ROBUSTNESS OF BUILDING DESIGN WITH RESPECT TO ENERGY RELATED OCCUPANT BEHAVIOUR

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ABSTRACT

Occupant behaviour is often the first reason for the discrepancy between designed and real total energy use in buildings. A possible solution to bridge this gap is designing buildings whose performances show little variations despite of alternating occupants' behaviour.

The aim of this work was to investigate how occupants' behaviour varies according to the building envelope design: different input values have been chosen for three design features – thermal mass, transparency and solar shadings – in order to discover the most robust ones.

The study is carried out through simulations on an office building in 3 weather climates and probabilistic models for window opening and use of shading, based on real occupants' behaviour, have been implemented.

By testing the influence of building's design on occupants' behaviour, the present contribution highlights the importance of the robustness' evaluation of a building during the design phase in order to obtain more realistic energy predictions.

INTRODUCTION

Energy consumption data depend on a complex array of factors often causing a significant discrepancy between the designed and the real total energy use in buildings. These factors, listed in framework of the IEA-ECBCS Annex 53 project, are: 1)climate, 2)building envelope, 3)building equipment, 4)building operation and maintenance, 5)occupant behaviour and 6) indoor environment conditions.

The reason for the well-known discrepancy lies in the fact that in the current practice they are not studied with the same level of investigation. While designers' approach is focusing on the first 3 factors, defined by *Schweiker et al.* (2010) the building "hardware", many studies prove that the latter 3, related to human behaviour, called by Schweiker the "software", can have an influence as great as or greater (*Schweiker et al.* 2010).

Since predictions of building energy consumption are developed using simulation software, deficiencies in describing human related factors have to be identified in these tools.

However limitations of simulation tools in understanding users' behaviour can be justified: while methods of analysis investigating buildings' thermal performances are based on deterministic heat transfer and thermodynamic equations, occupants' behaviour is the result of a continuous combination of several factors crossing different disciplines and therefore is still object of investigation.

Several field surveys conducted in a wide range of environments (*Nicol et al.* 1999, *McCartney and Nicol* 2002) proved that people have a natural tendency to adapt to changing conditions in their environment. This natural tendency is expressed in the adaptive approach to thermal comfort, developed by *Nicol and Humphreys* (2002), whose underlying principle is conceptually clear: "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort".

The main difficulty in translating this statement into predictive models of occupants' behaviour lies in the definition of "discomfort" according to different users. Moreover occupants have many possibilities of interaction, named "action scenarios" (*Fabi et al.* 2011), with the indoor environment: they can operate directly aiming at controlling the indoor environment i. e. using thermostat, operating on windows or shadings, they can affect it unintentionally, i. e. by appliances and equipment usage, and finally they can adjust themselves to the existing environmental conditions.

Uncertainties arising from drivers and action scenarios' description are the evidence of difficulties in modelling occupant behaviour in simulation programs.

In office buildings, a possible solution to avoid discrepancies between predicted and real energy consumptions due to users' actions could be using totally automated energy management systems. These modern control systems offer the potential to improve individual comfort and reduce energy consumption at the same time. However, fully automatic control is not the complete answer: studies of building-related ill-health (for instance the Office

Environment Survey, "OES", 1987) reveal fewer symptoms and greater productivity as the perceived level of individual control increases. Therefore, in a sector where personnel costs dominate all other costs related to building operation by two orders of magnitude, appropriate workplace conditions are of the utmost importance for the economic success of companies.

Wagner et al. (2007) with their field studies on thermal comfort in German office buildings, proved that in summer occupants appreciate naturally ventilated and passively cooled buildings, with positive perceptions of thermal comfort even outside the temperature limits set in standards. Moreover both in summer and in winter the perceived effect of possible interventions on indoor climate strongly influences the thermal satisfaction. It may be concluded that user's influence on indoor environment is a prerequisite for a correct functioning of the human body.

The growing extent of users' actions in influencing energy consumption comes out clearly, stressing the importance of reliable occupant behaviour models despite the predictive uncertainties first listed.

Handling occupants' behaviour's uncertainties and providing a satisfactory indoor climate, while maintaining the highest degree of user's freedom, should be one of the main purposes in energy efficient building design. Therefore a further step of application of occupant's behaviour models is verifying the "robustness" of the building thermal behaviour with respect to the users. Once the user's behaviour has been characterized by a model and it is verified its impact on energy performance with a number of simulations, it is interesting to check what happens changing the building properties and equipment with the same user behavioural pattern.

Hoes et al. (2009) define "robustness" as "the sensitivity of identified performance indicators of a building design for errors in the design assumptions". Since among the most erroneous design assumptions occupants' behaviour has a major role, the main question arising when dealing with the building's robustness is:

How different buildings respond to differences in user's behaviour?

The aim of this paper was to analyse the relationship of two actions related to users' behaviour in office buildings (interaction with windows and with solar shadings) with building envelope characteristics and building performance and to evaluate how various users' behaviour impact different envelope designs.

CASE STUDY

The case studies were performed using the Reference Office Building as the case study for this research.

The selected Reference Office Building is the result of a survey carried on by the Italian institutions CRESME (Centro Ricerche Economiche, Sociologiche e di Mercato) and ENEA (Ente per le Nuove Tecnologie, Energia e Ambiente), with the aim of defining office typologies useful for energy analysis of the whole Italian office building stock. Report RSE/2009/164 shows the reference models coming out from the research, characterized by different design features according to period of construction and location. As building features result from a survey of Italian office buildings, conclusions deriving from this work can be reasonably applied to a wide range of buildings. The most recent model, located in the north of Italy, was chosen.
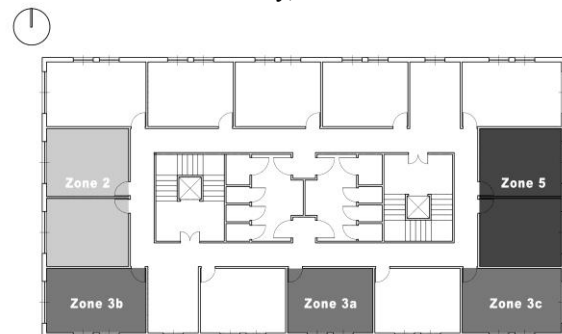

Figure 1 Considered thermal zones of the Reference Office Building

The specific subject of the study is the standard floor, characterized by the typical cellular office distribution. It is divided in five thermal zones, among whom only zones where orientation has a more significant influence on energy consumption are taken into account: as shown in Figure 1, zones facing west (zone 2), south (zone 3) and east (zone 5) are considered. Moreover the zone facing south has been divided in 3 sub-zones, corresponding to the cellular offices located at the building corners (zones 3b and 3c), and an office facing south (3a). Each of them has been modelled as a naturally ventilated office with a water radiator and a cooling device. Zones' characteristics are summarized in Table 1.

Table 1
Zones' characteristics

Zone	2	3a	3b	3c	5
Area [m²]	40	20	24	24	40
Length [m]	8	5	6	6	8
Depth [m]	5	4	4	4	5
Height [m]	3,5	3,5	3,5	3,5	3,5
Orientation	West	South	South, West	South, East	East
Windows area [m²]	7,20	3,42	7,02	7,02	7,20
Window/Floor ratio	0,18	0,17	0,29	0,29	0,18
Heating MAX power[kW]	6,3	3,15	3,78	3,78	6,3
Cooling MAX power[kW]	2,5	2,5	3	3	2,5

Simulation approach

To consider the actual influence of occupant behaviour during the design phase, realistic mathematical models describing users' interaction with the building's controls were selected for being implemented in the simulation tool. Using these models entails both input and output to be considered a probabilistic distribution of values, in contrast with the exact and single values provided by a static definition of users' patterns.

The software IDA ICE has been used in the study with this goal: in this dynamic simulation software mathematical models are described in terms of equations in a formal language, NMF, so that at the advanced level probabilistic equations describing users' interference with any type of controls can be implemented.

Following findings of *Raja et al.* (2001), in this research the focus is on the occupants' interactions with windows and mobile shadings, while occupancy, lighting, equipment and plants' operation time and temperatures are defined by deterministic schedules. In fact *Raja et al.* (2001), performing a field study in fifteen naturally ventilated offices across UK, found out that opening windows and drawing blinds are the most extensively used building controls to modify indoor thermal conditions.

Therefore two different statistic models, one referred to the use of windows and one referred to actions on blinds, were implemented in IDA ICE.

The selected behavioural model for actions on windows was published by *Haldi and Robinson* in 2009 and it has been developed after seven years of continuous measurements in the Solar Energy and Building Physics Laboratory (LESO-PB) in Lausanne, Switzerland.

Fourteen south-facing cellular offices of the LESO building were monitored from December 2001 to November 2008 and the following variables were measured: indoor temperature, occupancy, window openings and closings, outdoor temperature, mean wind speed and direction, relative humidity and rainfall.

The authors demonstrated the higher predictive power of the discrete-time Markov process approach with sub-models for different occupancy statuses. Therefore the proposed model based on Markov process was chosen to be implemented in the in the Reference Office Building model built in IDA ICE.

Guided by the preliminary observation that actions on windows mostly occur when occupants arrive or leave their office, different transition probabilities between the states of a window have been inferred for actions on arrival, at departure and during occupancy, as proposed by *Herkel et al.* (2008). For each sub-model the logistic regression is performed on the most relevant environmental parameters.

In order to convert the calculated probabilities into deterministic signals, which could be implemented in the simulation program, each of them was compared to a random number between 0 and 1. Since the calculated probability was the probability of a window opening or closing within the next five minutes, the comparison was made with a random number that changed every five minutes. The sets of uniformly distributed random numbers were generated by Excel and loaded into IDA ICE as an external source file. If the probability was higher than the random number, the window would open. The window would then stay open until the probability of closing the window was higher than the matching random number.

A probabilistic distribution of energy consumption depending on user type was obtained by running ten simulations, switching ten times the random number list in the simulation program.

Since the degree of opening was not a measured data during the monitoring campaign, a fixed degree of opening was assumed in the model, corresponding to a tilting angle of 20% of the total window opening area.

Dealing with the users' interaction with mobile shadings, the behavioural model for the blinds' use developed by *Haldi and Robinson* (2008) has been chosen for being implemented in IDA ICE.

The logistic model considering outdoor temperature was selected. This choice was driven by the consideration that lowering blinds could influence indoor temperature, with the possibility that the variable and the expected probability influence each other.

The same implementation method used for the window opening behavioural model is followed.

Simulation strategy

Since robustness is "the sensitivity of identified performance indicators of a building design for errors in the design assumptions" (*Hoes et al.* 2009), a robust building is a building that shows little variation in performance despite of variable occupant's behaviour. Therefore the behavioural models implemented on IDA ICE for the Office Reference Building are used for checking what happens if changing the building's properties with the same user behavioural pattern. A variation in the probability distribution of energy performance's results among models with different envelope designs is the expected outcome: varying several times the occupants' profile for each model variation, not robust models will show a wide difference in energy consumption, while robust buildings' energy performances will be similar to each other.

In order to illustrate the impact of office design on occupant behaviour and on energy use in the building, several version of the basic Reference

Office Building are created with alternative design features.

The investigated design features are thermal mass, transparency and shading. These passive design solutions can play an important role in reductions of energy use for heating and cooling as well as of energy consumption's variations due to changes in occupant behaviour. For each design feature, different input values were chosen: high and low thermal mass, higher and lower transparency ratio respect to the basic model, shadings' absence or presence, with different shading strategies. These characteristics were combined, as shown in Figure 2, to create 15 scenarios. To widen the research, the considered five thermal zones of the analysed floor of the Reference Office Building, are simulated in three weather climates – Stockholm, Frankfurt and Athens – with the aim to investigate how the different building design's options affect the building's performances and robustness when location and orientation are varied.

Data analyses

Results of the analysis of each scenario dealt with three performance indicators: ventilation rates, energy use for cooling and for heating. Heating and cooling energy consumption are the pointer of the building energy performances, while in a naturally ventilated building the effect of building design on user's behaviour is revealed by variations in the air change rate. In fact, variations in air change rate were the evidence of a shift in the window opening behaviour governed by a change in the indoor climate large enough to influence the probability of the window to be opened.

Results were expressed by the average values for the performance indicators and the results' variation for each scenario due to different users' types. This variation, which is the measure of the sensitivity of performance indicators (energy consumption, air change rate) with respect to changes in occupant's behaviour, was expressed through the relative

standard deviation respect to the basic model (RSD ref.). RSD ref. has been calculated by relating the standard deviation typical of each model with the reference average values, defined in this research as the results obtained from the Reference Office Building simulations with its original design, consisting of light envelope, medium dimensions glazed surfaces and no shadings. The smaller the RSD ref., the more robust the building's design.

The average value was useful to analyse the contribution of the building features in modifying the energy performance, while the RSD ref. allows understanding the building features' contribution in modifying the occupants' influence.

Trends coming out from the investigation of the influence of building design on cooling and heating energy consumption and air change rate's average values confirmed the general concept of building design, therefore they are not object of this analysis.

The focus of the research, instead, was on how the building envelope design, the zone's orientation and the weather climate modify the robustness' degree of the building.

Analysis was carried on gradually. First, to clearly asses the influence of the varied building designs, every scenario was tested in the thermal zone with one external wall facing south in Frankfurt.

Then, all the thermal zones of the office located in Frankfurt were analysed with the fifteen different scenarios, in order to investigate how the building envelope design modified energy consumption and occupants' interaction with windows in different ways in different zones.

Finally, the combined effect of varying the design features and the thermal zone in every weather climate was considered, to explore in detail if building features have the same robustness' degree in every climate.
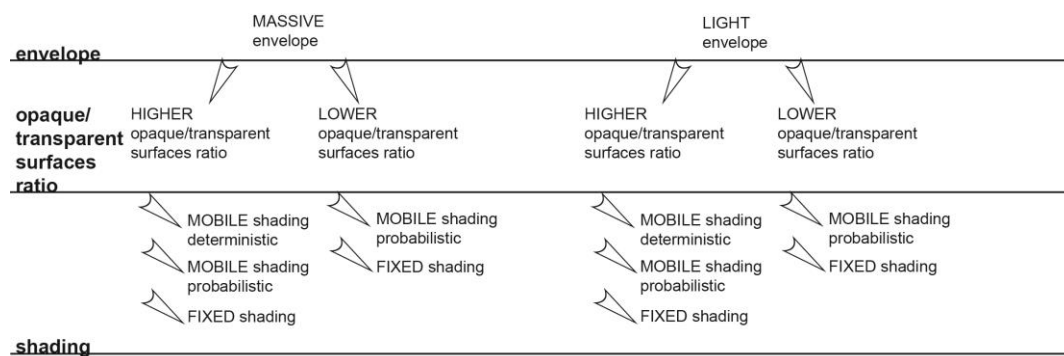

Figure 2 Scenarios created from the building envelope features' combination

RESULTS

To understand the robustness of each scenario with respect to all the performance indicators in the different climates and thermal zones, two series of graph are shown. As a sample for the influence of weather climate, Figure 3 and 4 shows the RSD ref. in zone 3a, facing south, in Stockholm, Frankfurt and

Athens, for air change rate and average values derived from the RSD ref. values for heating and cooling energy consumption. Figure 5 and 6, 7 and 8, 9 and 10, instead, take into account the influence of the zones' design and orientation on the robustness degree respectively in Stockholm, Frankfurt and Athens.
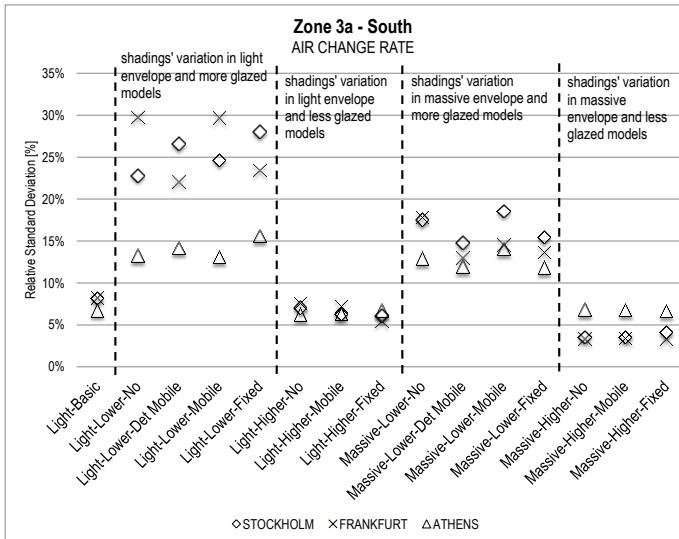
Figure 3 RSD ref. for air change rate in zone 3a in Stockholm, Frankfurt and Athens
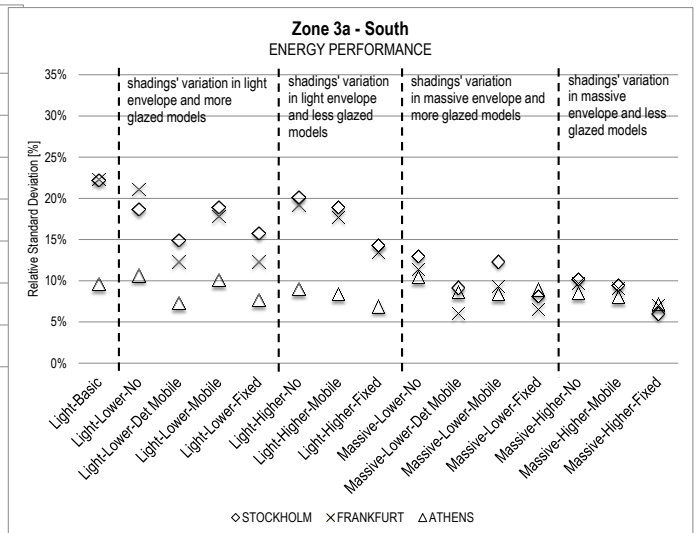
Figure 4 RSD ref. for energy performances in zone 3a in Stockholm, Frankfurt and Athens
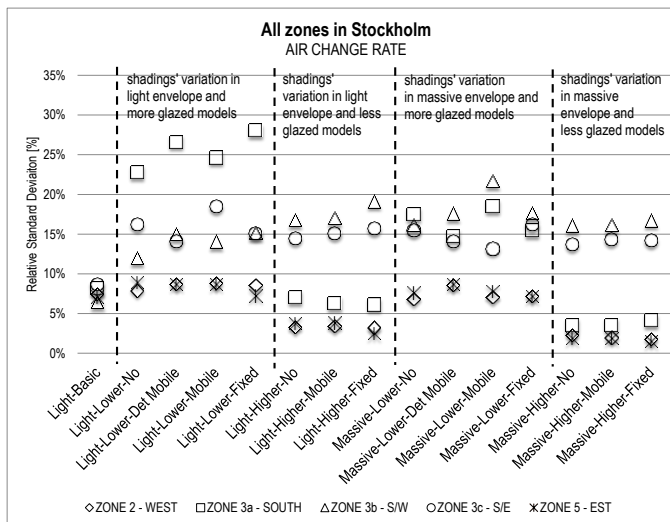

Figure 5 RSD ref. for air change rate in all the analysed thermal zones in Stockholm
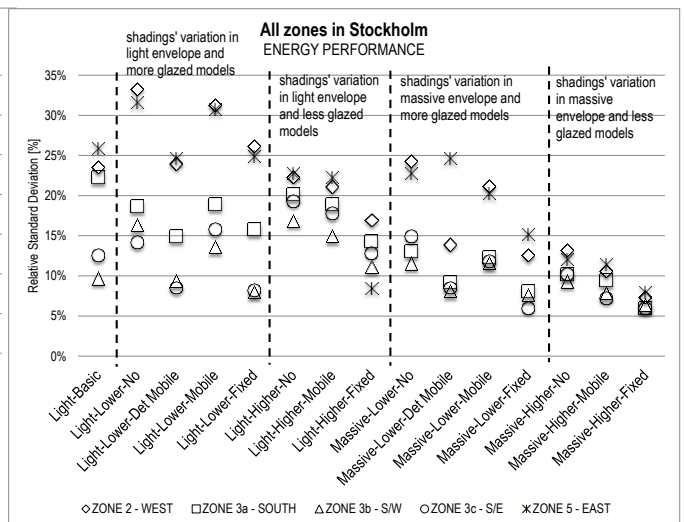

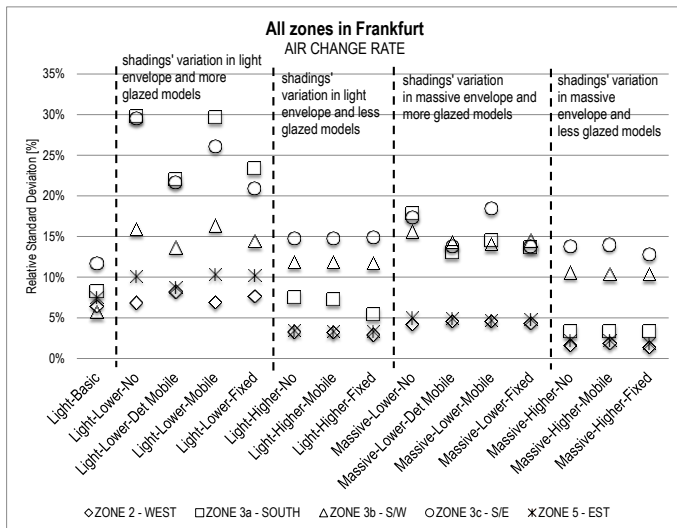*Figure 6 RSD ref. for energy performances in all the analysed thermal zones in Stockholm*

Figure 7 RSD ref. for air change rate in all the analysed thermal zones in Frankfurt
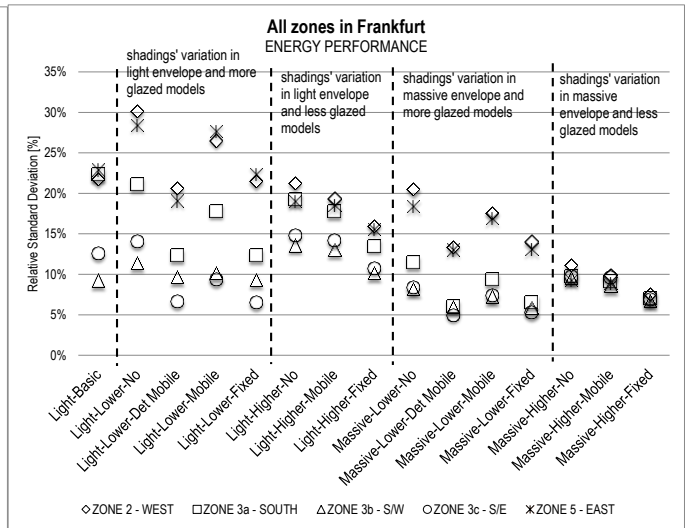

Figure 8 RSD ref. for energy performances in all the analysed thermal zones in Frankfurt
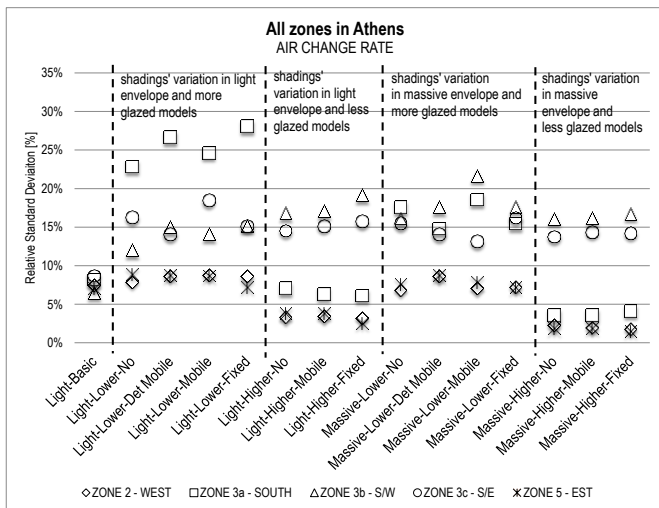

Figure 9 RSD ref. for air change rate in all the analysed thermal zones in Athens
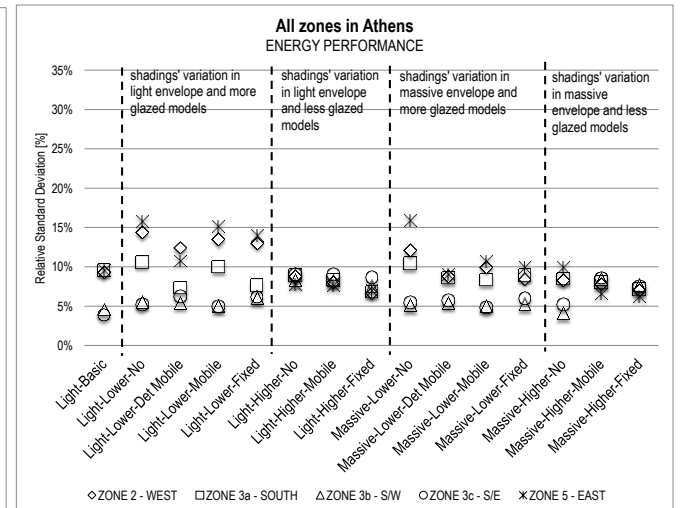

Figure 10 RSD ref. for energy performances in all the analysed thermal zones in Athens

DISCUSSION

Conclusions drawn from the analysis of both the relative standard deviation for air change rate and the average relative standard deviation are summarized to obtain some general remarks about how building features, thermal zones' orientation and characteristics and climate influence occupants' behaviour and the building's robustness. Even if with different impacts due to the climate and thermal zones' characteristics, massive envelope, closed façade and fixed shadings were the most robust building features. Thanks to their ability to slow down the response of the building to changes in outdoor conditions, these characteristics allow to stabilize the indoor temperature so that occupants, exposed to similar condition for a longer period, are led to interact with windows according to similar patterns more often. Dealing with the impact of

climate, it can be stated that in Athens both the RSD ref. for air change rate and the average RSD ref. were the lowest and that the building envelope design had the lowest influence on the occupants' behaviour. The role played by the building features in modifying occupants' behaviour was more significant in the cold climates: in Frankfurt and Stockholm varying the building envelope can have a significant influence in centring the probabilistic results' distribution with respect to the average value.

Some general remarks about how variations in the building's envelope affect occupant's interactions with windows and robustness' degree in different thermal zones could be made as well. Dealing with cooling and heating energy consumption, the robust characteristics (high thermal mass, small windows and fixed shadings) drastically reduced the difference in robustness (in RSD ref. values) caused by the different zones' design and orientation. On the

contrary, for air change rate the results' fluctuation for the more robust scenarios was still related to the zones' characteristics: since variations in air change rate results' fluctuations stand for variations in occupant behaviour, differences among zones were assumed to be a remarkable influencing factor in modifying users' actions on windows. Moreover, comparing the same zone in different climates, results highlighted that in zones with one external wall the impact of building design was defined for every climate, following the general trend previously described (being massive envelope, closed façade and fixed shadings the most robust building features). On the opposite, in zones with two external surfaces no similar trends could be noticed when switching from one climate to another and in every location the building design did not consistently modify the robustness. Therefore in zones with a high external surface/floor ratio the climate had a deeper impact on occupants' behaviour and general robustness' degree than the building design. The authors used the statistical models presented in Haldi and Robinson (2010) to simulate the occupants, window opening and shading behaviour. The shading model was a result of a field survey conducted in 2006 in several non-air-conditioned office buildings located in Switzerland, with the aim of developing a new predictive model of overheating risk. Therefore, the analysis presented by Haldi and Robinson, concerning the prediction of the probability of occupants' interactions with a range of personal and environment characteristic, is a by-product. Consistent with the main aim of their field study, non-thermal variables were not studied: the measured physical parameters were just indoor and outdoor temperature. Beside measurements, longitudinal questionnaires were given to volunteers from each building at regular intervals, asking for evaluations of clothing and activity level, thermal sensation and preference and adaptive opportunities exercised (including actions on blinds). In order to infer a probability distribution for the whole range of temperature (both internal and external) the logistic regression is used to study each adaptive action. In their conclusions, Haldi and Robinson raise doubts about the predictive power of every proposed model, stating that, since lowering of blinds allows reducing solar heat and glare, radiance should have been a considered parameter as well. Moreover, only lowering of blinds, and not rising, is considered. Despite the highlighted deficiencies, we decided to use this model for three main reasons:
- It is one of the most recent works analysing several monitored control actions, including the use of blinds, with a statistical approach.
- The proposed logistic regression model can be implemented in IDA ICE.

- The field survey was performed in Switzerland, as well as the field survey investigating windows opening. Since occupants' behaviour is influenced by social and contextual factors, using behavioural models derived from observations on users from the same area can be a warranty of coherent use of the building controls.

CONCLUSION

Building envelope's design played an important role in modifying occupant behaviour, which is a key factor in obtaining more realistic simulations' results. Having a massive envelope, a closed façade and fixed shadings provided the lowest fluctuations in results when switching the users. Therefore these building's features, able to centre the simulations' set results respect the average values, were the most robust ones. This observation was most evident in Frankfurt and Stockholm particularly in zones with one external wall. Conversely, in Athens designers have more possibilities to choose the envelope's features, since they did not affect so the results' variation to the same degree. This robustness study showed how dynamic simulation software can be used as tools during the design phase: detailed occupants' behaviour's description will allow better defining the building's features' robustness' degree when different design options are compared, in order to obtain the proper solution.

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