MODELIZATION OF URBAN ENERGY FLUXES FOR URBAN DESIGNS

A 3D morphological model for indoor-outdoor thermic and mobility

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ABSTRACT: We develop an integrated model of urban energy transfers for urban design. The goal is to capture the various effect of indoor and outdoor spaces, as well as their functions, on radiative, heat and mobility fluxes. It is composed of an urban canopy model, a building model, a radiosity model and a mobility model. We partially reformulate those models so that they depict a simple general 3D morphology. From this analytical formulation we deduce the governing morphological and technical parameters of urban designs energy. We also briefly discuss the possible outcomes and interpretations of such a model.
Keywords: energy, urban design, solar, mobility, urban canopy

INTRODUCTION

The relation between urban morphology and energy is perfectly illustrated by the example of a medina quarter. Its narrow streets just let enough sun in to be lit but not overheated, a good mix of courtyard and passage ensure sufficient air circulation, and the dense street network make it possible to access a very large number of buildings and shops within minimal walking distance. Put some modern office full of computers in place of handcraft shops, widen the canyons at the expense of courtyards just enough to allow some motorized transportation, and what seemed a perfect urban form might just end up into an urban heat island nightmare, with overly congested patterns and burning surface temperatures. The key point here is the relation between function, indoor and outdoor spaces, i.e. urban design. It would be then only natural for architect and planners to compare urban design solutions in term of solar, heat and mobility fluxes.

However, how the morphology actually acts on those energy related fluxes, and what are the related governing parameters remains a difficult question to answer. Studies on solar and building energy at urban scale point at passive volume, sky view angles [1] and canyon aspect ratio [2], a parameter also used in urban climate and building energy studies [3], with the addition of distribution of heat sources (both vertically and horizontally) [4]. The literature is more scarce concerning the mobility fluxes, but larger scale studies (regional/metropolitan) would hint at network topology

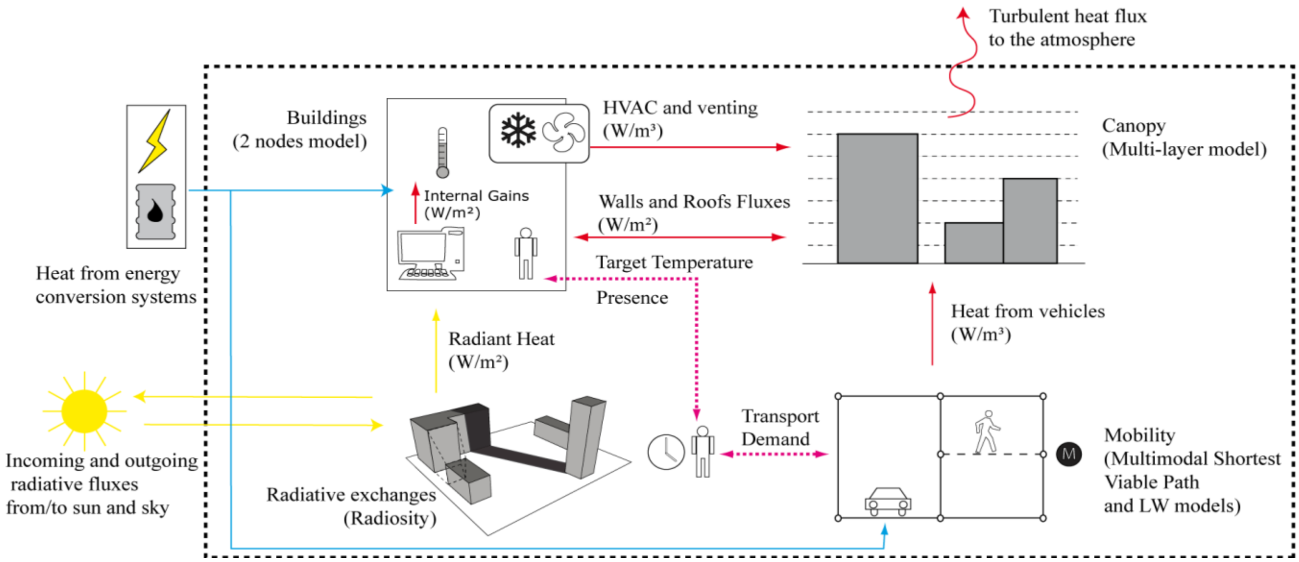

Figure 1: Flowchart of the considered energy and energy related fluxes Red: sensible heat, yellow: radiant heat, magenta: persons, blue: input from energy systems.

and path length [5], while at finer scale (one street, one crossing) the surface allowed seems to be determining [6]. Those parameters are the results of modelizations at different scales, on different systems, for different purposes. It is thus hard to fully capture the effect of the shape of built and free spaces and the distribution of functions inside them, although the raw material seems available.

The goal of this article is to use this existing material to form an integrated model of urban climate, building energy, radiative exchanges and mobility flow. We start by making an energy budget to analyse rigorously which fluxes have to be taken into account. Then we adapt a multilayer canopy model with general source term and couple it to a monozone building energy model and radiosity model to fully describe the thermal equilibrium. Finally we use a hydrodynamic model to capture the flow of people, which ultimately links the production of heat inside and outside of the buildings. In a last part we study the resulting system, its possible uses and more importantly how it should be interpreted.

ENERGY BUDGET

If we isolate an urban fragment there are three fluxes crossing the control volume: turbulent heat flux to the atmosphere, solar incoming and outgoing radiations and heat from energy conversion systems. Note that we consider that the conversion of energy happens outside of the control volume so that energy systems (e.g. boiler, lights) are not modelled. The underlying hypothesis is that we neglect transformation of solids and heat rejection to water and to the ground (under the considered layer), i.e everything is released to the canopy. This hypothesis has yielded good results in urban climate studies [7]. If the solar radiation and heat flux to the atmosphere are known, then the budget is closed and energy demand, as to be delivered by the energy systems, is known.

To determine the turbulent heat flux it is first necessary to model its diffusion, then to determine the anthropogenic heat from vehicles and buildings. The building budget requires itself the solar radiation scheme to be solved, giving both the internal and external flux. Then the flow of people determines internal gains in building and flow in streets. It can be considered as an indirect energy flux, and as such is fully modelled.

This simple energy budget shows that the shape of the canopy governs both surface to surface (radiations) and surface to air (sensible heat) energy transfers. The morphology of the canopy is a result of the buildings shape, which is itself a result of space occupied by streets and other free spaces. The canopy morphology thus indirectly contains pieces of information about the building energy budget and the mobility flow.

This simple energy budget (described in Fig. 1) specifies all the coupling, while underlining the hypothesis, and gives a physical base to the keystone role of the joint morphology of indoor and outdoor spaces.

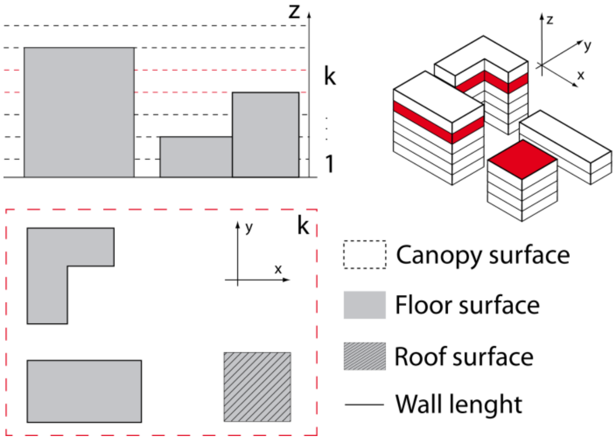

Figure 2: Geometry of the building and canopy in the discrete layer representation.

CANOPY, BUILDING AND SOLAR RADIATIONS

The goal of the thermal model is to reflect how space occupied by buildings affects the heat produced by building, the exchanges of radiations between buildings and the diffusion of heat in the canopy.

To do so we use a multilayer canopy model based on [8]. It represents the vertical diffusion of heat, horizontally averaged over the whole zone. We use a discrete layer formulation of this model, each layer representing one storey of constant characteristics. It enables us to relax the regular array hypothesis to represent a general 3D source term, while still representing horizontally averaged diffusion. With H_w and H_r the surface flux from walls and roofs, q_v the volume flux from HVAC, and venting and Q_t the turbulent flux from previous and to the next layer, it writes for each layer :

$$\rho C_p \frac{\partial \theta_c}{\partial t} = [Q_t(z^-)(1-\tan\alpha) - Q_t(z^+)] + H_w\, c + H_r \tan\alpha + q_v . e \tag{1}$$

$$Q_t(z) = K_h \frac{\partial \theta_c}{\partial z} \tag{2}$$

The edge density c is the ratio of linear wall over the canopy area, the floor index e is the ratio of floor area over canopy area, and the tangent of the opening angle $tan\ \alpha$ is the ratio of roof area over canopy area. These three parameters, with the addition of the implicit parameter that is the number of layers, represent the urban morphology governing the diffusion process. The eddy diffusivity K_h is determined by a first order k-l closure scheme [8].

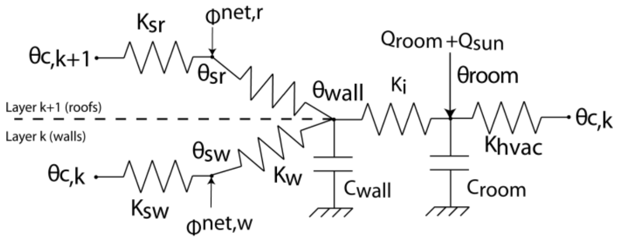

Figure 3: Equivalent electrical circuit of the building model. Φ^{net} is the net radiative flux on walls and roofs, Q_{int} and Q_{sun} the internal gain from sun and electrical apparels.

The source terms H_w, H_r, and q_v are computed with a 2 nodes building energy model [9] (with the addition of ground and vehicles terms in the first layer). Such models represent the heat storage in walls, inside air and conduction to the outside air both through walls (surface to air) and venting,/HVAC (air to air). This process is best described by its electrical equivalent (Fig. 3). It represents the two ordinary differential equations at each capacity, invoking wall (thermal mass), indoor air and canopy temperatures, completed by the algebraic equations of surface balance invoking the radiative flux.

We represent one thermal zone (one 2 nodes model) per layer and per building. The previous formulation enables us to directly sum each of these contributions on the general 3D geometry in every layer, with the hypothesis that the heat is released homogenously in the horizontal plan (i.e no canopy temperature variation in the horizontal plan).

We compute the radiative exchanges between surfaces, sun and sky, with the radiosity method. This method exists for general 3D scene in the form of matrix algebra. We can therefore apply it straight forwardly to the 3D scene, using one patch per wall of each thermal zone and each ground surface. It gives the relation between the emitted flux $\mathbf{\Omega}$ and the net flux $\mathbf{\Phi}$ [10] :

$$\boldsymbol{\Phi} = (\boldsymbol{I} - \boldsymbol{R})((\boldsymbol{I} - \boldsymbol{RF})^{-1}(\boldsymbol{I} - \boldsymbol{R}) - \boldsymbol{I})\boldsymbol{\Omega} \tag{3}$$

The reflectivity diagonal matrix $\mathbf{R}$ represents the albedo (shortwave) or emissivity (longwave) of the materials. The form factors matrix $\mathbf{F}$ is the governing morphological parameter of the process. It represents the "how much" each surface sees each other, taking account both distance and size. Although the terms of this matrix are hard to compute analytically, many numerical methods exists that we can take advantage of, e.g. image rendering as used in CitySim developed at EPFL [11], that we use in our study.

The full coupling of these models results in a differential algebraic system. Its outputs are the canopy layers temperatures, internal air temperature of each thermal zone, surfaces temperatures, as well as net radiative fluxes of surfaces and heating/cooling needs.

MOBILITY

We want to reflect how land dedicated to mobility spaces (streets, pavements, bike paths, plaza etc.) affects the mobility flows, possible mode combinations and the related released heat and energy input.

We represent the transport network by a graph with only monomodal arcs, with eventual trip production, attractivity or route change at vertexes. Mode changes are represented by fictive transfer arcs. For each origin we determine the tree of shortest viable path to every destination. A path is considered viable if it uses a possible combination of modes (e.g. foot to bus, but not car to bike to bus), a possible travelling length (e.g. no more than 500m by foot) and possible waiting time [12]. The results of this process are minimum spanning trees for each combination of mode. The topology of the network and length of arc is reflected by the Laplacian matrix of the network that is used to build the spanning trees [13].

We only directly model surface modes, underground modes are considered as punctual boundary conditions with fixed frequency.

The width of the arcs directly influences the travelers' density ρ on a path, and therefore their speed. To model this effect we use a macroscopic time-continuous hydrodynamic model [6]:

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial x}\left(\rho f^2(\rho)\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho f^2(\rho)\frac{\partial \phi}{\partial y}\right) \tag{4}$$

$$f(\rho) = \frac{1}{\sqrt{\frac{\partial \phi^2}{\partial x} + \frac{\partial \phi^2}{\partial y}}} \tag{5}$$

With $f(\rho)$ the speed, also known as fundamental diagram, and Φ the potential, i.e where travelers want to go. Although the formulation is the same for all modes, $f(\rho)$ and Φ differs for pedestrian, bicycles and automobiles. In most cases the flow is one dimensional (streets, pavement, bike path) in which case the second right hand term in (3) is null, and density directly depends on width w of the arc. Some pedestrian public space are two dimensional (e.g. plaza), in which case the related arc does represent a two dimensional space. This calculation gives the travel time of an arc.

The boundary conditions, the trip production and attractivity for each origin-destination pair, as well as mode choice probability are assumed to be known. This is equivalent to say that the number of trip per path is known. Multiple methods exist to determine those conditions, such as large scale simulation (see [14] for an organized review), census data (e.g. [15] in France), or simply hypothesis.

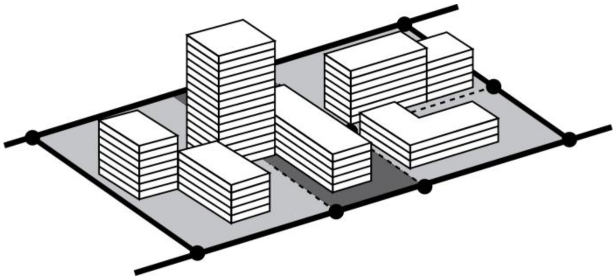

Figure 4: Representation of the resulting system, here with mobility surfaces embedded in arcs. It is close to master planning practice.

THE URBAN DESIGN SYSTEM

All of the governing parameters (morphological and technical) deduced in the previous parts characterize only the interrelation between outdoor and indoor space. They contain few to no information about architectural scale (e.g window placement) or regional planning scale (e.g. hinterland interaction). Furthermore the model is fully offline, both for climate and transport. This isolation of scale is a way to eliminate some of the complexity inherent to the city context.

This makes it possible to compare urban designs “all other things being equal". The output is then the relative difference (on temperature, heat flux, potentials etc.) between designs, on conventional values. Since the model is exogenous, every difference in the output can be related to changes in the parameters, making it an explanatory model. Such results must not be mistaken with the production of absolute values to assess existing district/neighbourhood. Existing neighbourhood do include the above mentioned complexity (architectural details, social context etc.), making both set up and interpretation hard to grasp, “all other things” never being equal between real urban places. The modelled system is thus the *urban design system*, defined in the previous parts, and must be carefully differentiated from the *neighbourhood system*.

The main applications of our model therefore lie in the conceptual field, such as early stage design or academic examples. That’s why the process of harmonizing models around a shared representation of urban morphology has been done with master plans in mind (in their 3D acceptation) rather than actual cities. This result is a physically based system, giving us access to a full range of mathematical and numerical methods, with inputs that are commonly manipulated by architects and planners.

Table 1: Summary of the morphological parameters. Vector data type indicate one value per layer.

Parameter	*Class*	*Type*
Number of layers	Topological	Scalar
Number of buildings	Topological	Scalar
Number of arcs	Topological	Scalar
Edge density	Metric	Vector
Floor Index	Metric	Vector
Opening Angle	Metric	Vector
Form Factors	Metric and topological	Matrix
Laplacian matrix	Metric and topological	Matrix

CONCLUSION

We present in this article a model able to capture the effect of morphology and function attributed to indoor and outdoor spaces. To do so we coupled models of urban climate, building energy, radiative exchanges and mobility. Those models were adapted to a general 3D, yet simple, descriptions of the morphology composed of multilayer buildings and canopy, soil use and transport network. From this study we deduce many morphological and technical parameters, some of which are simple and well known, but slightly adapted (e.g. floor area index of each layer) other more complicated and less used (e.g. laplacian matrix), but all of them giving explanatory power to the model, if carefully interpreted. The result is a model that can be manipulated by both architect or planner and engineers or physicists, making it possible to compare designs solutions from a variety of points of view.

Future work with this model will focus on theoretical cases, exploring trade-offs between space allocated to pedestrian, buildings or vegetation for example, as well as various stereotypical urban morphologies.

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REFERENCES

1. Ratti, C., Baker, N. & Steemers, K., (2005). Energy consumption and urban texture. *Energy and Buildings*, 37(7), pp.762–776
2. Robinson, D., (2006). Urban morphology and indicators of radiation availability. *Solar Energy*, 80(12), pp.1643–1648.
3. Bueno, B. et al., (2012). A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate. *Building and Environment*, 54, pp.116–125.
4. Ihara, T. et al., (2008). Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. *Applied Energy*, 85(1), pp.12–25.
5. Steemers, K., (2003). Energy and the city: density, buildings and transport. *Energy and Buildings*, 35(1), pp.3–14.

6. Hughes, R.L., (2002). A continuum theory for the flow of pedestrians. *Transportation Research Part B: Methodological*, 36(6), pp.507–535.
7. Sailor, D.J., (2011). A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. *International Journal of Climatology*, 31(2), pp.189–199.
8. Kondo, H. et al., (2005). Development of a Multi-Layer Urban Canopy Model for the Analysis of Energy Consumption in a Big City: Structure of the Urban Canopy Model and its Basic Performance. *Boundary-Layer Meteorology*, 116(3), pp.395–421.
9. Nielsen, T.R., (2005). Simple tool to evaluate energy demand and indoor environment in the early stages of building design. *Solar Energy*, 78(1), pp.73–83.
10. Panão, M.J.N.O., Gonçalves, H.J.P. & Ferrão, P.M.C., (2006). A Matrix Approach Coupled with Monte Carlo Techniques for Solving the Net Radiative Balance of the Urban Block. *Boundary-Layer Meteorology*, 122(1), pp.217–241.
11. Robinson, D. et al., (2011). *Computer Modeling for Sustainable Urban Design: Physical Principles, Methods and Applications*, Earthscan.
12. Lozano, A. & Storchi, G., (2001). Shortest viable path algorithm in multimodal networks. *Transportation Research Part A: Policy and Practice*, 35(3), pp.225–241.
13. Shrock, R. & Wu, F., (2000). Spanning trees on graphs and lattices in d dimensions. *Journal of Physics A: Mathematical and General*, 33(21)
14. Wegener, M. & Fuerst, F., 2004. Land-Use Transport Interaction: State of the Art. *SSRN Electronic Journal*.
15. Enquête Nationale Transport Déplacement 2008, [Online], Available:http://www.statistiques.developpement-durable.gouv.fr/transports/r/transport-voyageurs-deplacements.html [May 2013]