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Robustness of a building

Relationship between building characteristics and energy use and health and comfort perception

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Abstract

Buildings sometimes use much more energy than expected and occupants show high levels of health symptoms and low perceived comfort. This paper aims at showing that some building characteristics or combinations of building characteristics simultaneously lead to low energy use and higher perceived health and comfort and are therefore considered to be more "robust", meaning that these building types better live up to the expectations set up during design stage. This study is based on the statistical analyses of two different existing field study databases. The influence of various building characteristics and systems, like HVAC characteristics, design related characteristics or user interaction to the building characteristics, on perceived health and comfort and on energy use has been studied independently for each database and then compared. Specific combinations called 'design profiles' have been defined and have been compared with the same indicators. Statistically significant results showed that certain single characteristics and some design profiles clearly contributed to reasonable energy use, better health and comfort perception or to both, which confirms the robustness hypothesis.

Keywords

Perceived comfort and health, energy use, robustness, building characteristics, HVAC

Introduction

Countries like the Netherlands sharpen the energy efficiency requirements for buildings to induce lower energy use. At the same time, there is a high expectation on buildings for offering a comfortable and healthy environment. Both energy efficiency and indoor comfort are translated into rigorous lists of requirements that must be respected during building design phase and supposedly also after construction.

But in a real life situation, buildings do not always meet the requirements defined during the design phase. A study for SenterNovem (Climatic Design Consult, 2004) shows that in practice, buildings sometimes use more energy than expected according to design stage calculations. Another study (Schiller et al., 1988) shows that users of buildings where temperatures stay between the AHSRAE comfort zone limits are still not satisfied with their indoor environment. This same study even suggests that there is a correlation between high energy consumption and dissatisfaction about indoor climate. A study ordered by the Institute of Dutch Architects, BNA, and performed by BBA shows that even if physical measurements show that air quality and room temperature are within standard limits, perceived air quality and thermal comfort assessed by school building users is worse than what could be expected in that environment (Juricic et al., 2011). What is more, there is no correlation between money spent and quality of the building, which raises questions like whether complexity and expensive devices really can help having comfortable indoor environments.

These studies also suggest that certain buildings cannot meet expected performance, which means that maybe they have particularities that prevent them from performing as they should. In buildings where the energy consumption is higher than expected and where occupants declare health and comfort related complaints, certain building characteristics and systems could be expected to cause a building to perform badly, especially in cases where measurements of indoor environment parameters do not explain discomfort. And on the contrary, some other building characteristics might contribute to a lower energy use and to better perceived comfort and health.

Not being able to live up to the building performance expectations could also have an influence on productivity and health of building occupants, which involves costs at several levels. Fisk (2000) estimates the potential annual savings and productivity gains above the $40 billion and up to $200 billion in the US. Providing high performing buildings in practice is then not only an environmental issue but also a social and economic issue.

Purpose of the study

The purpose of this study is to evaluate relevant building characteristics and systems, as well as combinations of them and their influence on the ability of a building to perform as expected in the design stage.

The hypothesis is that there will be specific building parameters and combinations of parameters that lead to low energy consumption and at the same time a higher level of perceived health and comfort Therefore buildings with these characteristics are considered to be more “robust”, meaning that these building types better live up to the goals aimed for during the design stage.

Definitions

To begin with and from this point on, with building characteristics is meant characteristics of the building design itself, characteristics of the Heating, Ventilation and Air Conditioning (HVAC) systems and characteristics of user control. In this study, some building characteristics have been evaluated and are described in section methodology. What is more, one can consider that the term perceived comfort covers several aspects: perceived air quality, thermal comfort, visual comfort and acoustical comfort. All four of them will therefore be studied. Furthermore and unless it is specified, “comfort” will just refer to the general meaning, covering all four aspects. Health perception can be described by the amount of health related complaints occupants can have. Those symptoms attributed by the users to the building they work in and are called Building symptoms.

Because of limited data available, the study will only focus on office buildings. The buildings studied are located in Western and Central Europe, which have temperate climates.

Method

To perform this study, it has first been necessary to establish a list of relevant building characteristics, based on an analysis of heat transfers mechanisms in buildings, literature and personal assumptions.

Table 1: Building characteristics that have been selected for the present study

Design characteristics	Thermal mass for heat storage
	Glazed surface and orientation
	Insulating properties of the envelope
	Insulating property of the windows
	Floor area
	Compactness of the design
User influence	Individual control for heat and cooling
	Daylight control
	User occupation density
	Operable windows
	Artificial light management
HVAC	Ventilation rates
	Type of ventilation
	Humidification
	Active cooling
	Heat recovery
	Heating and cooling terminals

This list is then confronted to available data. For this exploratory study it has been chosen to use two existing databases. The first one, issued from the European HOPE project, contains a study of 66 office buildings. The second one is a Dutch study for NL Agency, and consists of calculations of the Energy Efficiency Coefficient and measurements of the actual energy consumption of 82 office buildings. In addition to studying each building characteristic separately, building design "profiles" have been defined. The profiles could be called design goals or ambitions of the design team. Each design profile consists of a combination of characteristics. The profiles have been developed on basis of three axes: energy, user and outdoor climate. The axis Energy describes if the building has a high energy efficiency ambition compared to the average building. The axis User describes buildings where the user is given or not the possibility to control the indoor environment. The axis Outdoor climate describes if the building is climate adaptive or not. The design profiles can then be either "oriented" or "ignoring" a given axis. The design profiles are described in following table as is the number of buildings responding to the definition in each database. The first column shows the three axes. The second and third columns show which characteristics describe the profiles depending on whether it is the ‘oriented’ or ‘ignoring’ declination. The four last lines show the description of combinations of the five main profiles.

Table 2: Description of the 9 design profiles studied

Three axis	Oriented	Ignoring
Energy	Relative low U value + Heat recovery (n_{HOPE}=17 n_{NOVEM}=10)	*Profile not considered*
User	Operable windows + Operable sun shading (n_{HOPE}=33 n_{NOVEM}=14)	No operable windows + No operable sun shading ($n_{HOPE}=1$ *(weak)* n_{NOVEM}=9)
Climate	Thermal mass available for heat storage + Natural ventilation + Operable windows (n_{HOPE}=13 n_{NOVEM}=9)	No thermal mass available for heat storage + Mechanical air supply + Active cooling OR High ventilation rates (n_{HOPE}=20 n_{NOVEM}=38)
Combinations	User oriented AND Climate ignoring (n_{HOPE}=7 n_{NOVEM}=6)	
	User oriented AND Climate oriented (n_{HOPE}=9 $n_{NOVEM}=1$ *(weak)*)	
	Energy saving AND User oriented (n_{HOPE}=9 $n_{NOVEM}=0$ *(weak)*)	
	Energy saving AND Climate ignoring (n_{HOPE}=6 $n_{NOVEM}=4$ *(weak)*)	

In order to study the impact of each building characteristic or the design profiles listed above, indicators relevant to the notions of energy use on the one hand and to health and comfort perception on the other hand have been defined from the data available in both databases.

A first indicator is actual energy use, in MJ/m²/year. It characterizes the direct influence of building characteristics on energy consumption.

$$E = \frac{Q_{gas,prim} + Q_{electricty,prim}}{m^2}$$

A second indicator, the energy use deviation accounts for the difference between expected and real energy use.

$$\delta = \frac{Q_{prim,real} - Q_{prim,expected}}{Q_{prim,expected}}$$

The energy use deviation indicator is given in (%). The higher the indicator, the higher the actual energy consumption in comparison to the expected energy use. The lower the indicator, the closest to the design expectations the building behaves.

Four different indicators have been selected to describe comfort perception. The occupants surveyed for the HOPE project assessed thermal comfort, light, noise and air quality by voting between 1 “not satisfactory” to 7 “satisfactory”. The mean values are used as comfort perception indicators. As for health perception, in the HOPE project, a Building Symptom Index had been defined, accounting for the average amount of building related health symptoms. One indicator, the BSI, includes 12 different symptoms. A second indicator, the BSI5, include 5 main health related symptoms (dry eyes, blocked or stuffy nose, dry throat, headache and tiredness or lethargy).

Robust building profiles

Building design profiles have been compared by means of three indicators: the energy use indicator, the energy use deviation indicator and the health perception indicator. The comfort perception related indicators were hardly interpretable, because the spreading was large and the comfort scores were close to one another.

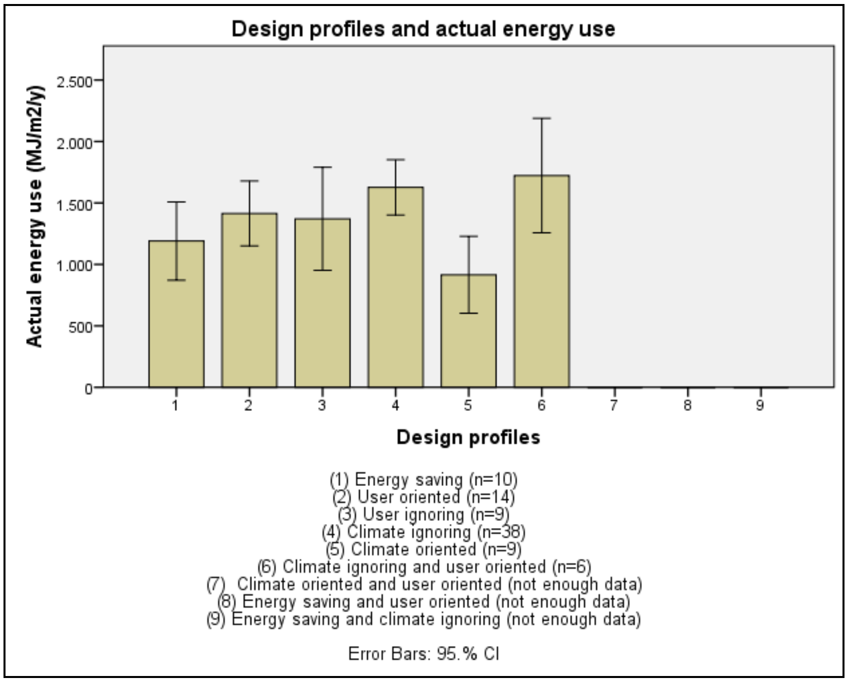

Figure 1 : Influence of the design profiles on the energy use indicator

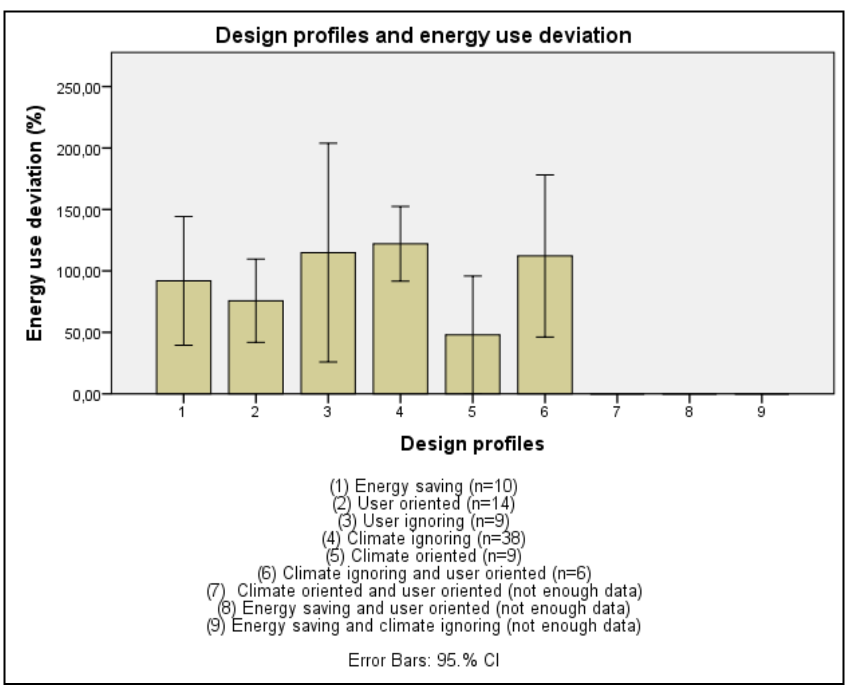

Figure 2 : Influence of the design profiles on the energy use deviation indicator

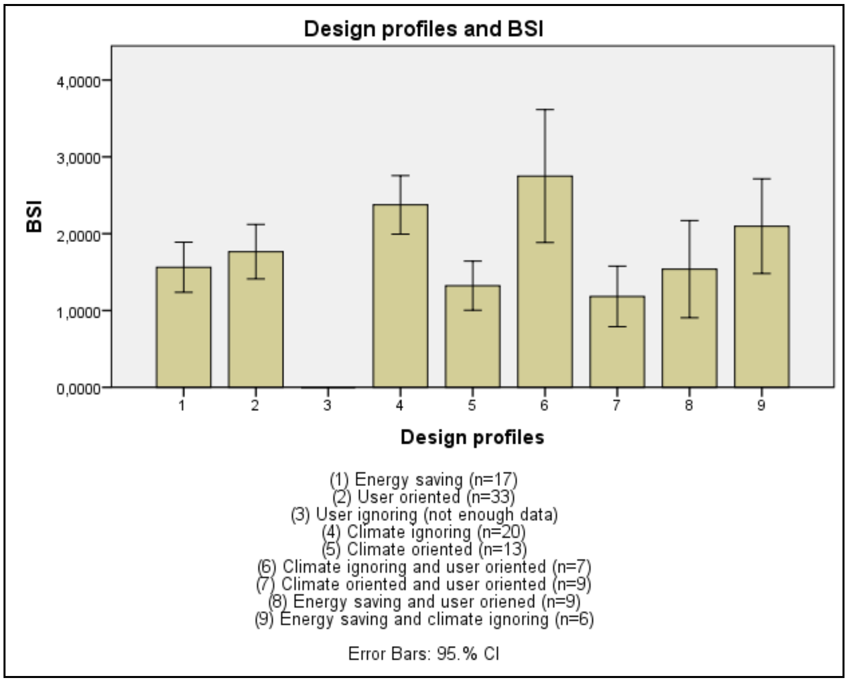

Figure 3 : Influence of the design profiles on the BSI indicator

Figure 1 showed very different behavior in energy use depending on the design profile. First, climate oriented buildings were much more likely to use less energy in practice than climate ignoring profiles. Secondly, no difference between the user oriented and the user ignoring profiles were found, which inspired the idea that giving the opportunity to the user to interact with their environment is not necessarily synonym with higher energy use. The energy saving profile was the second best, which could mean that the energy saving strategies work to a certain extent. Finally, the climate ignoring and user oriented profile had the highest energy consumption which probably is due to the climate ignoring character. It could also mean that there is an incompatibility: users should maybe not be given the opportunity to interact with their environment if the building has a climate ignoring profile. Indeed, climate ignoring profiles have complex and sensitive systems like mechanical ventilation. If they are misused, complex systems might not respond as expected and might need reconfiguration to fulfill their function. It ends up in higher energy use in the end.

From Figure 2 we see that certain profiles were more likely to have higher energy use than according to design stage calculations. Again, there was a clear difference, this time in energy use deviation, between climate ignoring and climate oriented profiles. Climate ignoring profiles used in average more energy than expected in comparison to climate oriented profiles. Finally, climate ignoring and user oriented profiles scored rather high in energy use deviation, which is once again very probably due to the climate ignoring side of the profile.

Figure 3 showed a clear influence of some profiles on the health symptom indicator BSI. First, all climate ignoring profiles have a higher chance to cause more health related symptoms. On the other side, climate oriented profiles showed the lowest prevalence on BSI-scores. What is more, user oriented profiles did not seem to score particularly low; however, the combination of a user oriented profile with another profile seemed determinant. The climate ignoring and user oriented profile had the highest prevalence of BSI whereas the climate oriented and user oriented had the lowest score. The issue is then to combine the right profiles together.

All in all, there seemed to be a pattern in the design profiles. The climate ignoring profiles scored always the highest and the climate oriented profiles scored the lowest. The energy saving profile scored average. User related profiles did not impact the indicators by themselves but did when taken in combinations. Because the data came from two different sources, the correlations of average scores for each profile have been calculated and are given in Table 3.

	Energy use deviation	Actual energy use
BSI	R = 0,915 Sig = 0,029	R = 0,938 Sig = 0,018

Table 32 Correlations between energy and BS indicators for design profiles

Average scores in each design profile showed to be related. A low BS index coincided with a low actual energy use and energy use deviation. There are then profiles that can contribute to both lower energy use and lower health and comfort related complaints. These profiles can be described as robust.

Discussion

Robust profiles are then among others the climate oriented profiles, especially in comparison to climate ignoring profiles. This result supports the thesis of van den Ham, Leyten and Kurvers (2009). A climate oriented design does not work against outdoor climate, which would make it use lots of energy. On the contrary, the indoor climate shows the same variations as outdoor climate, which makes it natural to building occupants. The use of passive solution to achieve such a profile uses then less energy than a climate ignoring profile, which uses installations to achieve acceptable indoor climate.

Mechanical ventilation scored in overall higher than natural ventilation indeed. The buildings with mechanical ventilation showed higher energy use and larger number of complaints. This leads to another deduction. Redundant systems cannot be considered as robust. A redundant system is a system that combines several functions in one. Mechanical ventilation often combines the function ventilation and the function heating or cooling. This doubles the chances that the system goes wrong and it complicates its functioning. If it is complicated to handle, the chance is lower that the system in use works as predicted, hence a higher energy use. Plus if it is complicated, occupants cannot grasp how it works and might misuse it. This leads to health and comfort complaints and to higher energy use again.

The results showing that active cooling was related to lower thermal comfort in summer were particularly unexpected. Active cooling is indeed supposed to lower air temperatures in the building during the warm days of the year and therefore guarantee thermal comfort of occupants. However, several aspects could explain this difference, for example too low temperature set points or the lack of air movement. Furthermore, lower temperature does not mean higher thermal comfort. Indeed, it is quite possible that temperatures are too low in comparison to what building users expect, which causes discomfort. Building users indeed expect indoor temperatures to follow the outdoor temperature fluctuations (Nicol and Humphreys, 2002 or de Dear & Braeger, 2002). Then, we can infer that complex building systems are difficult to grasp, not only from the occupants' point of view but also from the designer's point of view. The assumptions taken to design an active cooling function do not depict reality and the system is too sensible to variations from its original design. It is then more likely that it uses more energy.

Finally, some systems can hardly achieve acceptable indoor climate without either using more energy or being reprogrammed. Such systems that cannot adapt to a situation by themselves cannot be considered as robust. Mechanical ventilation again, or active cooling and humidification systems are non adaptive. These systems work with electrical power and try to reach set temperatures or relative humidity, sometimes fixed, which makes them non robust. On the contrary, passive solutions can be considered as adaptive and robust. Indeed thermal mass available for heat storage as well as natural ventilation were both related to lower energy use and lower health related complaints.

Finally, the user's opportunity to influence their indoor climate is one of the most important keys to robustness. In a climate ignoring design profile, which means in a design profile where systems cannot cope with changes from design purposes, the user should not be given the possibility to influence indoor environment. It increases energy use and does not even improve perceived health. But in a design profile that can bear variations, a user oriented profile improves health perception and contributes to even lower energy use.

Before coming to the conclusion, we would like to draw attention to the limits found in this study. We did not take into account the location of the buildings. Although they were all situated in temperate climate, we could not make any distinction and could not consider location as a control variable in the statistical analysis. Furthermore, the amount of data available depended on the databases we had. 82 buildings on one hand and 66 on the other hand was enough for a start, but did not allow us to check for multiple control variables effect during the statistical analysis. The analysis would not have been significant. The data available was also sometimes incomplete, which partly explains the weak amount of buildings in some design profiles.

Conclusion

In any case, this study is not meant to discredit or lend weight to robust or non-robust building characteristics. The results show on that matter that a single characteristic cannot explain by itself energy use or health and comfort perception. The study identified risk factors for higher energy use, perceived health and comfort. Thus, the study is rather meant to highlight the risk factors and suggest that actors bound to the design of a building take them into account. Indeed in order to achieve high performing buildings in practice, it is advised to design the building with a robust profile and with systems that are not considered as risk factors and this as long as it is possible and feasible. In cases where robust characteristics cannot be implemented, special care should be brought to the design to prevent higher energy use or lower perceived health and comfort.

Question is now really if these results can be used to build better performing buildings. The next step would be then to set up a prediction tool using the results of the present study or similar data. From design stage information, it could assess energy use deviation, health and comfort perception. Such a tool could be used as complement of any existing tool assessing the performance of a building and would be designed to help architects and engineers to improve their designs at early stage.

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