to be served by a district heating and cooling system.
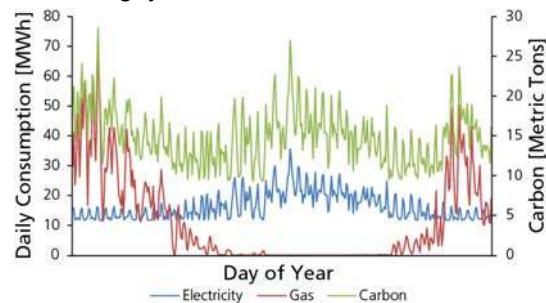

Figure 4: Hourly electricity and gas use as well as associated carbon emissions for the neighborhood from Figure 2.

Umi-Daylight

Using the previously developed Urban Daylight program, umi calculates annual daylight availability for each story in each building (Dogan, Reinhart and Michalatos 2012). The calculation is fully automated

Figure 3: Umi-Energy results of a mixed use development in Boston, MA, USA

and does not require additional input parameters beyond those for the energy model. Urban Daylight uses the Radiance-based Daysim program to calculate hourly radiation values on a grid of outward facing sensors that are laid across all building facades in the model (Reinhart and Walkenhorst 2001). The exterior radiation values are then converted into a grid of interior work plane sensors that define the contribution of a given façade segment to interior illuminance levels. The conversion is realized through a 2D light propagation algorithm that may account for a variety of facade layouts. This approach yields hourly interior illuminance level distributions for buildings of arbitrary shape at a fraction of the time required for a full Daysim analysis and at an accuracy level that is adequate for initial massing studies when interior space layouts are not defined, yet. The resulting interior illuminances are converted into climate-based daylighting metric distributions such as daylight autonomy (DA) or continuous daylight autonomy (CDA) (Reinhart, Mardaljevic and Roger 2006). DA corresponds to the fraction of the occupied time in the year when a target illuminance level at a point in a building is met by daylight alone. CDA corresponds to daylight autonomy with the exception that partial credit is given when daylight meets only parts of the target level at a given time step. Figure 5 shows the continuous daylight autonomy distribution in the mixed use neighborhood form Figure 2 assuming illuminance thresholds of 300 lux and 500 lux for residential and commercial buildings, respectively. For the overall neighborhood, 45% of the floor area has a CDA over 50%. In contrast only 14% have a DA over 50% which the IESNA LM-83-12 would consider 'daylit' (IESNA 2012).

Figure 6 shows an outdoor thermal comfort analysis of the mixed use neighborhood form Figure 2 using Umi-Daylight. In this case a simplified model is used which considers an outdoor space to be 'cold' if the outdoor ambient temperature is below $5^{\circ}C$ and no direct radiation is incident on an outdoor location. Hot spots correspond to locations and times when the ambient temperature is above $28^{\circ}C$ and direct solar irradiation is incident on the sensor. While this comfort model is crude and ignores mean radiant temperature and local wind effects, it already provides rich spatial information such as which parts of courtyards and streets might require local shading.
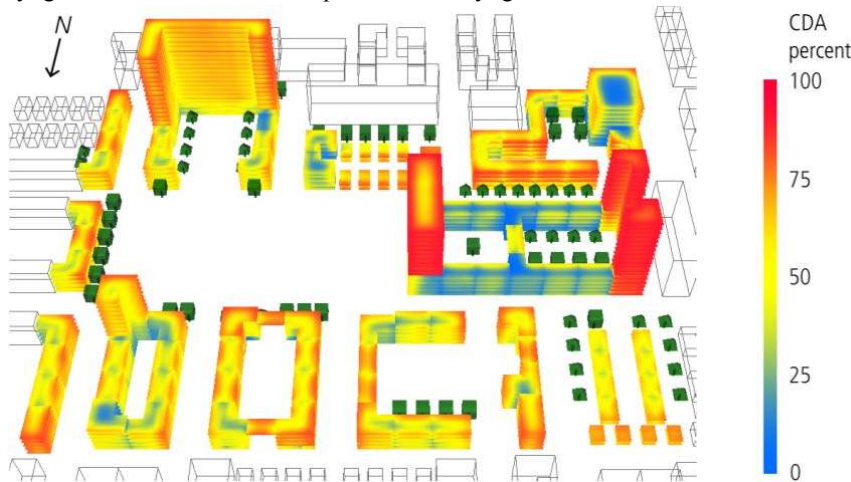

Figure 5: Umi-Daylighting analysis of a mixed use development in Boston, MA; the figure shows continuous daylight autonomy results with 300 lux and 500 lux thresholds for residential and commercial buildings
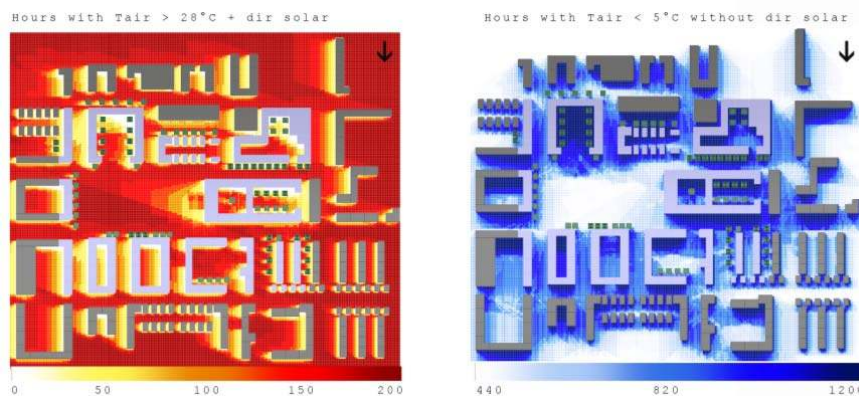

Figure 6: Umi-Outdoor Thermal Comfort analysis of a mixed use development in Boston, MA; hot spots in summer (left) are detected based on the hours with ambient temperatures above $28^{\circ}C$ and exposure to direct solar irradiation, cold spots (right) correspond to temperatures below $5^{\circ}C$ and no direct radiation

Figure 7: Umi-Walkscore analysis of a mixed use development in Boston, MA, USA

Umi- Mobility

Using the earlier described umi modules related to building energy and daylighting, an urban designer may for example explore various street width and building height ratios in order to find a suitable compromise between access to daylight and solar gains control. In a cooling dominated climate the two metrics "work against" each other and may hence yield plausible optimum solutions. Yet, in a heating dominated climate, more daylight and solar gains are generally equally welcome. In such a situation the designer may end up working in an unconstrained design space in which increasing street widths keep getting rewarded. As shown by Niemasz, Sargent and Reinhart (2013), oversized building offsets provide limited benefit for building energy use in single family residential dwellings while seriously compromising the walkability of neighborhoods. To help urban designers to identify holistic sustainable neighborhood solutions, umi therefore includes a sustainable transportation module (Rakha and Reinhart 2013). In its first version, the module concentrates on neighborhood walkability and associated carbon emissions. Walkability is a measure of how friendly an area is to walking. Walkscore® is an increasingly popular North American walkability metric that yields a point score between zero and one hundred for an address based on proximity to amenities such as grocery stores, restaurants, shopping, coffee, banks, parks, schools, books and entertainment (Walkscore 2013). It also rewards local street intersection density and average block lengths. In umi Walkscore values are calculated for each building based on a grid of streets and pedestrian pathways as well as amenities (Figure 7). For an urban designer, Walkscore type analysis is of interest because it rewards interventions at the building and street levels such as creating public passageways through city blocks. To overcome Walkscore's inherent North American cultural bias towards very short distances and non-essential amenities such restaurants and coffee shops, umi allows users to define their own amenity table and allowable distances through custom templates. As an example, Weismann *et al.* conducted a modified Walkscore analysis of an informal settlement in Port Au Prince, Haiti, using umi (Palen, Kim, Weissman and Yurkofsky). For the analysis grocery store, restaurants and shopping were replaced with water access, informal markets and mechanic shops, respectively. Rakha and Reinhart previously demonstrated that optimization tools, such as Galapagos in Grasshopper, can be combined with Walkscore to enhance land-use allocation in a neighborhood (2012). In an effort to translate walkability assessments into potential carbon emissions, the umi Mobility module combines a trip generator with Walkscore based probabilities, ambient temperature and rainfall data to predict how many trips throughout a year can be done on foot. For non-motorized trips carbon emissions are estimated with the ultimate goal being to directly compare carbon emissions from buildings and household travel behavior influenced by the built environment (Rakha *et al.* 2013).

DISCUSSION

The previous section introduced the details of a new urban modeling environment called umi for urban designers, architects and affiliated consultants. In the following, umi is positioned within current planning practice followed by a discussion of its potential use in existing neighborhoods and in education.

Urban Design Practice

In a recent article, Besserud and Hussey made the case that current urban design practice is mostly heuristic and in need for computational performance evaluation tools (2011). They then laid out a series of eight planning stages that characterize contemporary practice. These steps are listed in Table 1 along with a matrix of which of these steps can be supported through the various umi modules. The first four steps deal with defining program and size of a new neighborhood and connecting it via streets to existing

Table 1: Urban design stages plus applicability of the different umi modules

	Urban Design Stage	umi Modules		
		Building Energy	Daylighting & Outdoor Comfort	Walkability
1	Layout of a street grid to accommodate the flow of people and resources as well as public social interaction			
2	Placement of parks and public space		√	√
3	Programmatic layout of a city, definition of required program areas such as residential, commercial and facilities			
4	Distribution programs across blocks (zoning)			
5	Allocation of parking and public transportation		√	√
6	Definition of floor area ratios and urban massing	√	√	√
7	Building Massing; transition from the urban to the architectural scale	√	√	√
8	Adjustment of earlier decisions based on detailed 3D massing models	√	√	√

transportation networks. At this level the transportation and land use models mentioned in the introduction seem most applicable. As the planning process progresses and becomes three-dimensional, umi can begin providing relevant design information regarding massing decisions as well as local programing and pedestrian flow allocation. Umi may also be used to create comfortable outdoor spaces while weighing access to daylight against energy efficiency. Being based on Rhinoceros and EnergyPlus, urban designers may continue using umi as they start detailing indoor and outdoor spaces all the way through design development. While umi does not allow users to model the interior of a building in detail, a user may seamlessly transition to – for example – the DIVA-for-Rhino plug-in for arbitrarily detailed daylighting studies. Other EnergyPlus-based environments can be used to open EnergyPlus projects (IDF file) and refine the analysis. If users keep using umi's EnergyPlus simulation results output format, the results of more detailed building models can continue to be imported into umi for an urban level analysis (Figure 3). This suggests that umi may actually be used beyond the conceptual building design process.

Existing Neighborhoods

While the use of umi is optimized for the design of new neighborhoods, a common criticism of large scale urban construction projects in the US and Europe is that most projects are small, and the sustainable building design community should focus instead on retrofitting and urban densification. This is true. Fortunately, the laws of physics governing heat flows around new and existing construction are identical. Dealing with retrofitting and infill situations hence mainly becomes a nowadays increasingly streamlined data transfer issue from GIS databases into CAD. As a proof of concept the GIS data for the City of North Vancouver, Canada, is currently being linked to umi.

Adoption in Education and Practice

As described above, umi has been specifically developed to introduce environmental performance evaluation at the urban level to urban planners and architects. It offers a workflow that is complementary

with current planning practices and – through its link to parametric design – offers opportunities for exciting new design explorations tackling society's big questions. While this manuscript presented umi results for energy, daylight urban comfort and walkability separately, in order to explain the assumptions underlying these modules, the goal for practice and education is of course to combine these results for a more holistic analysis of different neighborhood designs. To test the feasibility of this proposition and to further enhance the relevance of umi results for the urban design community, umi has to date been used in two graduate level full semester courses for architecture and urban planning students. The general experience was that students were able to understand results provided by umi and further use them to influence design decisions. Simulation times tended to be less of a challenge than model setup. To give the reader a sense of the computational effort required by umi, the mixed use neighborhood from Figures 2 to 7 ran for 6 hours for the thermal simulations and 2 hours for daylighting on a 4 processor machine. Walkscore calculations are instantaneous. As with other building performance simulations, the authors generally observed that student interest in the simulation assumptions rises once they realize the models' value for design.

CONCLUSION

This paper introduced a new integrated urban modeling environment called umi that provides integrated operational energy, daylighting, outdoor comfort and walkability analysis of neighborhoods. The data provides actionable information to help urban planners and architects to improve the performance of their designs at the building and street scale. Going forward the authors will further work on integrating the various umi modules so that – for example – carbon emissions resulting from buildings and transportation can be directly weighed against each other. An initial version of umi can be downloaded from http://www.UrbanModeling.net.

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