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Influence of architectural building envelope characteristics on energy performance in Central European climatic conditions

Mitja Košir[a,*], Tamara Gostiša[b], Živa Kristl[c]

[a] Chair of Buildings and Constructional Complexes, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia
[b] Inpro 22 d.o.o., Ljubljana, Slovenia
[c] Infrastructure and Real Estate Management Department, European Faculty of Law, Nova Gorica, Slovenia

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ABSTRACT

During early building design stages, decisions are made regarding building's form, orientation, distribution, and size of glazing. Although these features are crucial for building energy performance, designers rarely base their decisions on elaborate energy simulations. The paper presents a study of the interconnectedness of building form, orientation and window area in regard to energy consumption for heating and cooling of a generic building in Central European climate. The study showed that for the considered climate, an elongated building form is more suitable than the compact one, because it allows larger window areas and thus more efficient solar energy harvesting. Even though this may be advantageous for the heating period, it represents a potential problem during the cooling season. Therefore, appropriate shading must be applied and thus the optimum solution is achieved in regard to the building's cumulative yearly energy consumption.

1. Introduction

In the near future low use of energy in buildings is going to become a reality required by stringent EU regulations – nZEB goal [11,12] and imposed by environmental aspects [26]. It is generally considered that the most significant influence on the final energy performance of buildings can be attained during the early stages of building design [10]. Because the majority of Europe has predominantly moderate to cool climate [24], designers tend to choose building features that reduce heat losses. At the same time, the influence of heat gains on the overall energy consumption is often underestimated ([13,41]). The same goes for legislation, which is in EU mainly focused on heating energy consumption of buildings and does not encourage designers to search for optimised and integrated solutions [25]. This situation can lead to misguided and non-optimised design solutions, which are pronounced in the design of building envelope [8]. The optimisation can be achieved with the existing energy analysis tolls, but the problem is that building form, orientation and openings are defined in the early design stages, while energy simulations are usually conducted during the final design stages. Consequentially, if energy simulation shows shortcomings, designers are mostly unwilling to make radical changes at the end of the design process and prefer to seek for HVAC solutions, although they are costlier and less energy efficient.

Several building envelope optimisation studies have been published in recent years, focusing on a variety of optimisation factors (e.g. life cycle costs, energy demand, thermal comfort, etc.) [9,10]. In the light of early stages of building design, the most significant influential factors are the ratio between building envelope size and volume (i.e. building form factor), window-to-wall ratio (i.e. WWR) and the use of thermal mass. All of them have substantial influence on the thermal response of a building [6], although the WWR is probably the most pronounced due to the complex impact of solar gains on heating, cooling and lighting energy consumption of a building [25]. Granadeiro et al. [15] state that the building envelope form has significant influence on building energy performance. It is generally thought that when buildings are heating dominated, compact building forms have better energy performance. Although this is to a certain degree true, Premrov et al. [34] have shown that in some cases less compact buildings are more energy efficient. The crucial element of the building envelope, the window, is probably the most important when considering the influence of the envelope on the indoor thermal environment [42] as well as energy consumption of the building. Yu et al. [43] as well as You and Ding [42] demonstrated that an optimum WWR can be determined for a given building, climate and fixed orientation. The optimum WWR is influenced by a multitude of factors, mostly by the climate, orientation and the thermal and optical parameters of the window. This interconnectedness of various influential factors was demonstrated by Ma et al. [28] in the case of 7 locations in the continental USA as well as by

* Corresponding author.
E-mail address: mitja.kosir@fgg.uni-lj.si (M. Košir).

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Echenagucia et al. [10] in the cities of Palermo, Torino, Frankfurt and Oslo. Both studies showed that an optimum window area is highly dependent on the climatic conditions of the building location. Even more influential is the orientation of the windows, as was shown by Echenagucia et al. [10], where the optimum WWR is substantially different for the differently oriented façades. In both studies the optimum size of the window was in the range from 0% to 50%, depending on the orientation and location. It could be argued that these sizes are relatively small, but it has to be stressed that in neither of the studies the influence of window shading was taken into account. Application of shading elements can have a significant influence on the energy consumption of the building, especially in regard to the cooling energy demand [43]. The study conducted by Goia et al. [14] on the impact of shading at different WWR values demonstrated that, similar to the findings of Ma et al. [28] and Echenagucia et al. [10], the optimum is in the range of 35–45%, but with the application of shading this range can be increased to larger WWR values. Differences in the total energy consumption of the building with WWR values between 25% and 65% were shown to be almost negligible. With the use of window shading the situation becomes even more complex, as the type of shading [5] as well as its operating strategy [23,44] can substantially influence the energy balance as well as indoor illuminance conditions.

It has been show by Al-Sanea et al. [2], Zhu et al. [45] and Hudobivnik et al. [17] that, generally, building envelopes with low (i.e. lightweight construction) or excluded building mass (i.e. internally thermally insulated) are underperforming in regard to energy performance when compared to massive building envelopes. Positive influence of building mass on the energy performance of a building was also demonstrated by Andjelković et al. [3], with greater impacts in cases when radiative heating and cooling systems were used. Similarly, Hudobivnik et al. [17] showed substantial positive effects of building mass on passive cooling of buildings in Central European climate. The study conducted by Kitek Kuzman et al. [20] established that the trend in construction industry is moving towards the use of lightweight structures. This means that the existing building models have to be reassessed, because thermal response of lightweight constructions differs from traditional massive buildings [1,16,18]. The question is what role thermal inertia will play in this context. Aste et al. [4] observe that studies report very different estimations on energy saving potential associated with the use of adequate thermal inertia, ranging from a few percentages to more than 80%. On the basis of the analysis performed by the authors for Milan climate [4] it can be concluded that the difference between the heating consumption of a building with low inertia compared to high inertia wall will be in the range of 10%. The difference between the cooling consumption of a building with low inertia compared to high inertia, may reach up to 20%.

Because the majority of studies in regard to energy optimisation of buildings focus on the study of single parameter, more has to be known about the joint influence of the above mentioned factors, especially on the performance of buildings with low thermal mass [17]. Pisello et al. [33] made a study consisting of three different prototypical residential buildings. However, the study is limited only to three specific building geometries. Therefore, a study of influences on a hypothetical, simplified and generic building concerning the envelope orientation, structure and building form in dominant Central European climatic conditions is needed and could be a basis for “rules of thumb” that could be used by building designers in the early stages of design. In the presented paper, we present a parametric study involving dynamic thermal simulation analysis of the impact of building form, orientation and WWR on energy consumption for heating and cooling, executed in a building model situated in a typical Central European climate. Although the presented study is conceptually similar to investigations executed by Olgyay [31] in the 1960ies, it is focused on the performance of buildings with envelope elements corresponding to modern-day legislation and standards. Additionally, the study was concerned with identifying the relative influence of cooling energy use in the Central European climate with different arrangements of building volume, envelope configuration and shading. This interest was fuelled by predictions emphasizing that cooling will become an important issue in the Central European buildings due to climate change [35]. The potential increase of cooling in residential buildings due to climatic changes was clearly illustrated by Pajek and Košir [32] in recently published study, which demonstrated that by 2050 in certain cases buildings in Central European locations could eventually become cooling dominated. Therefore, the insight into general behaviour of generic building models under Central European climatic conditions will represent a valuable resource to building designers at early stages of design. For this reason, this study used building performance simulations, which were carried out by using EnergyPlus [39] software and the Open Studio front end plug-in [30] for the Trimble SketchUp CAD application [37]. The expected results are a set of comprehensive data including the influence of building form, orientation and window size (unshaded and shaded) on the heating and cooling energy consumption of a building.

2. Methodology

The calculations were carried out on a simplified model of a building. The starting geometry of the model building, designated as A0, is cubical without windows. The dimensions are 10 × 10 × 10 m, with the total facade surface of 400 m^2 and roof and ground slab surface of 100 m^2. For the model building we presumed three floors and a total conditioned volume of 1000 m^3. The building was oriented to cardinal points. South orientation was designated as 0°. On the east side there is a door with the dimensions of 1.2 m by 2.1 m.

From the basic square floor plan of the A0 building further four variations with fixed volume but different form were devised. The model buildings designated as A1 and A2 have floor plans in ratios of 1:1.5 and 1:2, respectively. When windows are present in the geometrical model, they are positioned onto the longer façade. The B1 and B2 model buildings have the same shape as the A1 and A2 buildings, but with windows on the shorter façade. This represents the five basic forms of the model buildings, which define the baseline group. To investigate the influence of solar gains, the window area on the south façade was gradually increased in increments from 0%, 25%, and 50% to 100% of the southern façade area. Also the orientation of the buildings was changed in progressive steps of 30° from east through south towards west orientation. In Fig. 1 the principle and the method of generating the above described scenarios are presented. In total, 140 different configurations in the baseline group were calculated. Each case is marked in accordance with its basic simulation parameters (i.e. floor plan shape, window area and orientation). Therefore, for example, A1.25.0° represents a building with a rectangular floor plan in ratio 1:1.5 (A1), 25% (25) of glazing on the longer façade facing south (0°).

Walls were assumed to be composed of aerated concrete blocks with thermal insulation applied on both sides of the construction (16 cm of extruded polystyrene on the external side and 8 cm of mineral wool on the internal side of the wall). The external walls have a U-value of 0.14 W/m^2 K. In this way the thermal mass of the walls was in a large part excluded from the “active” part of the building envelope [17]. The floors and roof were assumed to be of traditionally used concrete slabs. The U-value of the roof and ground floor slab was 0.15 W/m^2 K. Therefore, the only thermal mass of the building was present in the floor slabs and the roof, which is a similar configuration to the low mass building used in the study of thermal mass impact on energy performance conducted by Andjelković et al. [3].

Another element with significant influence on energy use in buildings is the size and type of windows. Manz and Menti [29] present charts which display condensed information on the energy performance of glazing at eight European locations. By analogy to the studied locations, in the mentioned study triple glazing was chosen with one low-E coating and argon filling (U-value = 1.06 W/m^2 K, g factor = 0.58). The influence of window frame was not taken into consideration. The