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# Parametric study of a cost-optimal, energy efficient office building in Serbia[☆]

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ABSTRACT

Recent building regulations in Serbia prescribe the design of highly insulated, airtight buildings with low *U*-value glazing. Serbia has continental climate with hot summers, so that for office buildings, whose internal gains are higher from the presence of people, computer systems and lighting, this means that far more focus has to be put on cooling demands than on heating demands. This shift toward cooling is studied here through exhaustive simulation of combinations of selected passive solar design parameters for a model of an office building in Belgrade. Design parameters include glazing type, window-to-wall ratio of façades, presence of exterior shading and *U*-value of opaque envelope components. Optimal variants of the model have been determined with respect to construction cost and heating, cooling and lighting energy use. Results reveal that exterior shading, which has to sustain occasional strong winds in Belgrade, is too expensive to appear in cost-optimal solutions. Hot summers of Belgrade climate imply that cost-optimal solutions have close-to-minimal window-to-wall ratio at the southern façade and significantly larger window-to-wall ratio at the northern façade. Results further show that glazing in cost-optimal solutions has to have small *U*-value and medium solar heat gain coefficient, although specific choices of optimal glazing type, as well as thermal insulation level, depend on future electricity prices. The case study is repeated for climates of Frankfurt and Stockholm as well, which yield similar results with respect to glazing type and the absence of exterior shading, but with different patterns of window-to-wall ratios at the southern and northern façades.



## 1. Introduction

Building energy use essentially depends on the way buildings are planned, designed, and built. Buildings are one of the largest energy consumers today, with a significant amount of energy used for their heating, cooling and lighting. It is generally agreed among architects, civil, mechanical, and electrical engineers today that due consideration in the design process has to be given to energy saving, natural daylight, use of solar energy both for heating and cooling, natural ventilation and reduction of environmental impact, all without reductions in comfort or living standard. This agreement is evident through various concepts of low energy buildings, and mostly implemented through improvements in building envelope, the use of highly efficient technical systems, and the use of renewable energy sources [1]. Among these the concept of nearly-zero energy buildings was set as the goal for all new buildings in EU by 2020 [2]. It requires building energy efficiency to be raised to the next level through a coherent use of passive and active measures that jointly optimize complete building performance, but ensuring the lowest cost during estimated economic lifetime. Passive measures are usually both more cost effective and more influential than active measures (see, e.g., [3–5]). Hence determination of optimal combinations of passive measures, and in particular passive solar design measures, is a necessary first step in any such effort.

Passive solar design measures aim to use solar energy to help establish thermal comfort in buildings, without the use of electrical or mechanical equipment. The greatest opportunities for integrating such measures occur at the conceptual design level by determining the values of building envelope parameters that have critical influence on its performance. Bogenstätter [6] points out that early design stages determine up to 80% of building operational

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costs and environmental impacts. Fenestration is among the most important passive solar design measures. On one hand, it is important for adding aesthetics to the building design and providing adequate daylight illumination levels. On the other hand, it has twofold influence on building energy performance, due to its *U*-value that is usually higher than that of building opaque envelope components, and to its solar heat gain coefficient that regulates the admission of solar energy into the building [7].

Existing examples of good practice in passive solar design in Serbia [8] mainly suggest the design of large windows on the southern façade with exterior shading, small windows on the northern façade and the use of thermal mass. However, recent building regulations in Serbia [9] prescribe the use of highly efficient glazing in building design, together with low *U*-values of opaque envelope components and high building airtightness. This change greatly reduces the allowed heat transfer through the envelope and may easily shift the focus from heating toward cooling. This is especially true for office buildings that have high internal gains due to the presence of people, computer equipment and lighting during the work hours. While the internal gains are beneficial in heating season, they have high impact on the cooling load as they cannot be easily released through the envelope of highly insulated, airtight buildings in cooling season.

This shift toward cooling in office buildings under new building regulations in Serbia is studied here through assessment of cost optimal choices of passive solar design measures for a model of an office building located in Belgrade, Serbia. Cost optimality is defined through a relation between construction and energy costs, while studied design measures include glazing type, window-to-wall ratio of façades, presence of exterior shading and *U*-value of opaque envelope components. The building model response to applied design measures has been simulated for all combinations of considered design parameters with EnergyPlus, a validated whole building energy simulation program. The building model, determination of relative construction costs and the procedure for assessment of cost optimality are described in Section 2. Particular attention in this assessment is paid to the convex hull of Pareto front, as it gives a small subset of Pareto solutions that contains optimal solutions regardless of unknown future electricity prices. Computational results are given in Section 3. In addition to Belgrade, simulations have been performed also for Frankfurt and Stockholm, in order to get a better insight in changes of cost optimal solutions with respect to climate.

Analysis of cost optimal variants of the office building model in Section 4 reveals that they are quite different from earlier good practice. They now tend to have minimum feasible window-to-wall ratio at the southern façade, without exterior shading and with significantly larger window-to-wall ratio at the northern façade. These findings are in line with observations from earlier studies [10–17], that are reviewed in the next section together with other studies on passive design of office buildings.

### 1.1. Literature review

A number of existing studies show that cost-optimal choices of passive solar design measures in office buildings may differ significantly due to differences in climate of the location.

Flodberg et al. [10] show that limited WWR and well-insulated and airtight building envelope are essential for achieving low-energy office building in Stockholm (Köppen climate classification: Dfb). They also point out that it is crucial to reduce user-related electricity and internal heat gains, as cooling load may easily overcome the heating load even in cold climates.

Wang et al. [11] present a multi-objective optimization model aimed to assist at the conceptual design stage through focus on the parameters that have critical influence on building performance. Application to a case study office building in Montréal (Köppen climate classification: Dfb) shows that WWR of façade converges to the minimum feasible value, equal to 20% in Ref. [11].

Pikas et al. [12] show that for the cold Estonian climate (Köppen classification: Dfb) energy efficient and cost optimal design solutions rely on highly transparent triple glazed argon filled windows with small WWR and 20 cm thick thermal insulation of walls. These findings are further confirmed by Thalfeldt et al. [13], who also show that optimal WWR may be increased to 40–60% only if *U*-value of windows would fall down to 0.21–0.32 W $m^{-2}$ $K^{-1}$.

Goia et al. [14] study optimal WWR for three versions of a low-energy office building in four main orientations and with different HVAC system efficiency located in Frankfurt (Köppen: Cfb). They observe that the influence of the façade in the case of a low-energy building is much lower than it used to be in conventional building, provided that state-of-the-art technologies are adopted and that solar shading systems and their activation are optimally exploited. The results show that, regardless of the orientation, optimal WWR is found between 35% and 45%.

Vanhoutteghem et al. [15] consider the effects of size, orientation and glazing properties of façade windows in Danish nearly zero-energy houses. Although occupation and internal gains patterns in houses are different from offices, they come to similar conclusion that the use of high *g*-values and large WWR in south oriented rooms is less important for reduction of space heating demand in well-insulated houses than traditionally believed. Actually, windows in south oriented rooms have to be carefully dimensioned to prevent overheating. More flexibility in choosing window parameters was found for north oriented rooms: high *g*-values are recommended to reduce space heating demand and, at low *U*-values, large WWR can be used without having a more negative impact on space heating demand than a design with smaller WWR.

Evins [16] demonstrates the principle of multi-level optimization of building energy use on three levels: building design, system design, and system operation. For a case study office building he obtains a sequence of Pareto solutions that span the objective space from almost no additional cost, but with very high emissions, to emissions a magnitude lower, but at a very high cost. The rough sequence in which design options were added on building design level on a path from low cost to low emission solutions was: increased glazing on north façades, maximum insulation thickness, increased glazing on east and west façades, south façade glazing, triple glazing.

Li et al. [17] review energy efficiency measures and adoption of renewable energy technologies involved in the design of zero energy buildings. They highlight thermal insulation, thermal mass, glazing and daylighting as energy efficiency measures related to building envelope that have significant impact on building energy use. Thermal insulation tends to be more effective in colder climates than in warmer climates and that reduction of heat loss in overinsulated buildings tends to increase cooling load during cooling season [18,19]. Thermal mass integrated with night-time ventilation can be effective in avoiding summer overheating by lowering indoor daytime temperatures [20,21]. Minimization of heat loss and gain through glazing is generally approached through the reduction of WWR and the use of more energy efficient glazing [22–25]. They further mention that daylighting has great energy saving potential in cooling-dominated buildings through both savings in electricity use for artificial lighting and less heat dissipation from lighting installations [26–28].

Geng et al. [29] show that additional wall and roof insulation, increased airtightness and high performance glazing are most cost-optimal building energy saving technologies for office buildings in

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