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Article

Selection of the Optimal Window Type and Orientation for the Two Cities in Serbia and One in Slovakia

Jelena M. Djoković [1], Ružica R. Nikolić [2,*], Jan Bujnak [3,†], Branislav Hadzima [2], Filip Pastorek [2], Renata Dwornicka [4] and Robert Ulewicz [5]

1 Technical Faculty of Bor, University of Belgrade, 11 000 Belgrade, Serbia; jdjokovic@tfbor.bg.ac.rs
2 Research Center, University of Žilina, 01026 Žilina, Slovakia; branislav.hadzima@uniza.sk (B.H.); filip.pastorek@uniza.sk (F.P.)
3 Faculty of Civil Engineering, University of Žilina, 01026 Žilina, Slovakia
4 Department of Applied Computer Science, Faculty of Mehanical Engineering, Cracow University of Technology, 31864 Krakow, Poland; dwornicka@mech.pk.edu.pl
5 Department of Production Engineering and Safety, Czestochowa University of Technology, 42201 Czestochowa, Poland; robert.ulewicz@pcz.pl
* Correspondence: ruzicarnikolic@yahoo.com or ruzica.nikolic@uniza.sk; Tel.: +421-948-610520
† This author already passed away last year.

Abstract: The necessity of having windows on any building's façade is not questionable. However, not every window is suitable for any building. The selection of an adequate window must include the analysis of various factors—the most important ones are the type of window (e.g., single or double glazing); filling gas in cavities (e.g., air, argon or some other gas); and placing, i.e., orientation of a window on a façade (facing north, south, or east, etc.). The research presented in this paper is dealing with the calculation of the window thermal loading for the cities of Kragujevac and Bor in Serbia and Žilina in Slovakia. These three cities were selected because they belong to different climate regions, according to the Köppen–Geiger climatic classification. The first two cities in Serbia belong to the same region Cf with difference only in the category of summer—Kragujevac Cfa and Bor Cfb—while the third city—Žilina in Slovakia—belongs to the Dfb region. The calculated thermal loading through the window was obtained as a sum of the thermal loading due to the heat conduction and thermal loading due to the solar radiation. The objective was to find the optimal window construction and orientation of a building's façade for each of these cities, by varying the type of the window, its frame material and the filling gas. The results show that for the first two cities in Serbia, there is a difference in the window frame material in the optimal window construction, while for the third city (Žilina in Slovakia), the results are the same as for the second city (Bor in Serbia) despite the fact that they belong to different climate regions (Cfb and Dfb, respectively). These results support the fact that the climate affects the optimal window construction for any city/region in the world.

Keywords: energy efficiency; fillings; glazing

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1. Introduction

Windows are inseparable parts of the building's envelope. Since the windows are key places for energy loss, the easiest solution would be to have a building without any. However, they represent the source of daily light, provide visual contact with the environment and provide ventilation and natural cooling. On the other hand, the adequate orientation and dimensions of a window can positively influence the heating or cooling of a building, thus helping to control the building's thermal loading. The Office of Energy Efficiency in the USA estimates that 10 to 25% of energy losses of residential buildings can be assigned to windows [1,2].

The window consists of the glazing, which can be constructed of single- or multi-panel glass, frame, shading structures (blinds and/or rolling shutters) and insect screens (so-called mosquito blinds). Windows influence the energy needs of a building in four ways: by the heat conduction, solar radiation conduction, air conduction and daily light transmission. That influence also depends on the characteristics and orientation of windows, climate conditions of the building's location, solar radiation, building's heating and cooling systems. Energy losses through the window can be minimized by careful and adequate design, both of a window as a whole and of its individual elements [3].

The goal of the research presented in this paper was to calculate the heat load through the window, based on which one would be able to decide on the best or rather optimal solution of the window design, including the selection of its dimensions, frame material and the type of filling gas. The optimal solution would mean the most energy-efficient windows for the three considered towns in Europe: Kragujevac and Bor in Serbia and Žilina in Slovakia. The window's characteristics were estimated based on the value of the heat load through the window on the monthly and annual levels.

2. Literature Review

Investigating different problems related to windows was and is carried out from several points of view, yet the two interrelated group of problems are the most studied ones. The first group consists of problems concerned with the energy consumption by buildings, i.e., its optimization, whether the matter of speaking is heating or cooling or both. Here, the goal of studying windows is to find out how to contribute to that optimization. The other type of problem is related to lowering the harmful gas emissions, namely the protection of the environment. In studying the problems related to windows, there are numerous parameters to be considered: the window's design, including their geometry and dimensions, the glazing, filling gases, orientation and position on the building's façade, as well as the climate of the building's location, since each climate region has its own characteristics, namely the energy consumption requirements that can influence the selection of the windows design.

As in any other field of research, different methods are applied by different researchers, including the theoretical considerations, experimental investigations and numerical simulations. The presented literature review is given in a way that articles are grouped according to the types of problems considered, as well as in chronological order, as much as possible.

The authors of [3,4] studied the natural convection effects in the 3D window frames with internal cavities. Their two articles cover six different cases of window sections, including a simple square section in a single vertical cavity and two four-sided frame cavities and H- and U-shaped sections. The conjugate CFD (computational fluid dynamics) simulations were used to model the enclosed air cavities, the frame section walls and the foam board surround panel, while the boundary conditions at the indoor and outdoor air/solid interface were modeled using the constant surface heat-transfer coefficients with fixed ambient-air temperatures. The authors concluded that their simulations can be used for the evaluation of natural convection heat transfer in frame cavities.

The subjects studied in [5] were the capabilities and limitations of the window heat transfer design tools and compared the two related ISO standards, ISO 15099 and ISO 10077-2. The authors concluded that the first standard better takes into account the influential window and climate parameters and that it can be used as a basis for further improvements in the window frame heat transfer modeling. After a review of research on the frame heat transfer, they suggested the possible improvements for modeling the frame heat transfer and proposed six new priorities related to the window heat transfer design tools that should be included in ISO standards.

The optimal design of the dual-airflow window for different climate regions in China was considered in [6]. The researchers analyzed the thirteen parameters of the dual-airflow window design by the orthogonal method and concluded that the most important parameters are the outdoor air supply rate, window height, solar heat gain coefficient and window orientation. They found that with the optimal design, the dual-airflow window could save 25% energy in a warm climate region (such as in Guangzhou) and 34% in a cold climate region (such as in Harbin). Thus, they recommended that the dual-airflow window should be used in colder climate regions.

The establishment of five climate zones in Europe was proposed in [7], with regard to the energy performance of buildings, i.e., the amount of heating and cooling degree days. The proposed zones are: 1—high cooling needs, low heating needs; 2—high cooling needs, medium heating needs; 3—low cooling needs, low heating needs; 4—low cooling needs, medium heating needs; and 5—low cooling needs, high heating needs. The authors' conclusion is that the classification of climate zones, based on both heating and cooling degree days, leads to more realistic results, since nowadays cooling needs form a substantial part of the energy balance of a building, especially in Mediterranean regions.

The impact of window selection on the performance of residential buildings for two climate regions in South Korea was investigated in [8]. The results of the presented analysis indicated that selecting a glazing with a low solar heat gain coefficient is highly beneficial for large windows and for mild climates, and that any double-pane low-e glazing performs better on windows in residential buildings than the clear double-pane glazing required by the Korean building energy code.

The authors of [9] used statistical analysis to decide which of the window systems and climate parameters most influenced the energy performance of well-insulated residential buildings in four cities in Europe (Paris, Milan, Nice and Rome). They evaluated the impact of different kinds of glazing systems, window size, orientation of the main windowed façade and internal gains on winter and summer energy needs and peak loads.

The problem of glass selection for high-rise residential buildings with a window-to-wall ratio (WWR) of 50%, in the United Arab Emirates (Abu Dhabi, Dubai and Sharjah), was considered in [10]. The emphasis was on the influence of the selected glass thermal properties, namely the U-value and the glass solar heat gain coefficient (SHGC), as well as the glass costs on the total costs of the building construction. The simple payback period and the life-cycle cost reduction techniques were used to define the optimal glass thermal properties and the simulation software Integrated Environmental Solutions-Virtual Environment (IES-VE).

The influence of the glass-curtain wall on the heating and cooling load of a building was studied in [11]. The study included five types of glazing. The analysis was performed of the annual energy consumption of an office building, for three climates in India: composite (New Delhi), hot and dry (Jodhpur) and warm and humid (Chennai). The authors found that energy consumption increases linearly with the glazed area and that the minimum energy consumption is for the north orientation, as well as that a glass-curtain wall, made of solar control glazing (reflective), consumes 6 to 8% less energy than the standard window in the considered climate types.

In article [12], the influence of the window size and orientation on the energy balance of the so-called passive houses in Gothenburg, Sweden, was considered. It was investigated how decreasing the window size facing south and increasing the window size facing north in these low-energy houses would influence the energy consumption and maximum power needed to keep the indoor temperature between 23 °C and 26 °C. Different window orientations and types were tested by the simulation tool DEROB-LTH. The results show that the size of the energy-efficient windows does not have a major influence on the heating demand in the winter, but that it is relevant for the cooling needs in the summer. It is indicated that enlarging the window area facing north would also contribute to better lighting conditions.

The authors of [13] studied the impact of the window frames on a building's energy consumption in Thailand. They examined three types of glass, two frame materials (aluminum, PVC) and two frame configurations (fixed and sliding frames). The 6 mm thick clear glass was used as a reference case. They concluded that the building energy calculation may be performed by using only properties of glass with no frames for windows, as it is conventionally carried out, since the properties of window systems with frames added have insignificant impacts on the energy consumption of the building. The thermal and economic models of window design for different climate zones was created in [14] and those optimized models were applied to Amman, Aqaba and Berlin. The results have shown that the heating load is highly sensitive to the window size and type as compared to the cooling load. Another conclusion is that with a well-optimized glazed window, energy savings can reach up to 21%, 20% and 24% for Amman, Aqaba and Berlin, respectively.

The simulation modeling of a building was used in [15] for analyzing the annual heating, cooling and lighting energy consumption when the window systems of different types and properties are in a building envelope. The study of various window properties included the evaluation of the U-value, solar heat gain coefficient (SHGC) and visible transmittance (Tvis) for different window-to-wall ratios (WWR) and orientations in five typical Asian climates: Manila, Taipei, Shanghai, Seoul and Sapporo. Based on the performed analysis, the authors were able to propose the optimal window design for the studied regions, with the possibility to use their method for other regions as well.

In addition, in countries with cold winters, windows decrease the comfort of tenants due to their low thermal-resistance and due to large areas with high levels of humidity and harmful condensation, which all lead to a need for windows with high thermal resistance [16]. The authors considered the key elements and materials of window frames. They reviewed numerous frame constructions and proposed options for improving their thermal performance, which included an effective conductivity of 0.02 W/mK for both the spacer and existing thermal break materials, while for the thermal breakers, the new materials should be developed with a target conductivity of about 0.005 W/mK and for the structural insulating materials of 0.03 W/mK. They also proposed the development of new low-emissivity coatings, which should reduce the radiation heat transfer in the frame cavities (the target emissivity should be 0.05), as well as new window designs and frame designs and technologies. Dynamic modeling and simulation of the energy performance of two school buildings in Matera, Italy, were performed in [17] based on climatic conditions, and results were compared to the stationary condition results. A strategy to improve the energy performance of those buildings was proposed by using the trigeneration plant that allows the simultaneous production of the heating, cooling and power energy.

In [18], the researchers analyzed the influence of windows on the energy characteristics and performance of the office and residential buildings in warm Mediterranean climate conditions (namely in Athens, Greece). They concluded that windows with low thermal-transmittance are not always as efficient in cooling-dominating climates as in heating-dominating ones. For the office buildings, the conclusion was that appropriate solar protection or glazing with controllable properties could significantly improve the building energy performance, especially during the cooling season and for eastern or western façades.

The authors of [19] dealt with the life cycle assessment (LCA) of windows in Italian residential buildings. They performed a sensitivity analysis varying two parameters—the PVC profiles of windows frames and the climate classes—based on which they proposed a new criterion for the assessment of the carbon footprint (CF) of the PVC windows on the environment. A way for reducing the environmental impact would be using recycled PVC for window frames instead of the virgin one. The influence of the window type, orientation and shadowing on optimizing the thermal performance of the reference room in the climate region of Coimbra, Portugal, was discussed in [20].

The two-step parametric analysis was performed; the first step included an evaluation of the window type, orientation and size, while the second was an assessment of the impact of using the overhangs. The authors carried out the thermal assessment by calculating the degree-hours of discomfort using the dynamic simulation. The results showed that for the chosen location, triple glazing has better performance than single or double glazing, especially for a northern orientation. The worst window orientations were found to be the northeast and northwest, regardless of the window type. The authors' results have shown that the optimal window dimensions do not imply equal cooling and heating needs of a room, and that overhangs do not significantly improve the room's thermal performance.

An optimal model of windows for a house in the cold climate conditions in Estonia, where there is a need for a multi-month heating season, was presented in [21]. The authors tried to quantify the usual gap between the energy need of a building calculated with a simplified and a detailed window model. Using the former model can lead to errors in calculations, which then leads to an inadequate façade design. In the building without cooling, the difference in obtained values can be compensated; however, for buildings with both heating and cooling, that difference can be rather big; thus, for the mechanically cooled buildings in cold climates, the detailed window model application is recommended.

In [22], the authors performed an FEM numerical analysis, the results of which were validated by experimental tests of six different types of window frames and four types of the rolling-shutter boxes, to determine the optimal solution. The significant reduction of at least 30% in the thermal transmittance in the rolling-shutter box systems was achieved using the thermal reflective insulation material designed to insulate the walls. The researchers in [23] analyzed the influence of the geometrical and surface characteristics of cavities in aluminum window frames on their thermal performances. They conducted a theoretical analysis, based on the EN ISO 10077-2 procedures, as well as numerical simulation and experimental tests. The results show that the insertion of an adequate number of gaskets, which reduce the cavity dimensions and connections, reduces the thermal transmittance by about 10%. In addition, a significant reduction of 18% was acquired by lowering the emissivity.

A voluminous review of different window spacers and edge seals in insulating glass units was presented in [24]; the authors tried to define the research opportunities to improve those elements' performances. They showed that the edge seal thermal performance has a significant effect on the U-value of fenestration products and that the optimization of the thermal performance of individual spacers is necessary. Data on the products available on the market are provided as well. In [25], an extensive literature review is also presented on the role of window glazing in daylighting and energy saving in buildings; the optimization techniques used by various researchers in choosing a glazing and new glazing technologies are discussed, taking into account both static and dynamic glazing. The advantages of using the electrochromic and thermotropic glazing and photovoltaic (PV) windows as well as some innovative glazing are also pointed out. The authors also suggested that a techno-economic analysis should be performed when deciding on a suitable glazing for a particular type of building.

The authors of [26] analyzed the influence of the windows' geometrical parameters on calculations of the heat conduction coefficient through windows. Their results showed that the lowest value of the heat conduction coefficient is obtained when the plastic is used for the window frame (the PVC profiles), with chambers filled with argon, and that the heat conduction coefficient has much smaller values for the double-glazed windows than for the single-glazed ones.

In [27], a method to examine the improvement of the energy efficiency in a typical high-rise residential building through window retrofitting is presented. Twenty glazing alternatives were analyzed by the creation of a building design model. The research task was to predict the potential energy savings for the case of buildings with an identical orientation but located in different climate zones in China. The authors concluded that the obtained results show that the relatively expensive low-e window glazing has the best energy performance in all the climate zones. However, its performance regarding the energy efficiency is sufficiently close to conventionally glazed windows.

Zhelykhh et al. [28] presented the classification of energy-efficient houses proposed by international standards and its critical analysis. They constructed an experimental model of a solar collector, which was flat. The authors concluded that the solar collector would be effective for preheating the heat carrier in the energy supply system and that it was necessary to exactly establish the temperature characteristics, thermal power and efficiency of the solar collector in the direct-flow system.

Influence of glazing to wall ratio (GW) was analyzed for school buildings in different microclimate regions in Saudi Arabia (hot dry, hot humid and moderate) [29]. Values of the GW ratio considered were from 5% to 40% out of the external wall, by computer modelling and results validating by the field monitoring study. The globe thermometer was used to investigate the impact of student's position with respect to the glazing system and information on actual thermal comfort of students was obtained from a questionnaire. Results pointed out that the south and east directions are the worst and that the optimum value of the WWR should be 10% for all the investigated climate regions.

Xu et al. [30] studied the carbon footprint (CF) of residential housing in China, to be able to propose the mitigating measures. They applied the Geneva 2006 IPCC (Intergovernmental Panel on Climate Change) accounting method and the STIPRAT (stochastic impacts by regression on population, affluence, and technology) model to identify the driving factors of the housing CF. They proposed policy recommendations to lower the overall housing CF, which included controlling the population growth, promoting urbanization benefits, encouraging green consumption, optimizing the household energy consumption structure and enhancing residential building energy management. In addition, in their conclusions, the authors stated that their research had some limitations due to the data unavailability on non-commercial energy consumption in rural areas. They stated that neglecting the impacts of climate and temperature do not significantly influence their results, which the present authors cannot agree with.

Mousavi Motlagh et al. [31] considered the window allocation strategy to have the best trade-off among energy, environmental, and comfort criteria in a residential building. The case study included three alternatives for facades in small newly built part of Tehran, Iran—type A with two parallel facades, type B with two perpendicular facades and type C with three facades, with four possible orientations for each of them. Their results show that the best scheme is the type B façade, having windows on the north and east façades. Such a scheme has advantages over the other two types in lower heating and cooling energy consumption, lower CO_2 equivalent emissions and better thermal comfort.

Li et al. [32] considered the carbon emissions of prefabricated residential buildings, to be able to propose the optimal window design for such buildings. Their voluminous research consisted of a sensitivity analysis of various window parameters and included extracting the window design elements of prefabricated residential facade data and creating the objective function formulas. They concluded that the optimal window-to-wall ratio (WWR) with a low-carbon orientation is around 0.15 as compared to the optimal WWR value of about 0.38 under an energy-saving orientation. The most energy-efficient windows are not necessarily the most conducive to reducing the CO_2 emissions. For a WWR greater than 0.5, the influencing factor of the window height does not impact the CO_2 emissions.

The influence of the glazing-to-wall ratio (GW) was analyzed for school buildings in different microclimate regions in Saudi Arabia (hot dry, hot humid and moderate), [29]. Values of the GW ratio considered were from 5% to 40% out of the external wall, by computer modelling and results validated by the field monitoring study. The globe thermometer was used to investigate the impact of the student's position with respect to the glazing system and information on the actual thermal comfort of students was obtained from a questionnaire. The results indicated that the south and east directions are the worst and that the optimum value of the WWR should be 10% for all the investigated climate regions.

The following *verbatim* quotation Jaber and Ajib's (2011) article [14] arguably best describes the importance of studying all the aspects of the window's design: the "*Window is like a knife it has two sides: one is useful and the other is harmful. When heat radiates through windows on hot hours it requires more cooling energy to maintain a comfortable temperature. Conversely, when heated air escapes from inside to outside during cooled hours, more heating energy is needed to reheat the space in order to maintain comfort*".

3. Calculation of the Heat Load through the Window

As it was explained in the previous sections, the heat load through the window depends on several factors: its construction, the materials used, its position on the building's façade, and the climate conditions in the region where the building is constructed. Here, the window constructions are considered in three towns in Europe: two in Serbia and one in Slovakia. They belong to different climate regions according to the Köppen–Geiger climatic classification [33–35]. The Serbian city of Kragujevac belongs to the climatic region Cfa (moderately warm, humid, hot summer); the city of Bor belongs to the Cfb region (moderately warm, humid, warm summer); the Slovakian city of Žilina belongs to the Dfb region (moderately cold, humid, warm summer)—see Figures 1 and 2. The cities of Kragujevac and Bor lie at an approximately 45° north latitude, while the city of Žilina lies at a 49° north latitude. These data were taken into account in calculations through values of the heat conduction coefficients, obtained from tables in the corresponding standards on the energy performance of buildings, Directive 2010/31/EU of the European Parliament [36] and subsequent Serbian and Slovakian national standards [37–41].

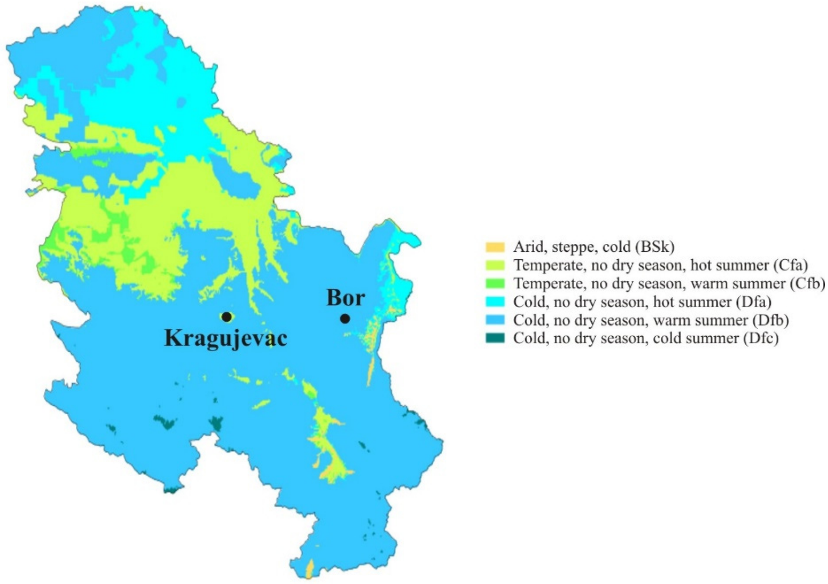


Figure 1. Climate regions of Serbia.

Figure 2. Climate regions of Slovakia.

The heat load through the window is calculated as a sum of the heat load due to the heat transfer and the heat load due to solar radiation [42], as:

$$Q_{hl} = Q_{hl,tr} + Q_{hl,sol} \tag{1}$$

where $Q_{hl,tr}$ is the heat load due to the heat transfer through the window and $Q_{hl,sol}$ is the heat load due to solar radiation.

In calculations such as this, it is usually considered that there is no heat accumulation in the window itself due to the fact that the window glazing is made of thin glass surfaces, which have a low heat conduction coefficient. Therefore, the computation here was performed assuming that the heat transmission through the window is instantaneous.

Thus, the heat load due to the heat conduction through the window was calculated for the considered moment in time, as follows, with the current temperature difference between the inside and outside air:

$$Q_{hl,tr} = U_w \cdot A \cdot (T_{out} - T_{in}) \quad (2)$$

where U_w is the window heat conduction coefficient, A is the total window area, T_{out} is the outside air temperature and T_{in} is the interior air temperature.

When the heat losses are calculated for the winter period, it is usually assumed that the heat conduction conditions are stationary and that the heat conduction is one-dimensional. That means that the heat flux is in the direction of the maximum temperature gradient. It is also considered that all the physical variables are constant with respect to the temperature and that the materials are homogeneous.

Based on the standards' recommendations [36–41], the heat conduction coefficient of the window can be calculated if the heat conduction coefficients of individual window elements are known, as:

$$U_w = \frac{A_g \cdot U_g + A_f \cdot U_f + l_g \cdot \psi_g}{A_g + A_f} \quad (3)$$

where A_g is the area of the glass and A_f is the area of the window frame, U_g is the heat conduction coefficients of the glass and U_f is the heat conduction coefficient of the window frame, l_g is the glass area perimeter and ψ_g is the linear heat conduction coefficient (the temperature correction factor for the heat bridges between the frame and the glass).

The values for the heat conduction coefficient U_g were taken from Table 3.4.1.4 and for U_f from Tables 3.4.1.5–3.4.1.7 (for wooden, PVC and metal frames, respectively) and for the correction factor ψ_g from Table 3.4.1.8 of standard [43] for the towns of Kragujevac and Bor in Serbia. The values for the same variables for the city of Žilina in Slovakia were taken from Tables 19–22, respectively, of the standard STN EN ISO 13790/NA [41].

The values for the heat conduction coefficients for windows without thermo-insulating glass (the so-called glass packages) are taken as 3.5 W/m^{2}K for the "wing-to-wing" windows and 5.0 W/m^{2}K for the single-pane windows.

The heat load due to the solar radiation through the window is calculated according to the mentioned standards as:

$$Q_{hl,sol} = F_{sh} \cdot g_{gl} \cdot (1 - F_f) \cdot A \cdot I_{sol} \cdot \tau_{sol} \quad (4)$$

where F_{sh} is the room shading factor; g_{gl} is the glass solar radiation transmittance coefficient, which depends on the type of the glass; F_f is the solar heat loss coefficient of the frame; and $I_{sol} \cdot \tau_{sol}$ is the average sum of the solar radiation, Table 6.9 [43] and 23 [41], for Serbian and Slovak towns, respectively.

The room shading factor is calculated as:

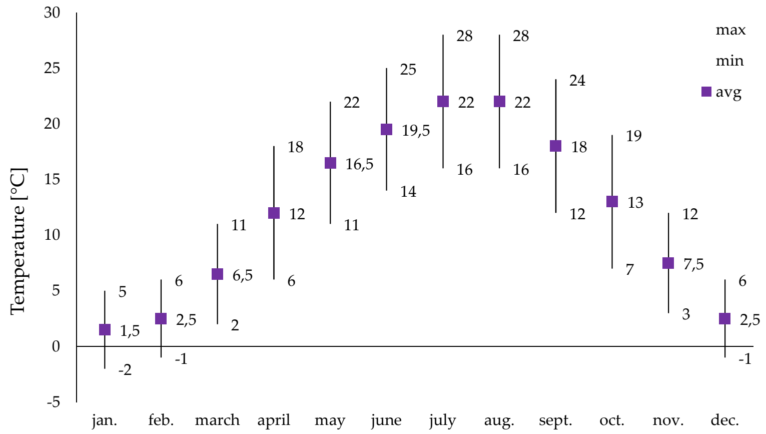
$$F_{sh} = F_{hor} \cdot F_{ov} \cdot F_{fin} \quad (5)$$

where F_{hor}, F_{ov}, F_{fin} are the correction factors according to Tables 6.6–6.8 [43], respectively, for a 45° north latitude (Kragujevac and Bor) and according to Table 23 [41] for a 49° north latitude (Žilina).

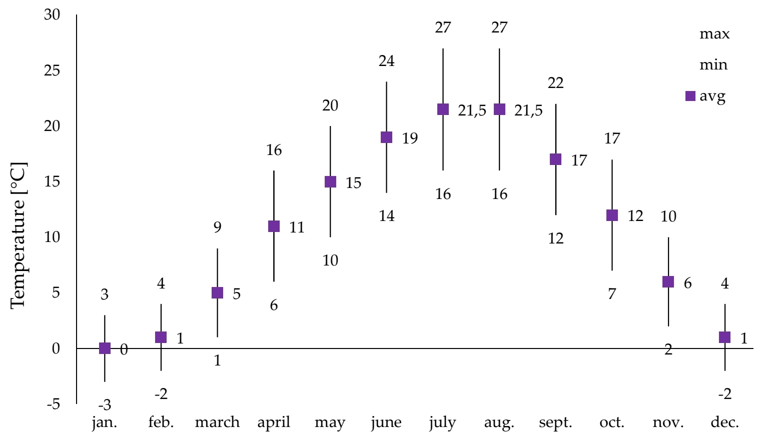
4. Results and Discussion

Based on Equations (1)–(5) and data obtained from the corresponding standards and data tables, the heat load through the window was calculated for the three selected building's locations.

Since the heat load of the room (i.e., coming through the window) depends on the outside air temperature, the data on average monthly temperatures for the three selected cities were necessary. The data obtained from the meteoblue.com for Kragujevac, Bor and Žilina are presented in Figure 3 [44]. The average temperature from those diagrams was taken as the outside air temperature T_{out}, while for the interior air temperature, the value was taken to be T_{in} = 22 °C (295 K).



(**a**)



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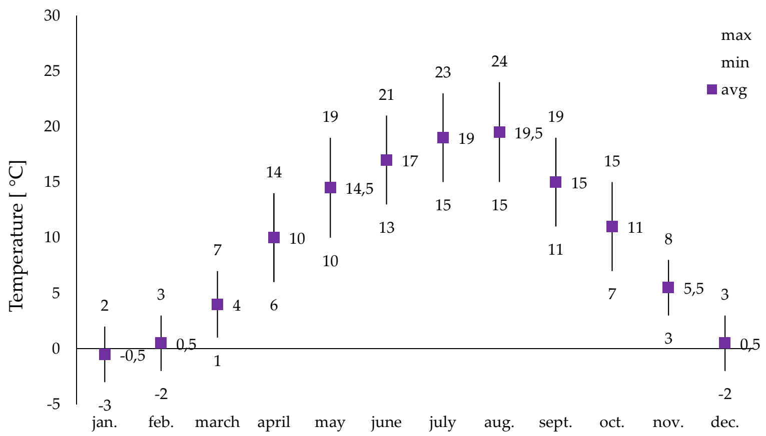

(**c**)

Figure 3. Average monthly temperatures for (**a**) Kragujevac, (**b**) Bor and (**c**) Žilina.

The three types of windows were analyzed: (1) the single-pane fixed window, (2) the double-pane window with an air filling and (3) the double-pane window with an argon filling. The glass dimensions were 1196 × 1196 × 4 mm. The selected frame materials were: (1) wood, (2) PVC and (3) aluminum. The frame dimensions were 1200 × 1200 × 66 mm. The four positions of the windows (placements) were considered: (1) south (S), (2) east (E), (3) west (W) and (4) north (N) façade.

The specific theory of sensitivity analysis was conducted. Each town was considered separately, for each of the considered window parameters, while the other parameters were kept constant. Thus, presenting the results of the calculations is carried out in several steps. For the city of Kragujevac in Serbia, first, the optimal window orientation was determined. Other parameters (window type, frame material and filling) were considered as constant. The results are presented in Figure 4.

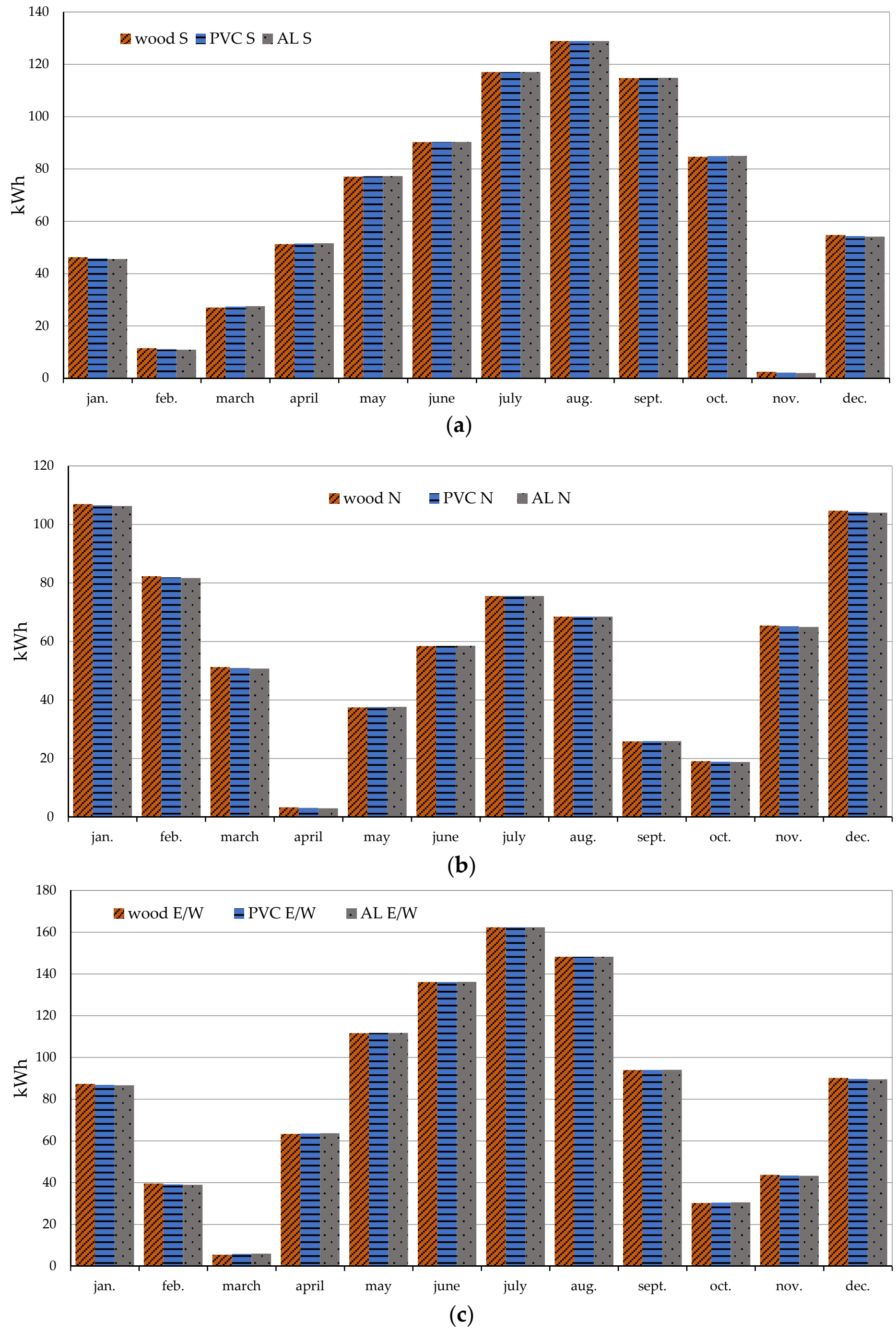

Figure 4. Analysis of the window orientation influence on the window heat load for the city of Kragujevac, Serbia: (**a**) window placed on the southern façade; (**b**) window placed on the northern façade; (**c**) window placed on the eastern or western façade.

From Figure 4, it can be concluded that the best orientation for the window in the city of Kragujevac is on the northern façade, regardless of the window type. In the further analysis, this parameter is kept constant, while the window frame material is varied—see Figure 5.

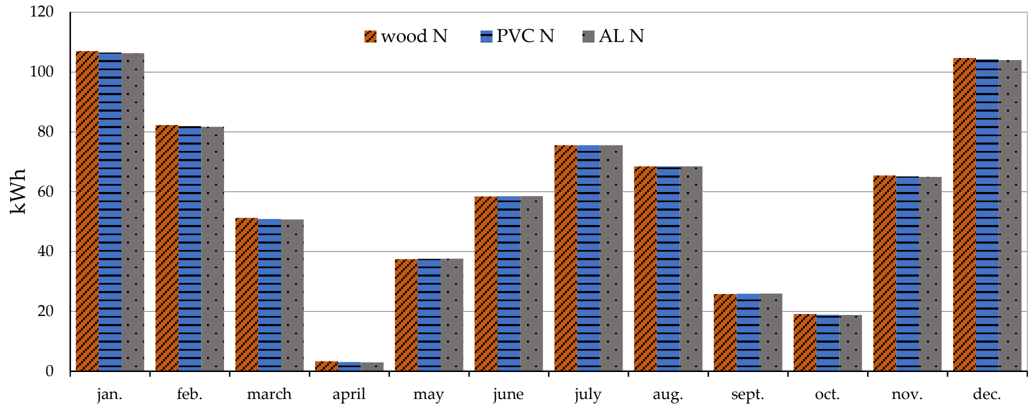

Figure 5. Analysis of the window frame material influence on the window heat load for the city of Kragujevac for the window placed on the northern façade of the building.

From Figure 5, it can be seen that the best frame material for this city is the AL. Finally, for the window, the frame is made of AL, which is placed on the northern façade of the building, and the type of glazing is considered, i.e., the glass and filling—see Figure 6.

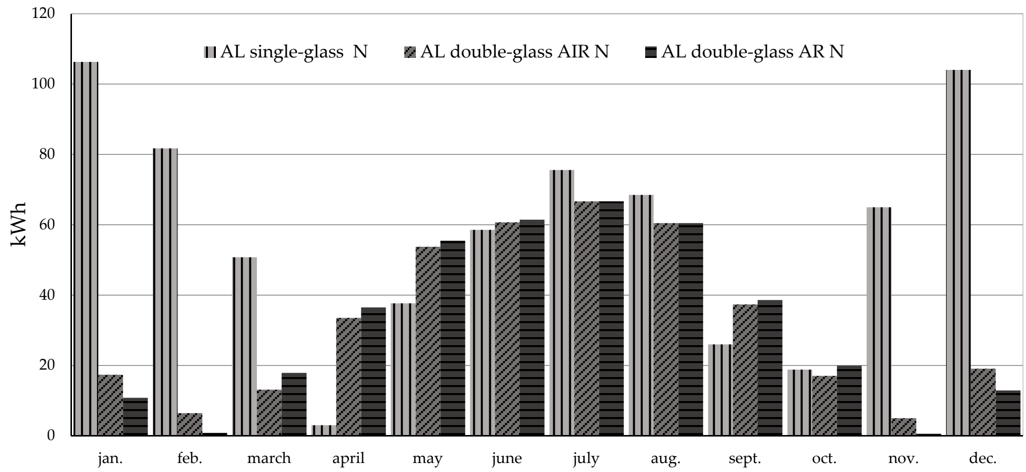

Figure 6. Analysis of the window glazing influence on the window heat load for the city of Kragujevac for the window placed on the northern façade of the building.

From Figure 6, one can conclude that the best glazing type is the double-pane window with an argon filling.

Thus, the optimal window for the city of Kragujevac is the window placed on the northern façade with a frame made of AL and double-pane glazing with an argon filling.

The analogous analysis is then performed for the other two cities. For the city of Bor, in Serbia, the results obtained are the same as for Kragujevac for the window orientation and glazing, while for the window frame material, the optimal solution was PVC—see Figure 7. This is no surprise since the two towns are located in the same climate zone, Cf (moderately warm, humid), but with a difference in the type of summer, Cfa (hot summer) for Kragujevac and Cfb (warm summer) for Bor.

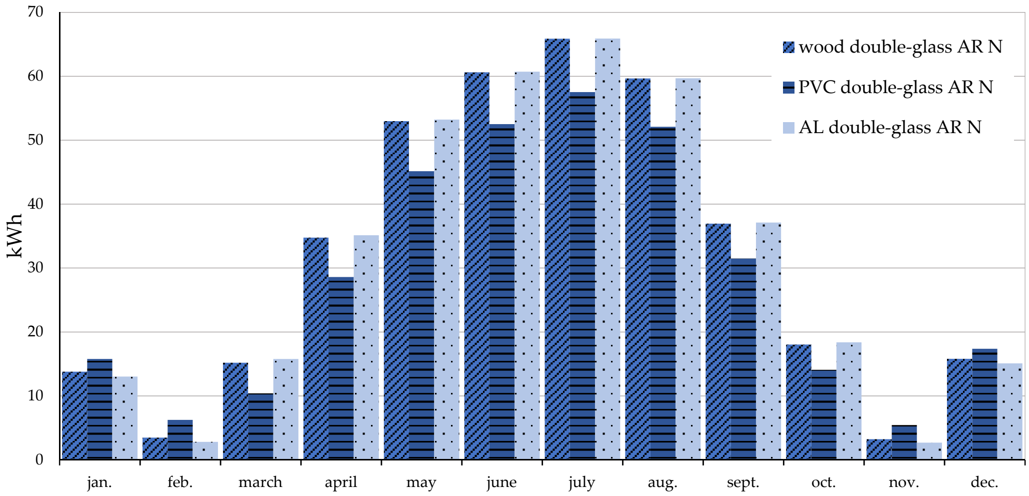

Figure 7. Analysis of the window frame material influence on the window heat load for the city of Bor for the window placed on the northern façade of the building with double-pane glazing and an argon filling.

Analysis was then performed for the city of Žilina in Slovakia. The results obtained were the same for the window orientation and glazing, while for the window frame material, the optimal solution obtained was PVC—see Figure 8.

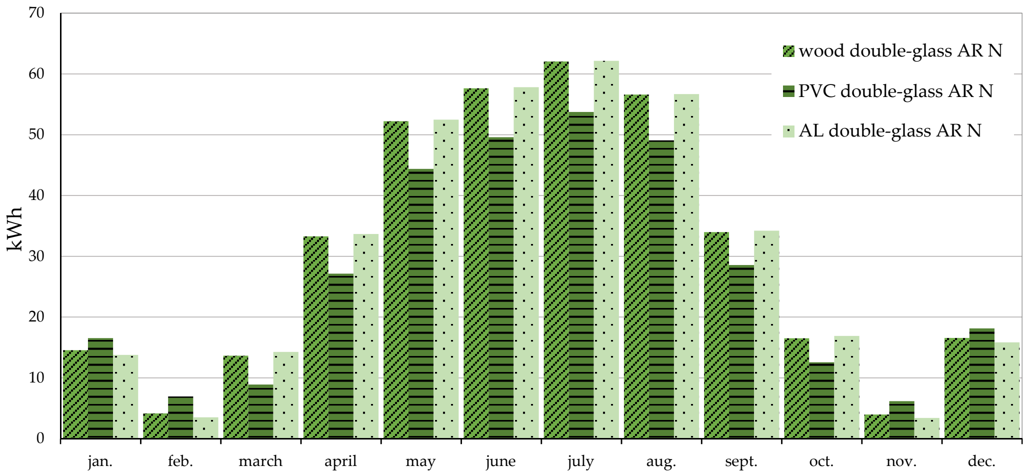

Figure 8. Analysis of the window frame material influence on the window heat load for the city of Žilina, for the window placed on the northern façade of the building with double-pane glazing and an argon filling.

Figures 9–11 present the summary results of the calculated monthly window heat load in kWh for the selected cities, for different window frame materials and placements on the building's façade. Each figure has three parts representing results for the three considered types of window.

From diagrams shown in Figures 9–11, it can be clearly seen that there are differences in the calculated heat load values, first for each city during the year, which is normal since the heat load directly depends on the outside air temperature. Next, one can notice differences between the three parts of each figure for a single city, which are related to the three different types of window. Finally, if one compares the results presented in the same parts of each figure (for example, (a) for the single-pane fixed window), one can notice the differences in the heat load between the selected cities (the same goes for the other two parts of each city's figure).

Figure 9. Monthly window heat load for Kragujevac as a function of the material and orientation: (**a**) single-pane fixed window, (**b**) double-pane window with air filling and (**c**) double-pane window with argon filling.

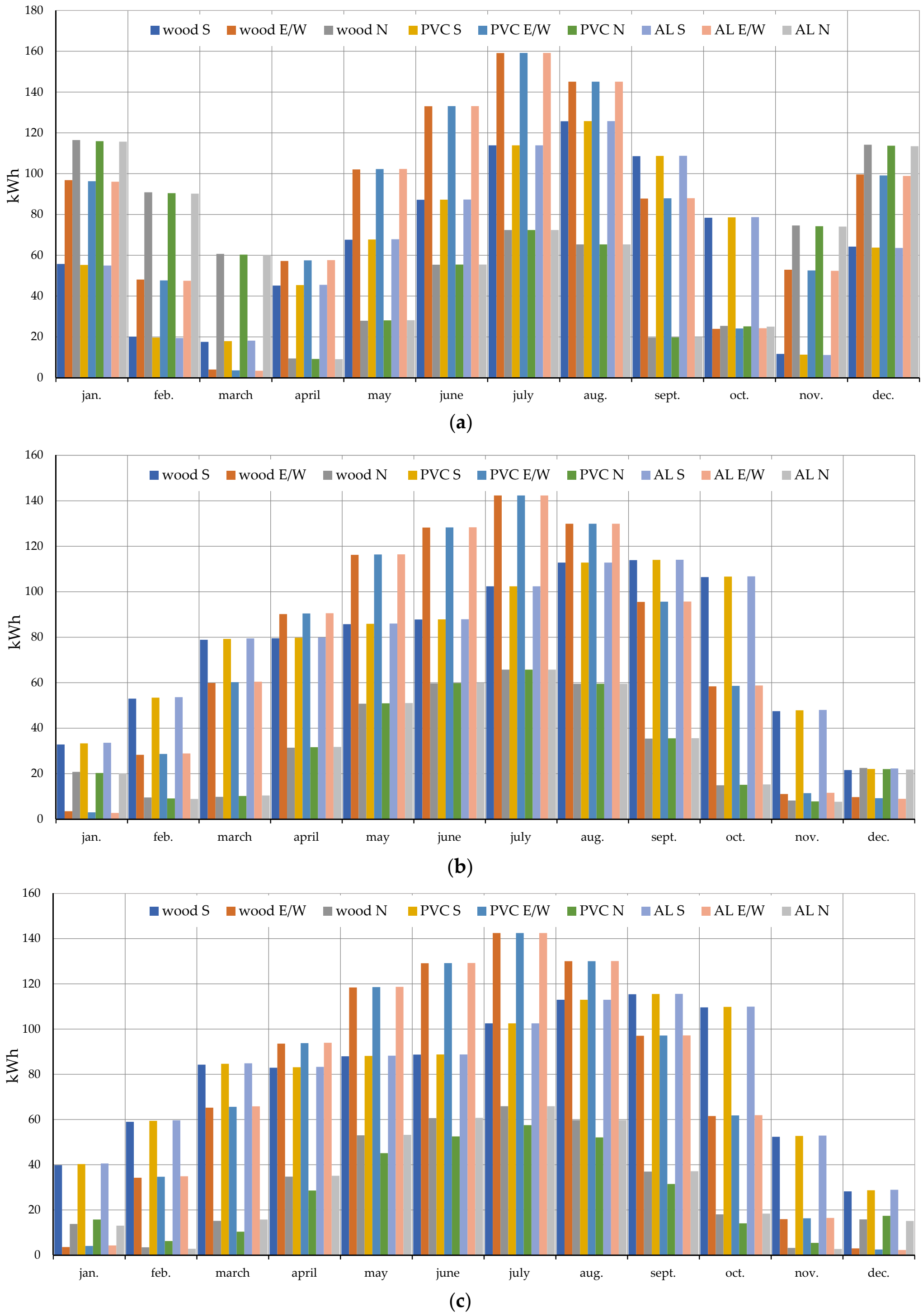

Figure 10. Monthly window heat load for Bor as a function of the material and orientation: (**a**) single-pane fixed window, (**b**) double-pane window with air filling and (**c**) double-pane window with argon filling.

Figure 12 presents the results of calculations of the annual heat load for the three considered cities for various types of widow frame materials, window fillings and window placements. This analysis was performed for the sake of verification of the previous conclusions, to establish which of the window parameter combinations is optimal for the window heat load for the three selected cities. This summary figure supports the previous conclusions.

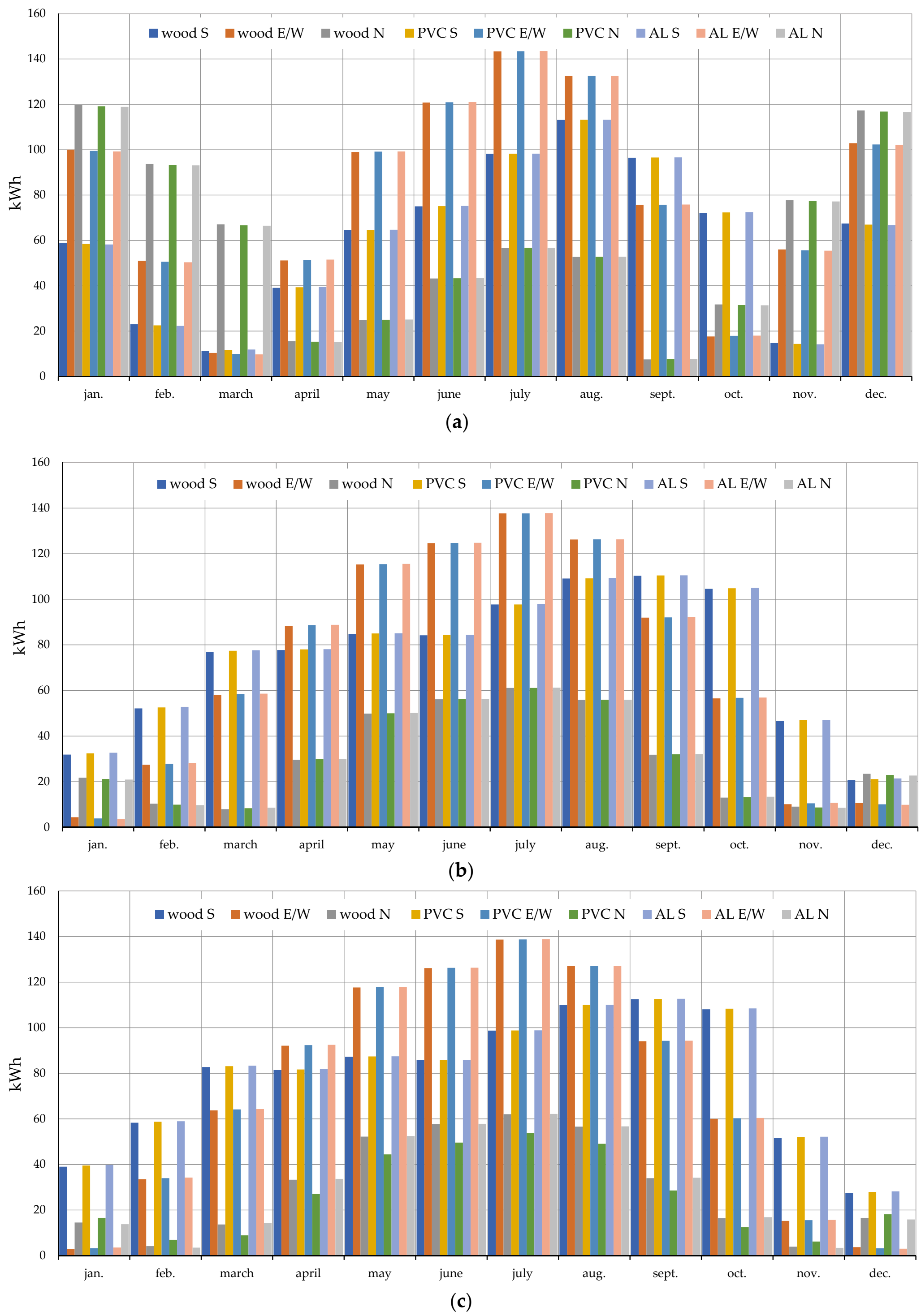

Figure 11. Monthly window heat load for Žilina as a function of the material and orientation: (**a**) single-pane fixed window, (**b**) double-pane window with air filling and (**c**) double-pane window with argon filling.

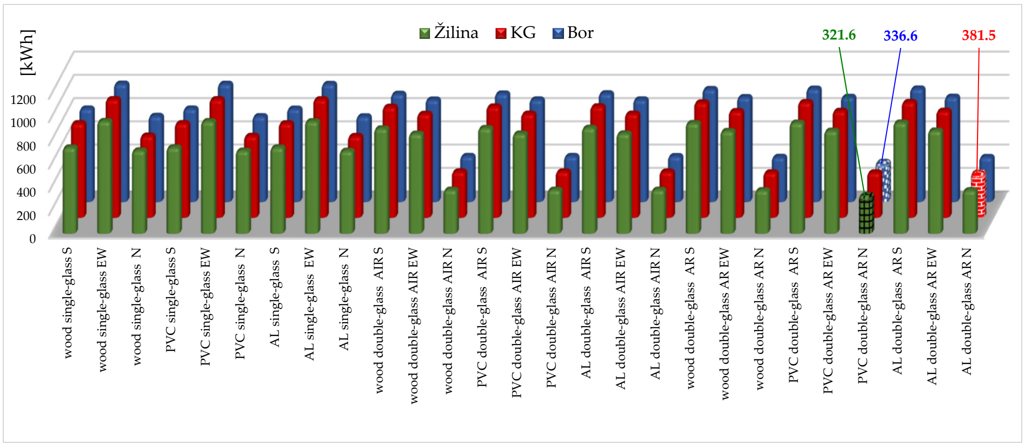

Figure 12. Annual window heat load for Kragujevac, Bor and Žilina as a function of the window type, frame material and window orientation.

5. Conclusions

This paper has presented the results of calculations of the window heat load for three cities in Europe: two in Serbia and one in Slovakia. The two cities in Serbia (Kragujevac and Bor) have similar but not identical climate conditions, while the city in Slovakia (Žilina) belongs to an entirely different climate region. The objective of the research was to find the optimal combination of several window parameters, namely the glazing, filling, frame material and placement of the window on the building's façade, for each of those three cities.

The heat load through the window was calculated as a sum of the heat load due to the heat transfer and heat load due to solar radiation. The inside temperature was taken to be 22 °C (295 K), while the outside temperature was taken as an average from the data obtained from the meteoblue.com website [44].

The three parameters varied were: the frame material—wood, PVC or aluminum; the window orientation—placement on the northern, southern or eastern/western façade of the building; and the glazing—single- or double-pane window with an air or argon filling.

The results obtained from calculations show that the optimal combination of those parameters for the city of Kragujevac is the double-pane window with an argon filling, with the frame made of AL and placed on the northern façade. The results for the city of Bor show that the optimal window solution is the double-pane window with an argon filling, while the window frame material is different, PVC, which was expected since the two cities, according to the Köppen–Geiger climatic classification, belong to the same climate region, Cf (moderately warm, humid), but with a difference in the summer, a hot summer (Cfa) for Kragujevac and a warm summer (Cfb) for Bor, and a difference in altitude (Kragujevacis at 173 m and Bor is at 381 m). For the city of Žilina, which belongs to the Dfb region (moderately cold, humid, warm summer) with an altitude of 342 m, the optimal window solution also includes the double-pane window with an argon filling, placed on the northern facade, with the window frame made from PVC.

The calculations of the heat load through the window were performed based on the given geometrical characteristics and available climate data for the monthly heat load, while the calculations carried out on the annual level verified the said conclusions.

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