ENERGY EFFICIENCY OF URBAN BUILDINGS: SIGNIFICANCE OF URBAN GEOMETRY, BUILDING CONSTRUCTION AND CLIMATE CONDITIONS

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Abstract

The energy consumption of urban buildings is affected by i) the surrounding microclimate which differs from standard weather data and ii) by mutual obstructions between buildings, which decrease sunlight and wind potentials for internal solar gains and passive cooling. The building construction itself affects both outdoor and indoor microclimate. This research addresses these interdependences in respect with energy performance. Several urban structures are investigated with various geometries (H/W, solar orientation) and building properties (thermal insulation and inertia, glazing ratio, etc.) and three different climate regions are considered: a mid-latitude location in Germany and two in the subtropics: hot-humid (Algiers) and hot-dry (Ghardaia). The numerical method used combines the urban canyon model TEB, and the robust building energy model (TRNSYS) for simulating building energetic and thermal responses to external and internal settings. Target quantities are heating and cooling loads, day-lighting, and natural ventilation potential. The huge amount of outputs is analyzed statistically (i.e. Design of Experiments). This paper is an introduction to an extensive research underway for the first time, and some results are presented exemplarily to illustrate the high relevance of this issue, the method applied and the significance of all investigated factors.

Keywords: building energy simulation, urban microclimate modeling, TRNSYS, TEB.

1. INTRODUCTION

Urban designers and architects increasingly face up to produce environmentally high quality urban buildings which effectively reduce the global energy consumption and gas emissions. The project introduced here aims at investigating the interdependences between urban and building scales in respect with energy performance, because the urban context and urban climate are often neglected in building energy analysis. The main objectives are to answer the following questions:

1. How the urban structure modifies the microclimate: air temperature, wind flow and irradiation quantities?
2. How this “new” urban microclimate affects the energy efficiency of an urban building?
3. At urban level: What are the effects of the street vertical profile and plan density in combination with solar orientation on the energy efficiency of an urban building?
4. At building level: To which extent are building describers like thermal insulation and thermal inertia, glazing ratio, material properties, etc. decisive?
5. How will the climate conditions influence the whole energy performance of the building?

Target quantities are: heating, cooling and total energy loads, as well as lighting and ventilation loads, and thermal Comfort. The present paper reports on first intermediate results.

2. METHOD

The method relies on numerical modeling with combination of two calculation models: at i) urban level by means of the urban canyon model TEB (Masson 2000) and ii) at building level with the powerful TRNSYS model. TEB is used for simulating the urban heat/cool effects on one hand (i.e. new urban air temperatures adjusted from standard climate data), and TRNSYS is used for simulating the energy demand indoors as shown in Fig. 1.

The mask effects due to neighboring buildings have been included in TRNSYS. Solar radiation fluxes and day-lighting potential for each building thermal zone facing the in-canyon have also been adjusted in the building model according to the obstacles effects.

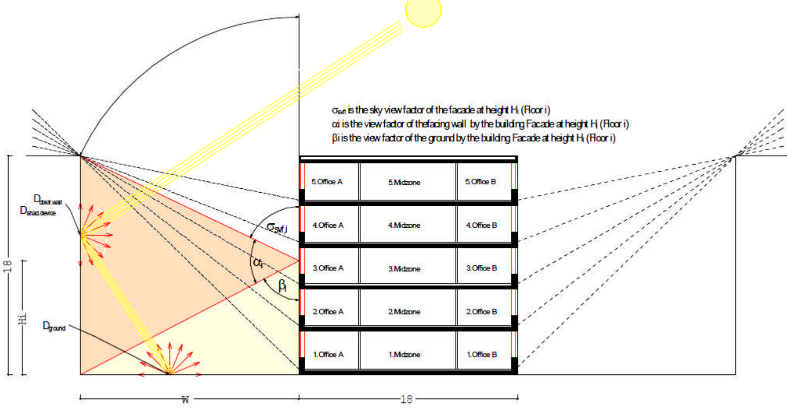

Fig. 1: Office Building in a row-type urban structure as simulated with TRNSYS 16, including 10 thermal zones with external exposure.

The investigation consists of a parametric study where urban describers, building describers, as well the climate are varied (Table 1). A number of urban structures are investigated with various urban canyon geometries and building properties (height-to-width ratio, solar orientation, building envelope, materials, etc.). First, the urban microclimate changes due to the urban structure itself is assessed including thermal, irradiation components and wind flow, as these constitute the actual ambient climate under which the urban building performs. Secondly, thermal conditions, passive solar gains, heating & cooling loads are quantitatively investigated for one office building in each urban context for variable building describers as given in Table 1. Table 2 lists the main settings.
The "Design of Experiments DoE" statistical method is used for analyzing the huge amount of outputs by highlighting within a hierarchy i) the individual effects of each investigated parameter on the resulting energy quantities, ii) the multiple interactions between the input parameters and their effects on the target outputs and finally iii) by providing an overall prognosis formulae which expresses the output Y in dependence with all relevant x_i inputs ($Y = f(x_1, x_2, x_3 \ldots x_n)$). The final goal is to provide the urban designer and architect with useful guidelines at early design stages for optimized use of renewable energy. This research is a contribution to an integrated methodology which links between the urban scale (urban microclimatology) and the building scale (building physics).

Table 1: Variables of the parametric study used for TEB and TRNSYS simulations

	ID	coded form →	-1	0	1
Urban context	A =	vertical profile*	H/W = 0.2	H/W = 1	H/W = 1.8
	B =	solar orientation*	NS	NESW	EW
Building	C =	glazing ratio*	30%: hole facade	60%: row facade	90%: glass facade
	D =	thermal heat insulation*	U_{wall} = 0.15 U_{window} = 0.7 U_{roof} = 0.10	U_{wall} = 0.40 U_{window} = 1.5 U_{roof} = 0.35	U_{wall} = 0.65 U_{window} = 2.3 U_{roof} = 0.60
	E =	thermal inertia	light construction	-	massive construction
Climate	F =	climate	Mannheim: 49.31°N	Algiers: 36.24°N	Ghardaia: 32.34°N
* Values are set equidistant to be appropriate for the DoE statistical analysis. Climate data for Mannheim are provided by the test reference year TRY 12; for Algiers and Ghardaia by the software METEONORM 5.0. Total number of simulations runs with all possible variables combination (full factorial): 486.					

Table 2: General settings for the TRNSYS simulations

Building description	Office building with 5 thermal zones on each orientation.
Occupation Period (OP)	8:00 - 18:00 on weekdays. No use on week-ends.
Heating	6:00 - 20:00 during OP. set temperature T_a = 20°C. 17°C outside OP (night-time sink).
Cooling	Set ON from if operative temperature $T_{op} \geq 26$°C during OP. No cooling outside OP
Ventilation Rates*	Daytime during OP: 4 vol./h if 20.5°C ≤ $T_{op} \leq$ 23°C and $T_{a,ext} < T_{op}$. and 1.6 vol./h if $T_{op} >$ 26°C and $T_{a,ext} \geq T_{op}$. 0.1 vol./h as infiltration rate and used outside OP. Night-time: 1vol./h. when 17.5°C ≤ $T_{op} \leq$ 23°C.
Internal Gains	Persons: 2 persons 75W / person. Equipment: 230 W (PC's) Artificial Lighting: 10 W/m^2, fluorescent light. All during OP.
Shading Devices	Shading factor = 0.75 (75% of solar radiation reflected away)
* The simulations here are based on ventilation rates but further simulations are underway which consider the potential of natural ventilation as modified by the urban structure calculated by means of TRNFlow.	

3. RESULTS

3.1. Urban Air Temperatures

Figure 2 shows as an example urban air temperatures calculated with TEB on hourly basis for one case study (C = -1, D = -1, E = 1, A & F = all, B indifferent). It shows that urban air temperatures are effectively different from standard climate data with a clear trend of warming of the canyon up to 2 K as far as the geometry is concerned. Basically, both heating and cooling effects are more significant for the arid subtropics (GHA) due to more global radiation on one hand and to shading effects on the other alternatively. Extreme values of air temperature deviation (urban- rural) in both positive and negative cases are attributable to the relative inertia of the urban structure which makes it react slowly to occasional abrupt variations of the standard data used as inputs. Figure 2 also makes clear that standard climate data are not representative for building energy simulation in urban context and case to case adjustment of air temperature at hourly basis is necessary for including the impacts of the urban geometry, geographic location and building construction. Systematic investigation of more combinations is underway with focus on a detailed analysis in respect with TEB and TRNSYS simulation settings.

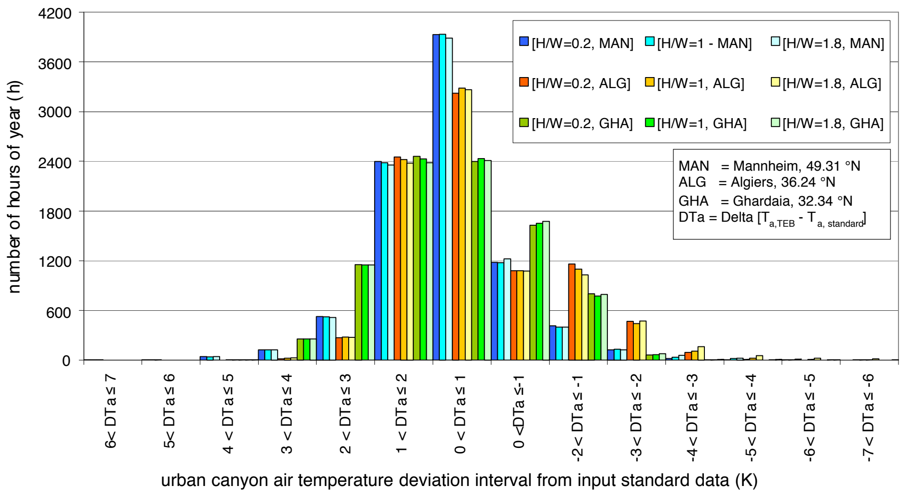

Fig. 2: Example of TEB-simulated urban canyon air temperatures deviation from standard climatic data for various vertical profiles, massive building construction with hole façade (30%) and high thermal insulation, for 3 climate locations.

3.2. Heating and Cooling Energy Needs

Energy needs shown in this paper are average values for the 10 thermal zones of the building having external façades. These values are surface-related and calculated over one year and expressed in kWh/m^2a.

Figure 3 shows one example of energy demand calculations for the climate region Mannheim, Germany (49.31°N) with adjusted air temperatures to urban context.

Table 3 summarizes the results of the statistical analysis for the same case study and lists the regression coefficients showing the main impacts of each individual input as well as the double interactions between inputs and their effects on outputs. Positive values reveal a proportional effect whereas negative values mean inversely proportional effect. The sign x means no relevant effect.

As an example, the resulting formulae (in coded form [-1, 0, 1]) which allows the heating energy calculation is as follows:

$$Y = 38.61 + 2.20A + 11.21C + 18.05D + 8.40D^2 + 1.10AC + 6.79CD + 1.32CE - 0.56DE$$

And for the total energy demand:

$$Y = 47.98 + 0.92A + 13.32C + 17.75D - 3.98E + 5.25D^2 + 6.32CD$$

Table 3: Example of a statistical analysis for Mannheim (i.e. TRY12 adjusted for urban context with TEB).

Variable	Heating	Cooling	Total
Intercept	38.61	7.62	47.98
A	2.20	-0.89	0.92
C	11.21	1.80	13.32
D	18.05	-0.30	17.75
E	x	-3.84	-3.98
D^2	8.40	-2.71	5.25
A : B	x	-0.26	x
A : C	1.10	-0.52	x
A : E	x	-0.41	x
C : D	6.79	-0.43	6.32
C : E	1.32	-0.82	x
D : E	-0.56	0.32	x

Basically all parameters have opposite effects on heating (+) versus cooling (-) except C, the glazing ratio, which has the particular effect to raise both heating and cooling if increased. Heating needs increase with increasing H/W, more glazed façades, less thermal insulation; whereas cooling needs decrease with deeper streets, less thermal insulation and massive construction. Hierarchically, parameter D (thermal insulation) and then C (glazing ratio) are the most influencing the energy demand, followed by E (thermal inertia). D^2 is a squared term which means a quadratic and not linear relationship between thermal insulation and energy demand. Increasing the vertical profile H/W (A) leads to an increase of the total energy demand due to more heating needs as a result of more shadowing of the canyon and so the building facades, although less cooling is required for the same reason. The parameter B (solar orientation) shows no decisive effect because the energy demand values reported here are averaged for 2 orientations each time (i.e. N & S, E & W, NE & SW); yet a separate evaluation would better reveal the own impact of B. In addition to these main effects of individual parameters, double-interactions exist which influence the energy demand: For example A is interactive with the solar orientation B, glazing ratio C and thermal inertia E, especially for cooling. Building describers C, D and E are all interactive with a dominant effect of the pair glazing ratio – thermal insulation C : D.

Figure 3A shows the energy demand at a glance. Figs. 3B and 3C show the difference in the energy need if standard data are used versus adjusted urban air temperatures. Cooling needs increase when the urban heat island effects are included (T_a adjusted with TEB) and this is more evident for light construction and low density (because high density provides more shade). By contrast, heating demand is basically lower if urban context is well modelled because of higher outside air temperatures, except for not well insulated light-constructed buildings.

The hierarchical importance of all investigated variables as well as the urban context relevance briefly introduced here is specific to the location of Mannheim (49.31 °N). Very different energy patterns are found for Algiers and Ghardaia (not shown here) for which the subtropical location characterized by intense solar radiation, higher temperatures, etc. are much strongly influenced by urban describers like the vertical profile or the solar orientation and where the building describers affect the energy demand in another way. For example thermal insulation has a less decisive impact. Extensive results for all cases with the corresponding analysis will be made available soon.

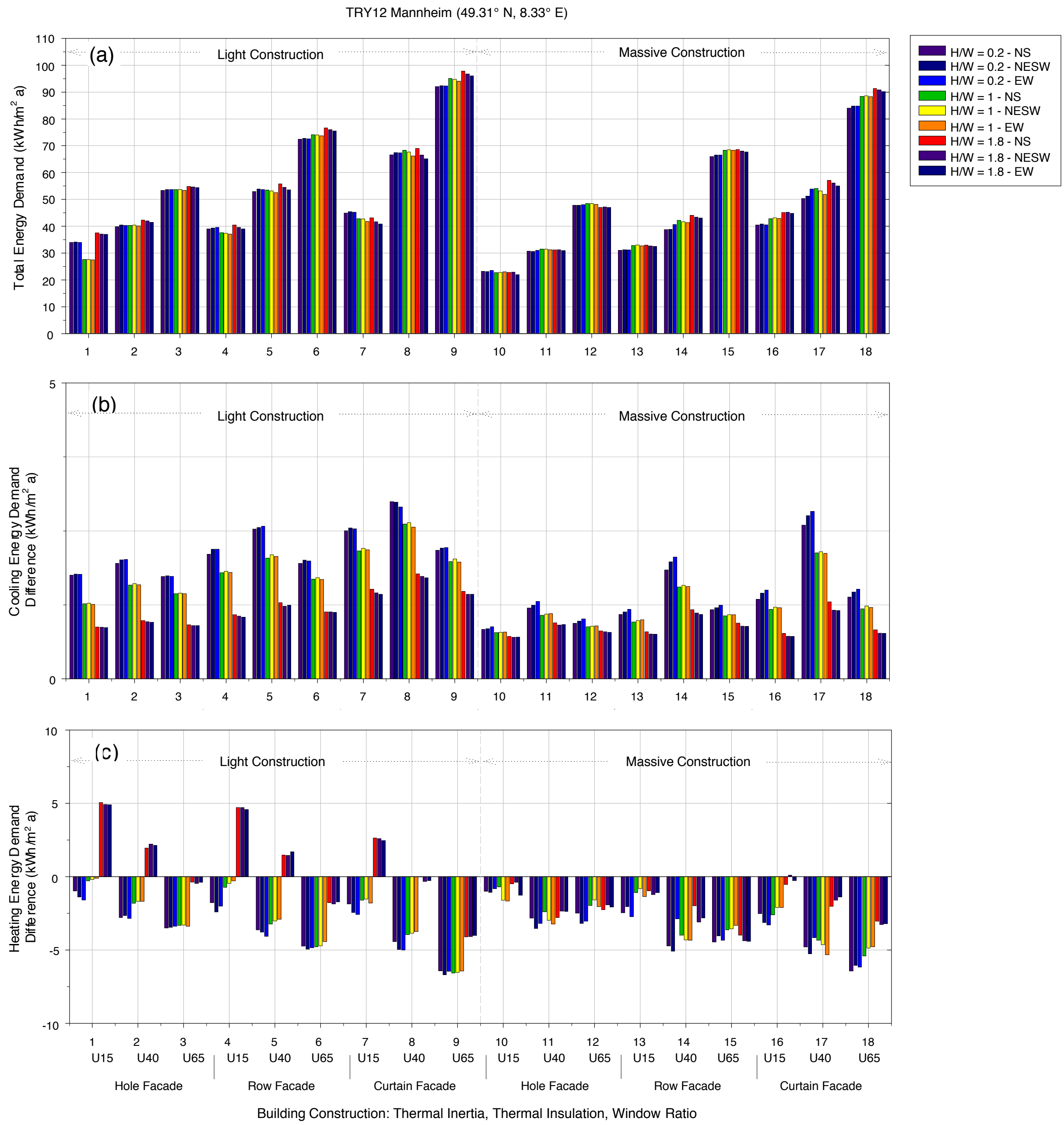

Fig. 3: (a) Total energy demand for Mannheim (49.31 °N) in dependence with urban and building describers and a comparison for (b) cooling and (c) heating between urban climate data versus standard data as inputs

4. CONCLUSION

The present paper has shown exemplarily some intermediate results on an ongoing project which aims at exploring the effects of urban context, building construction and climate on internal energy needs. The relevance of adjusting air temperatures according to urban context including vertical profile geometry, urban density and building materials has been shown. The importance of all building describers has also been addressed for one case study. The present research is gathering by modelling more knowledge about these interdependences which will be reported on soon together with a discussion of the capabilities of the models used as method.

References

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