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AUTOMATED CONVERSION OF ARCHITECTURAL MASSING MODELS INTO THERMAL 'SHOEBOX' MODELS

Timur Dogan[1], Christoph Reinhart[1]
[1]Massachusetts Institute of Technology, Cambridge MA, USA

ABSTRACT

Many attempts have been made to automatically convert architectural 3D models into thermal models for building performance simulation. This paper describes a method that is capable of abstracting an arbitrary building massing into a meaningful group of thermal shoebox models. The algorithm is meant to bridge the existing gap between architectural and thermal representations of the same building and to facilitate the use of energy models during schematic design by providing instant performance feedback from the massing stage onwards. The method uses varying facade insolation levels as the key form-related parameter. Discrete facade segments are then grouped by similarity of their local "solar microclimate". Each group is represented by a reference shoebox model, which consists of a two-zone thermal model for perimeter and core regions. Computed shoebox results are then extrapolated and mapped back to the architectural model. Thus, the relationship between the simulation output and the provided architectural geometry is strengthened and easier to communicate. Combined with a parametric modeling environment, the method may be used to identify optimized local massing solutions. It can also be applied at the urban level to break down a whole neighborhood into a representative subset of simple thermal models, allowing the estimation of urban energy use intensity in a feasible and timely manner.

INTRODUCTION

Recent developments in the field of dynamic building simulation have provided powerful toolsets for environmental engineers that allow them to predict and manipulate key architectural qualities and economic performance measures such as thermal comfort and energy use intensity. However, architects still rarely use building performance simulations and generally do not consider existing simulation environments as supportive and generative *design* tools [Morbitzer et al. 2001, Robinson 1995]. Energy models tend to be especially underrepresented in the fast-paced early design phase. The importance of implementing evaluative tools during the early design phase, however, is self-evident given that decisions made at this point such as building proportions and their spatial interrelationship with the context, largely "make or break" the intrinsic energetic performance of a building.

The reason for the lack of acceptance of simulation tools in the early design phases may be traced back to their complexity and slowness. In addition, the computational representation of an architectural CAD model has only limited relation to the input required for a building energy model (BEM). This incompatibility between the two model types nowadays requires a specially trained engineer to translate the model so that it can be used for simulations [Morbitzer et al. 2001, Smith et. al. 2009]. In order to avoid, this time consuming and error prone process, a number of researchers previously worked on methods that could either facilitate the data exchange between the different design professions or directly auto-convert the architectural CAD model into a thermal model.

Before reviewing these methods, we should further clarify that - within the context of this paper - an architectural CAD model consists of individual surfaces organized on various layers without further building information model content (BIM) such as construction assemblies and thermal zoning. Though commercial BIM environments, which offer this additional content exist we believe - based on our everyday experience in a school of architecture that - BIM tools should only be used for the production of the construction drawings whereas the methods presented in this publication would rather be used in the more creative, exploratory design phases.

Returning to previous work auto-conversion models, Christoph van Treeck introduced a method that performs a "Dimensional reduction of 3D building models using graph theory" [Treeck 2006]. Treeck's algorithm uses Boolean operations to decompose the input geometry and then performs surface overlap tests to establish a connectivity network for a multi-zone energy model. The introduced method is very applicable in later planning phases when a detailed BIM model exists. However, the required geometric information such as allocation of rooms or morphologic details of building components (e.g. wall thickness) as well as the high geometric modeling precision requirements for the Boolean operations, render it unsuitable for the early design process. Typically, the schematic designs do not yet carry detailed architectural information. In addition the CAD models coming out of practice and studio are generated rapidly and thus tend to have imperfections like unhandled intersections and overlaps. For larger models the decomposition process becomes computationally expensive.

Smith, Bernhardt, and Jezyk introduced a tool that automatically converts a massing model into thermal zones [Smith et al, 2001]. However, for larger ensembles or taller structures the model yields a large number of thermal zones, which translates into thermal models that require long simulation times and that have results that are difficult to analyze. The method is hence somewhat limited for early design or urban projects.

Pratt et.al. [2012] described the advantages of early design simulations and identified automatic model conversion as the key facilitator. The envisioned workflow allows maximum modeling freedom and can handle model imperfections. Pratt did not mention the implementation of the geometric algorithms in detail but the authors would like to note that processes like Boolean decomposition, capping holes in imperfect models and correcting surface normal orientations can be error prone and time consuming especially for large, polygon-rich models. For urban designs also previously mentioned concerns apply.

In order to avoid some of the complications mentioned above, we would like to take a step back and re-evaluate the actual needs and requirements of both the architectural and the thermal model in the early design phase.

Architectural CAD models are created to convey a certain design intend. The models are mainly used to produce 2D perspective views as well as plans and sections of a design. Due to the technical affinity of architectural rendering software and ray-tracing based radiation simulations, architectural CAD models are very suitable for insolation and daylight studies. On the contrary, thermal simulations are usually based on resistor network calculations where connecting surfaces and spaces are described with an electrical analogy in a 1D graph. The second and third dimension is usually just needed to include the area of the building surfaces as well as the volume of air in the model. As a consequence, thermal simulation techniques tend to neglect spatial complexity and focus on providing high temporal resolution. Only, the solar radiation calculation modules as well as any external wind analysis for natural ventilation truly rely on an exact 3D representation. In order to reduce simulation time and model complexity it is common practice to simplify the thermal model by grouping several rooms into one larger zone if their loads and thermal behavior are expected to be similar. This process is commonly

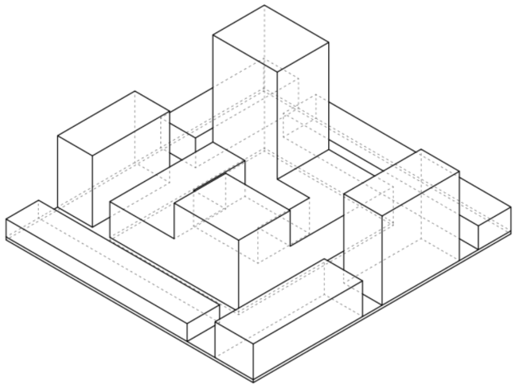

Figure 1 Input Geometry

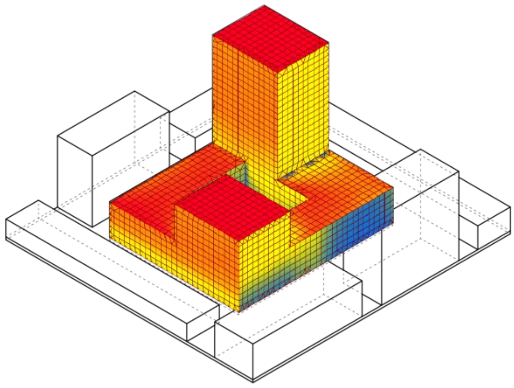

Figure 2 Insolation Analysis Mesh [high(red) low(blue)]

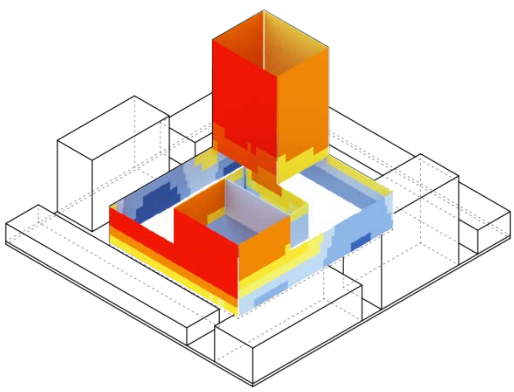

Figure 3 Clustered Facade

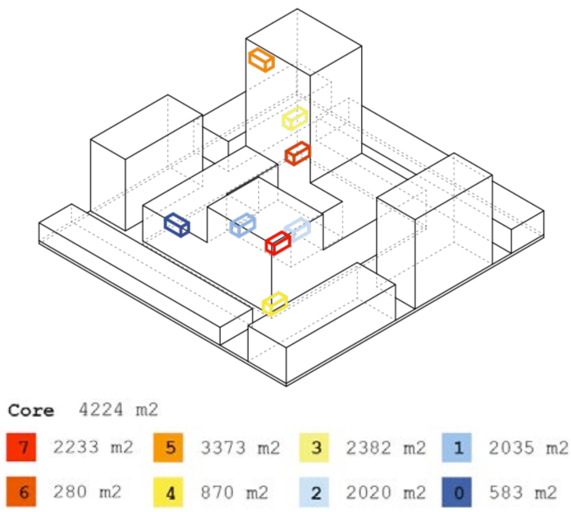

Figure 4 Sample Thermal Zones

done manually and requires a certain amount of experience on the modeler's part. If done correctly, "these approximations ... reduce the complexity of the model while minimally impacting model accuracy" [Georgescu et al. 2012]. Georgescu further mentioned that the error introduced by zone reduction can be so small (191 zones reduced to 10 zones with a 13.13% error) that it is hardly ever worth to invest in the extra modeling effort and simulation time. This is especially true if a thermal model is to be used to form generating purposes where relative comparisons matter most. Georgescu's finding thus lead the authors to the hypothesis that - if the zones are maintained at similar temperatures - one can expect an equally small error if each thermal zone in a building is modeled individually assuming adiabatic interior surfaces by simulating each zone independently and that the energy use intensity (EUI) of the whole building may be extrapolated based on the results of the individual zones. Building on this hypothesis, this paper hence proposes the following method to rapidly generate a thermal model out of an arbitrary massing model:

- Input: 3D geometry of the architectural massing model.
- Insolation analysis for the envelope. (One may later add isothermal CFD for local CP values)
- Cluster all facades based on similarity of their temporal solar loads.
- Determine the area weight of each cluster per building.
- Generate a representative thermal shoebox model for each cluster.
- Simulate the shoeboxes.
- Combine and integrate results weighted by area and remap results on the building envelope.

The method is described in detail in the following section. Simulation results of the method for a large office building with urban context are compared to a multi zone "whole building" Energy Plus model. The ensuing discussion addresses limitations and potential applications of the method.

METHODOLOGY

Input

As input the method requires a 3D CAD model that describes the volumetric form of an architectural design plus urban context. An example model that will be analyzed in the following is shown in Figure 1. Context and target building(s) have to be stored on separate layers. The appearance of these models usually differ greatly from modeler to modeler: For example, the building could be modeled as one envelope (one poly-surface) or as stacked boxes (multiple poly-surfaces) without interior subdivision. Sometimes basic zoning ideas are tested by splitting a floor into several boxes such as one core and

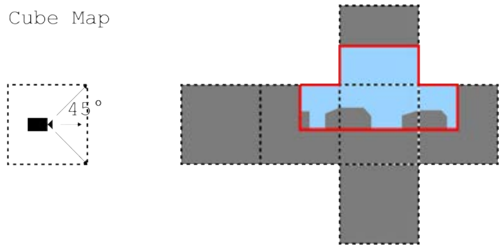

Figure 5 Cube mapping. Red: half hemi cube.

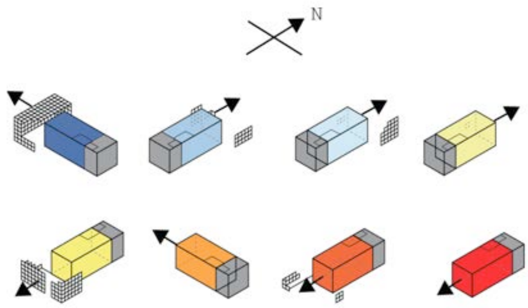

Figure 6 Thermal zones with abstract shading elements and core zones.

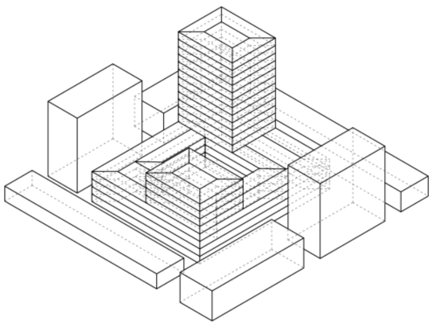

Figure 7 Reference "whole building" Energy Plus model.

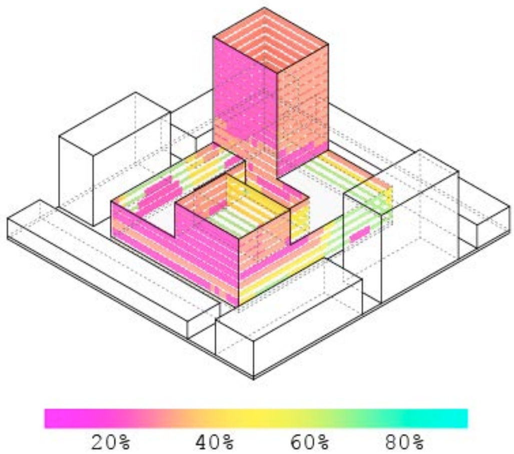

Figure 8 Suggested WWR by parametric study.

stacked units and by moving these units around. Given that there is no convention how a designer should build massing models, it is crucial to come up with a robust method that can handle as many input geometries as possible without requiring manual model cleanup.

Insolation Analysis

Using an approximate floor-to-ceiling height, cutting planes are auto-generated to compute polygon outlines at the middle height of each floor of all target buildings. [We assume that the intersection with the input geometry produces closed polygons. Small gaps can are bridged automatically] Along the polygon outlines a series of virtual sensors are placed at which incident solar radiation levels for different time intervals, e.g. seasons, are calculated. The distance between sensors can be varied with more sensors being advisable for more complex local shading situations. The calculation method used for the radiation analysis should be able to reliably consider local weather data as well as the effect of neighboring buildings. Example methods are described in Duffie and Beckman [2006] and a comparison of selected methods is offered in Ibarra and Reinhart [2011]. For this paper the envelope radiation data was generated using the "Urban Daylight" toolset that is based on DAYSIM [Dogan, et. al.2011, Reinhart et. al. 2001].

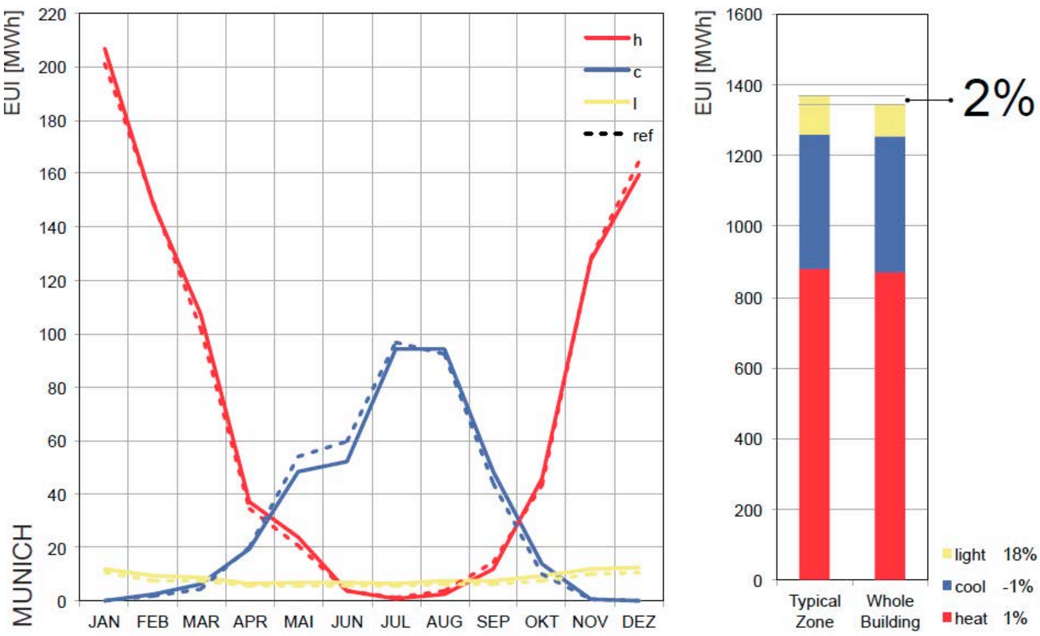

Figure 9 Whole building model [Figure 7] vs. new method. Construction scenario 1. 8 samples.

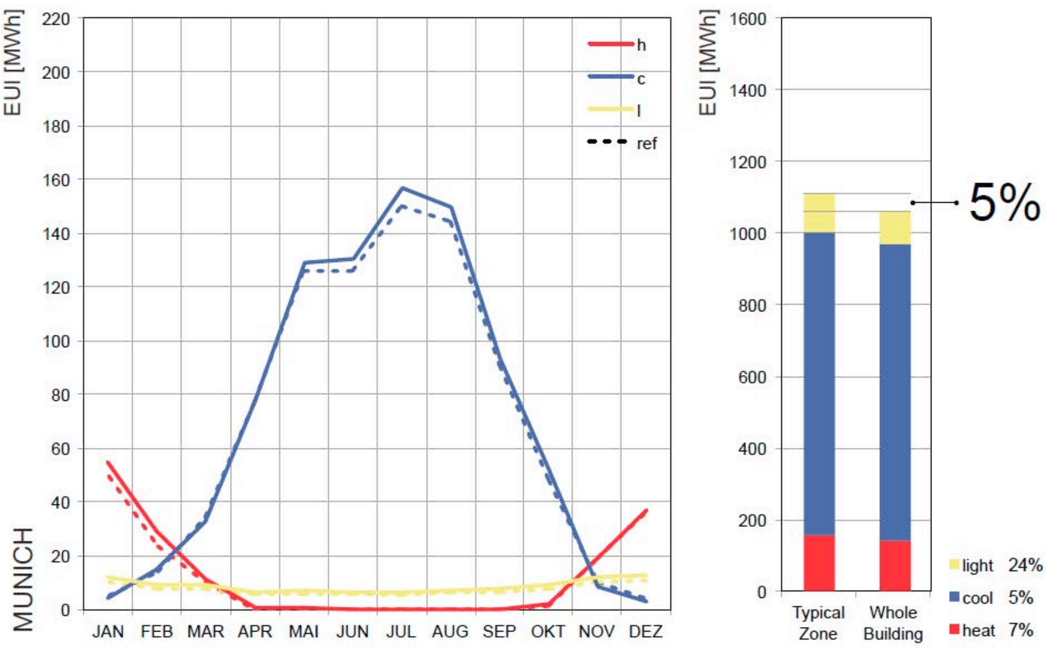

Figure 10 Whole building model [Figure 7] vs. new method. Construction scenario 2. 8 samples.

Clustering

For the clustering algorithm each radiation sensor represents a slice of a single story façade. Based on a user defined, maximum number of groups the method divides the sensors into similarity clusters. For the example in Figure 3 and 4 the building is divided into a core region plus eight façade-clusters. These clusters represent regions of similar seasonal solar load and have to be represented in a thermal model in the next step. Therefore, we identify the sensor point closest to the mean incident solar radiation of a group and capture its shading situation for the thermal model (Figure 4).

A “cube-mapping” technique [Greene, 1986] allows us to detect sky view obstructions at the above mentioned sensor point similar to a shading mask [Marsh, 2005]. Cube-mapping is done by six small resolution renderings with a 90 degree viewing angle looking in all cardinal directions as well as up and down. Mounted together we get an unfolded cube projection of a 3D environment shown in Figure 5. Since we are mostly interested in the sky view obstructers for vertical walls we can discard the lower half of the cube as well as the pixels behind the wall - resulting in a half hemi cube marked in red in Figure 5.

With this information we can then build the geometry of a “shoebox” thermal model with the orientation of the point and the correct shading situation like in the “architectural” model. The shoebox models for the example building are shown in Figure 4. The shading situation of the architectural model is resembled by simple wing-wall or overhang like shading elements generated based on the pixel data of the cube map texture (Figure 6). Small area patches in each shoebox, corresponding to building specific area ratios, represent additional boundary conditions such as “ground” or “roof”.

Shoebox Simulations

Having gathered all required geometric information, we still have to determine the physical and usage characteristics of the buildings such as materials, construction and glazing types as well as schedules and internal loads. Especially at the urban scale the variety of building or even floor specific particularities can be very high.

However, for early design architectural explorations the authors find it useful to reduce the “overwhelming” complexity of too many input parameters by providing basic templates that include lightweight, heavy constructions and good, poor isolation standards as well as usage pre-sets. A user may of course choose to refine these settings during the iterative simulation process. Using more than one building template requires the user to organize the input envelopes on different layers. For the example a single building type was assumed for the entire scene to facilitate the visual interpretation of the results. The simulation assumptions for this type are documented in the table below.

Table 1
Energy model parameters for 2 scenarios:

OPAQUE	
U-Factor with Film [W/m2-K]	2.9 / 0.35
Partitions	Heavy / light
FENESTRATION	
Window to wall ratio	50%
Glass U-Factor [W/m2-K]	1.96
Glass SHGC	0.69
Glass Visible Transmittance	0.74
Shade Control	No
LIGHTING	
Target Illuminance, zone/core [lux]	300/100
Lighting Control	Linear Dimmer
Lighting Energy [W/m2]	5
EQUIPMENT & OCCUPANCY	
Equipment Gain [W/m2]	12/1.8
Occupancy Density [people/m2]	0.11/0.02
Minimum Fresh Air [l/s-person]	10
Occupancy Schedule, zone/core	Office/Circulation
ENERGY SUPPLY	
COP heating and cooling	1.0/1.0

Once building templates have been assigned to all perimeter and core zones, reference shoebox models can be generated and thermal simulations can be auto-run for each cluster. While we used EnergyPlus the method itself is simulation engine agnostic.

Mapping Results onto the architectural Model

Based on the simulated EUIs for the individual shoebox models, the EUI for the whole building(s) can be generated by weighing the results for each shoebox with the floor area that the pertaining cluster occupies within the buildings. Figure 9 shows an example output that can be plotted for each building.

To further demonstrate the capabilities of the new method we performed a basic parametric study. In our example we altered the opening ratio from 20% to 80% in steps of 10%. We can compare the aggregated results for each variant but we can also compare the individual behavior of each sample zone. This allows us to identify the optimal solution among the simulated variants for each cluster e.g. we can give a recommendation which part of the building should have which opening ratio. Figure 8 shows the optimal opening ratios from our search space mapped back to the original input geometry.

Table 2
Mean Percentage Error for different shapes [Climate Munich]

	PLATE [50X20X60]	BAR [40X20X9]	BOX [20X20X12]	BASE, COURTYARD & 2 TOWERS [ILLUSTRATED CASE]		
	No context, 4 Samples				8 Samples	Context & 8 S.
LIGHT	1%	-4%	1%	24%	18%	18% / 24%
COOL	4%	2%	1%	-8%	5%	1% / 5%
HEAT	3%	2%	1%	15%	7%	1% / 7%
SOLAR G.	0%	0%	0%	-17%	-8%	-10%
TOTAL	**3.6%**	**1.6%**	**-2.9%**	**-3.3%**	**5.5%**	**2% / 5%**

"Whole building" vs. shoebox

In order to evaluate the accuracy of our new method we compared it to the "whole building" modeling approach. Three simple shapes, a plate, bar and box as well as the shape shown in Figure 1 were tested against a full EnergyPlus models (like in Figure 7) in the climate of Munich. The first three, simple geometries where approximated with four samples and simulated without context. The shape from Figure 1 was simulated with four and eight samples, with and without context. For this shape the construction scenarios where also altered as indicated in Table 1.

RESULTS

In this section we compare and analyze the simulation results computed with the new method and the "whole building" modeling approach. Table 2 provides an overview of the behavior of different shapes, sample count sensitivity and the influence of the context.

The first three example buildings yield deviations around -4 to 4%. The shape illustrated in the center of Figure 1, shows much larger deviations (-8% to 24%). The same simulation with eight samples yields an error range of -8% to 18%. The last column in Table 2 represents two construction scenarios simulated with urban context [Figure 1]. Figures 9 and 10 present the last column graphically and in a monthly resolution. The figure also shows the order of magnitude of the heating, cooling and lighting energy demand and thus explains why some deviations in Table 2 have little impact on the total EUI estimate.

The simulation time for the "whole building" model [Figure 7] was around 28min whereas the shoebox approach required 1min for model generation and simulation time.

DISCUSSION

Model Comparison

If context and self-shading situations are absent, a small sample size like shown with the first three example buildings yields good results. For the more complex shape the increased sample size can bring down the error mostly due to an improved estimate of the solar gains. Additionally, the shading context is reinterpreted in a simplified way to speed up the simulations. The "cube-mapped" shading geometry is only "correct" for one point and thus is just an approximation of the real shading situation for radiation receiving surfaces like walls and windows.

In comparison with the impact of divergences in the received solar radiation on heating and cooling the impact on the lighting calculation is significant. Consequently, we notice the largest error among the estimated lighting electricity demand. This divergence is also influenced by the fact that we compare different room sizes/widths. The "whole building" energy model behaves more like an open plan office type whereas the shoebox represents an individual office space with a smaller window area per floor area.

Limitations

The decoupled zone plus core approach has obvious limitations. The heat exchange between adjacent zones with significantly different zone temperatures cannot be modeled. However, based on our experience this is an exception and it is feasible to assume that this can be handled outside of the automated process. E.g. zones that have exceptional behavior could be simulated in a manually created extended multi-zone "shoebox" and still be included in the summary results of the tool.

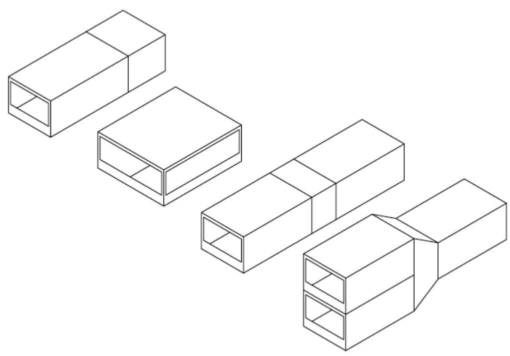

Figure 11 Enhanced shoeboxes for complex simulations
[single room, corner room, cross ventilation, duplex]

The absence of a connectivity network between the zones does not permit airflow network based natural ventilation simulations. To perform meaningful airflow network simulation results good pressure coefficient data is required at the openings of the envelope. For complex morphologies this is very difficult. Such data would have to be created with multiple isothermal CFD simulations like done in previous research [Wang et. al. 2012]. The authors encountered simulation times longer than a day for eight wind directions. This is not feasible for the early design process. However, once local pressure coefficients can be obtained more efficiently, the introduced method could easily adapt and switch the simple, single room shoebox-typology with a more complex shoebox as depicted in Figure 11 to take ventilation strategies such as cross ventilation into account.

Possible Applications

The EUI graphs presented above, show a very condensed form of information that summarizes the overall performance of the design well. However, the design process is also a learning process and the EUI number might not always be intuitive. Thus, it is necessary to provide more detailed information, if desired. For example solar gains, heat loss or peak loads could help understanding the behavior of the thermal simulation. This data is already available in the simulations and can be extracted easily. The data can then be mapped back on the facade patches of the input geometry and directly point to problem areas in the model. This closes the loop of the workflow form the architectural model to the shoebox simulations and back.

The results from the parametric study shown in Figure 8 show the tool-suggested opening ratio distribution over the example building. Even with this rather trivial study we observe a small surprise. Highly shaded regions, where we would have expected larger opening ratios to be the better solution, are rendered with the smallest opening ratio. The assumed positive effect on daylighting of a greater opening is overpowered by the negative effect of greater heat loss through the glazing.

Similarly to the WWR study, we could test any other variation of the shoebox like different shading system designs. This shows the potential of the tool to go beyond the capabilities of a simple analysis tool and become a generative design tool.

We see the biggest potential of the new method in informing master plan designs. For the first time one can perform fast urban energy analysis's with a minimal model setup effort. The speed benefit (~28 times faster) becomes significant for models with hundreds of buildings. This would allow extremely large parametric search spaces at the urban scale. Even a link to a genetic algorithm is possible.

The gained findings could then be used to give simulation based recommendations for the optimal grid spacing, allocation of residential and commercial usages based on their different microclimatic needs, optimal opening ratios and more.

CONCLUSION

The introduced method can express any architectural massing model in the commonly used "shoebox energy model" language. This allows fast feedback loops in early design and bridges between the usually separate design and engineering professions. With an average precision of a RMSE of 3.4% among the tested cases, the introduced method predicts the EUI of an arbitrary massing model within a more than feasible error range for early design. The flexibility of the tool allow us perform simulations with adaptable detail and complexity while at the same time allowing us to scale up the workflow to urban design without any extra effort. Its capability to perform parametric optimization studies at a local level paired with its displaying capabilities make the method a powerful design tool for facades and urban design.

FUTURE

A possible enhancement of the workflow would be to link it to more sophisticated daylight simulations. In previous research the authors introduced "Urban Daylight", a fast method to predict continuous daylight autonomy for large-scale models [Dogan et. al. 2012]. Using this simulation approach should improve the accuracy of the electricity demand for lighting. The Continuous daylight autonomy could also be used to inform the clustering at the very beginning of the methodology.

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