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Influence of the building shape on the energy performance of timber-glass buildings located in warm climatic regions

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ABSTRACT

An optimal proportion and appropriate orientation of glazing surfaces in timber-glass building play an important role due to the exploitation of solar radiation as a source of renewable energy for heating, applicable in most cases only to buildings located in cold and moderate climatic regions. However, the situation of timber-glass buildings located in warm climatic regions is completely different, since the energy demand for cooling represents a major contribution to the annual energy demand. The optimal solutions in such cases should therefore avoid overheating, which has not been extensively analysed in scientific literature discussing timber buildings. In the present study a total of 216 timber box-house models with a parametrically varied building shape (aspect ratio, horizontal and vertical extension), the thermal transmittance of the building envelope components, along with the varied glazing size and its position in the south or north façade, undergo separate analyses for locations in Athens and Sevilla. Climate conditions are intentionally selected and encompass very similar average temperatures but rather different solar radiation. The influence of the described parameters on the annual energy demand is thoroughly analysed and can serve architects as a systematic guideline in designing timber-glass buildings also for regions with warm climate conditions.

1. Introduction

Climate changes of the last few decades do not only encourage researches into the origins of their onset but they also mean a warning and an urgent call for a need to remove their causes and alleviate the consequences affecting the environment. Many investigations have been carried out towards 100% renewable and sustainable energy solutions in many different areas [1–4]. As commercial and residential buildings consume almost 40% of the primary energy in the United States and Europe, eco-friendly solutions in residential and public building construction remain our most vital task, whose holistic problem solving requires knowledge integration, taking into account multiple and usually competitive objectives such as energy consumption, financial costs, environmental performance, renewable energy use, etc., Diakaki et al. [5]. Moreover, combining building materials with different material properties while fully respecting their possible advantages in a hybrid structural composition of buildings could be a relatively new approach in designing high energy-efficiency buildings and can lead to architecturally attractive and energy-efficient solutions at the same time. Owing to specific technological development and appropriate use, timber and glass are nowadays becoming essential construction materials as far as the energy efficiency is concerned.

Only in recent decades has timber been rediscovered, partly due to the contemporary manufacture of prefabricated timber elements and partly on account of high environmental potential of this renewable natural building material. On the contrary, glass can definitely not be treated as a sustainable material and it long used to be treated as the weakest point of the building envelope from the thermal point of view. Nevertheless, dynamic evolution of the glazing in the last decades has resulted in insulating glass products with highly improved physical and strength properties, suitable for application to contemporary energy-efficient buildings, not only as a material responsible for solar gains and daylighting, but also as a component of structural resistance. However, due to significant differences in material properties, such as the thermal transmittance, the thermal expansion coefficient, strength, the modulus of elasticity, sensitivity to humidity, etc., their combined use is extremely complicated, from the energy efficiency and structural points of view, with the latter aspect residing in glazing being treated as a load-bearing structural component, [6]. However, appropriate consideration of all the features of both building materials led to the

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development of a new type of structures, the so-called timber-glass buildings, [7]. In such buildings an optimal proportion and appropriate orientation of the glazing surfaces play an important part due to the exploitation of solar radiation as a source of renewable energy within a passive use of energy for heating.

A great number of studies treat the influence the glazing size and building geometry exert on the energy demand of buildings located in cold climate conditions [8–14]. They all point out a strong correlation between the final energy use for heating and the shape of the building located in cold climates. A general suggestion was that a cold climate may increase the impact of the building shape on the transmission heat losses and consequently on the energy need for heating. Thus the optimum form of the building has a minimum external surface and usually a rectangular shape. Moreover, in such cases an optimal proportion and appropriate orientation of the glazing surfaces usually play an important role due to the exploitation of solar radiation as a source of renewable energy for heating, most often applicable only to buildings located in cold and moderate climatic regions. With regard to the latter, it is sometimes important to simultaneously investigate the solar heat transfer through the south-orientated glazing in order to avoid overheating, which is particularly relevant to climate conditions with relatively warm summers. Mingfang [15] defines southern orientation of a building as the optimum from the viewpoints of the solar heat gains in the winter and the solar heat control in the summer, while pointing out that the optimal building proportion to ensure solar control is a rectangular floor plan.

On the other hand, buildings located in warm climatic regions face a completely different situation. The energy demand for cooling is usually the main contributor to the total annual energy demand owing to a higher solar heat transfer through the glazing. Bouden [16] investigated the appropriateness of glass curtain walls for the Tunisian local climate. The influence of windows on the energy balance of apartment buildings in Amman, Jordan, was analysed in the study performed by Hassouneh et al. [17]. The impact of relative compactness (RC) on the building's annual cooling energy demand and the total annual energy demand was dealt with by Al Anzi et al. [18], whose research involved a prototypical building with over 20 floors based in Kuwait. The results of the latter study indicate that the energy use decreases as the relative compactness increases. An interesting research into energy efficiency design of residential building in the Mediterranean region including energetic, economic and environmental points of view was presented by Jaber and Ajib [19]. The windows were separately placed in the east-, south-, west- and north-oriented façades. The research outcome pointed to a 28% annual energy consumption saving achievable by choosing the best orientation, the optimum window size and the optimum U-value.

For the purpose of the present research our interest goes to studies related to warm climate conditions in Europe, where a slight energy need for heating may occur, in addition to that for cooling. A number of interesting analyses have been carried out with a focus on defining the optimal architectural geometry of the building, e.g. the impact of windows on the heating and cooling demand, Inanici and Demirbilek [20]. Depecker et al. [9] studied the relationship between the shape and energy requirements during the winter season in two French localities with different climate conditions. They found no correlation between the energy consumption of a building and its shape in mild climates. Albatici and Passerini [21] were encouraged to research new indicators of the energy performance in mild and warm climate conditions relative to the building shape. Thus, they presented heating requirements of buildings with different shapes placed in the Italian territory, which confirms that compactness is more important in cold localities than in warm regions.

The parametric study of a cost-optimal energy efficient office building in Serbia with very hot summers was presented in Ref. [22]. Hot summers of Belgrade climate imply that cost-optimal solutions have close-to-minimal window-to-wall ratio (AGAW) at the southern façade and significantly larger AGAW value at the northern façade. Studies on the impact of climate change on energy use in buildings in the different parts of the world were reviewed in Ref. [23], where it was pointed out that the most significant adverse impact of climate change on energy use in the built environment would occur in the hot summer and warm winter climate zone where building energy use is dominated by cooling need, which is important also for our study. Badescu et all [24]. analysed the first Romanian passive office building constructed in 2009 in warm climate region in Bragadiru, 10 km south of Bucharest. They proved that the overheating rate and the cooling load are higher for a passive building than for a standard building and suggested that an active cooling system should be used when passive buildings are implemented in the Romanian climate. Florides et all [25]. investigated the importance of the roof insulation on a typical model hollow-brick house in the Nicosia area, which resulted in a reduction up to 45.5% of the cooling load and up to 75% of the heating load.

On account of great many parameters having a considerable influence on the energy behaviour of buildings, the presented studies usually treat only a few simple building models, mostly within selected climate regions. Identifying the building parameters which significantly impact the energy performance is a complex and an important step towards enabling the reduction of the heating and cooling energy loads in the design stage, with a special focus on implementing passive design techniques. Regarding theoretical facts about the heat transfer through the building envelope components, multiple parameters have to undergo a careful analytical or semi-analytical investigation via mathematical optimization or sensitivity methods which are correlated with several passive design parameters, such as the shape of the building, its orientation, the size and orientation of the glazing to suit the given climate conditions. Having started in 1984, Radford [26] used multicriteria optimization of a prism-shaped multi-storey office building in Australia applying the criteria of minimum thermal load ratio, minimum capital cost and maximum net usable area. The purpose of the analysis of Marino et al. [27] was to verify the existence of an optimal size of the window surface, a size allowing for minimum overall energy consumption, and the variations that this optimum might undergo if the climate conditions, insulation features of the façade or luminaries input power change. The study was performed on an office building whose structure and configuration represent a typical reference case of the Italian building stock. Nevertheless, the authors suggested highlighting the existence of even more design factors calling for further investigation within future research, such as the influence exerted by the position and shape of the window. In the study of Aksoy and Inalli [28], a transient heat transfer problem in the building envelope with or without insulation is solved by using the finite difference method for a city located in a cold region of Turkey. The treated buildings with different shapes are placed on the ground with the azimuth angles ranging from 0^0 to 90^0. Zhang et al. [29] provide a method with a Modelling–Simulation–Optimization framework simultaneously considering the solar radiation, the shape coefficient and the space efficiency. The method is applicable to a free-form building design that receives more solar radiation through the shape optimization and takes into account the other two objectives mentioned above. The method has been tested for severe cold China climate conditions.

Several approaches relying on sensitivity analysis have been recently developed to balance between a number of parameters