Material Aspect of Energy Performance and Thermal Comfort in Buildings

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ABSTRACT **Modern design and construction strives to establish an appropriate relationship between three characteristic poles: man – the user, the building, and the environment. This chapter seeks to highlight this problem by considering the relevant characteristics of the building's thermal envelope, i.e. the impact that the choice of materials has on the behaviour of the building as a whole. Today, we are intrigued by the behaviour of a building as a system, mostly through the prism of the amount of energy it consumes during its existence. On the one hand, this leads us to the need for adequate knowledge of the basic principles of building physics, and on the other, to the awareness of the relevant properties of the materials that we use in the construction process, in order to meet the comfort requirements of the user. Although this chapter emphasises the problem of meeting the thermal comfort requirements, in the example of the review and analysis of characteristic types of residential buildings in the Belgrade area, the scope of meeting the overall comfort requirements has been considered, as well as the interdependence that exists between different types of comfort (thermal, indoor air, sound, and light).**

KEYWORDS parameters and comfort conditions, buildings' behaviour, heat and mass flow, thermal insulation and thermal mass, vapour permeability

1 Introduction - Contemporary Attitude Towards the Issue of Thermal Protection of Buildings

Modern society requires a large amount of energy for its operation. As that energy has largely come from non-renewable sources, the question of energy consumption has become one of the most important problems that modern society has faced since the energy crisis of the 1970s. Given that buildings have been proven to be the largest consumers of energy, this problem refers directly to their design and structure.

At first, attention and care were primarily directed towards the need for more rational energy use, contributing to the development of regulations in the field of thermal protection of buildings. Nowadays, however, the attitude towards the environment is understood in a much broader way, known as the sustainable development doctrine, which, from the viewpoint of energy, would mean that the original approach regarding the need for energy conservation has evolved over time into a holistic concept of energy efficient buildings. The problem of the energy efficiency of buildings is, in general, related to the need to control operational energy consumption. However, it could be expected that, in time, with the increase of energy efficiency, the problem of energy use will shift towards a problem of so-called embodied energy of materials and components, giving more importance to the issue of material selection in achieving overall energy efficiency (Zöld & Szalay, 2007).

The energy performance of energy efficient buildings and their energy consumption undoubtedly depends, to a great extent, on the achieved thermal characteristics, but also on other factors that play an increasingly important role, such as heating and air-conditioning installations, the application of energy from renewable sources, passive heating and cooling elements, shading, indoor air-quality, adequate natural light, and the design of the building (The European Parliament and the Council of the European Union, 2010). It should be stressed that such buildings should be designed and constructed in such a way that they consume a minimal amount of energy, but with the simultaneous provision of maximal living comfort. Such an integrative approach to the architectural design process has three equal poles of interest – man, building, and technology, and is often understood as climate design (Hauslanden, de Saldanha, Liedl, & Sager, 2005).

The appropriate selection of materials has a direct impact on the achievement of the required thermal properties of a building. However, comfort is affected by many parameters, such as temperature, humidity, air movement, air quality, lighting, noise, etc. (Sassi, 2006), which are also dependent on the material properties or the fabric of the house. Therefore, this chapter will analyse the complex correlation between a contemporary building's thermal requirements and the material aspect of the building, bearing in mind the expressed need for the creation of a comfortable environment.

The discussion of the problem in this chapter is divided into several parts that explain:

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- basic aspects and parameters of comfort in buildings;
- relevant elements of building behaviour through the basic principles of building physics, taking into account the hygrothermal properties of building materials and those elements relevant for the adequate thermal behaviour of a building envelope and a building as a whole.

In the last part of the chapter, the interconnection between the choices of materials, the behaviour of the building, and the resulting comfort level is analysed and presented in the form of case studies. As a result of a previous study that focused on the rate of achievement of overall living comfort of Belgrade building stock (Đukanović, 2015), and as a model for this particular investigation, several representative buildings were chosen. Since Belgrade is a capital city, and the largest in Serbia, the study indicates the wider picture and refers to the quality of living comfort in the whole country. Bearing in mind the location of the selected model, the achievement of living comfort was evaluated with respect to the relevant Serbian regulations.

2 User Requirements – Achievement of Comfort in Buildings

It could be said that one of the principles and goals of contemporary design is the achievement of the so-called user's requirements. Although, in general, the user could be either a human or any living being, or a thing for which the building is designed and built, in most cases man is the focus of a design interest. The level of the fulfilment of the user's set of requirements or, in other words, the overall impression of the quality of the space is, on one hand, individual, and a result of the perception of our senses, but on the other hand, it is also related to the compliance with standards that define limiting measurable values of representative parameters. In both cases, the impression is based on the achieved comfort of the place. The term comfort could be understood as everything that makes life more comfortable, or it could be defined as "a state of physical ease" (Sassi, 2006).

Although the terms comfortable and healthy are not synonyms, the comfort of a place is closely related to the notion of a healthy place. Hence, the modern desire for designing for comfort could be understood as a prerequisite for the achievement of a healthy environment (Sassi, 2006). Accordingly, nowadays research and practices strive to define relevant health and comfort indicators (Bluyssen, 2010).

Meeting the physical aspect of the comfort level means to provide:

- adequate indoor temperature relative to outside temperature;
- adequate relative humidity level and its impact on temperature;
- ample natural light and good quality lighting without glare;
- adequate sound separation between buildings – from the outside and within a building; etc.

These aspects could be understood as specific types of comfort: thermal, visual or lighting and acoustic or sound. Bearing in mind that creating a healthy environment requires the provision of adequate quality of air which is free from toxic substances, we could also discuss indoor air comfort, which could be referred to as air comfort.

The built environment affects us through our sensory organs (Szokolay, 2004), and our experience of comfort depends, to a large extent, on the sensitivity of our senses, which is an individual category. However, there are also various building-related parameters that affect all types of comfort. The relationship that exists between different types of comfort, our senses with which we perceive them, and physical parameters by which we describe, explain, and measure these types of comfort is shown in Table 2.1.

TYPE OF COMFORT	THERMAL	AIR	VISUAL	ACOUSTIC
Sense	skin	nose, mouth	eye	ear
				
Related physical parameters	temperature	O_2:CO_2 ratio	illuminance	loudness
	humidity		glare	sound level
	air movement	ventilation rate	colour temperature	noise
	mean radiant temperature	presence of pollutants	daylight factor	

TABLE 2.1 Type of comfort sense-parameter relation

Although thermal comfort is just one type of comfort, it is considered the type of comfort that is linked with a sensation of complete physical well-being (Harris & Borer, 2005).

Thermal comfort is understood as "the condition of mind that expresses satisfaction with the thermal environment" (Szokolay, 2004). It could be also explained as a thermally neutral environment in which there is no feeling of discomfort, and the regulatory mechanisms of the organism are burdened minimally, that is, where thermal equilibrium of the body is achieved (Jovanović Popović, 1991). The metabolism of a human body continuously produces heat by its processes and, depending on the environmental thermal conditions, different thermal adjustment mechanisms might be activated (such as: vasoconstriction, vasodilatation, evaporation and shivering) in order to maintain the thermal balance of the organism. Both the rate of heat dissipation from the body, as well as the type of mechanism that might be activated depend on several groups of variables, presented in Table 2.2. The groups of variables could be named as either environmental, personal or contributing factors (Szokolay, 2004), or as objective or subjective parameters (Jovanović Popović, 1991).

GROUP OF VARIABLES (AFTER SZOKOLAY, 2004)		
ENVIRONMENTAL	PERSONAL	CONTRIBUTING FACTORS
Temperature	Metabolic rate (activity)	Food and drink
Humidity	Clothing	Body shape
Air movement	State of health	Subcutaneous fat
Mean radiant temperature	Acclimatisation	Age and gender
OBJECTIVE	SUBJECTIVE	
PARAMETERS (AFTER JOVANOVIĆ POPOVIĆ, 1991)		

TABLE 2.2 Type of variables, i.e. parameters related to the perception of thermal comfort

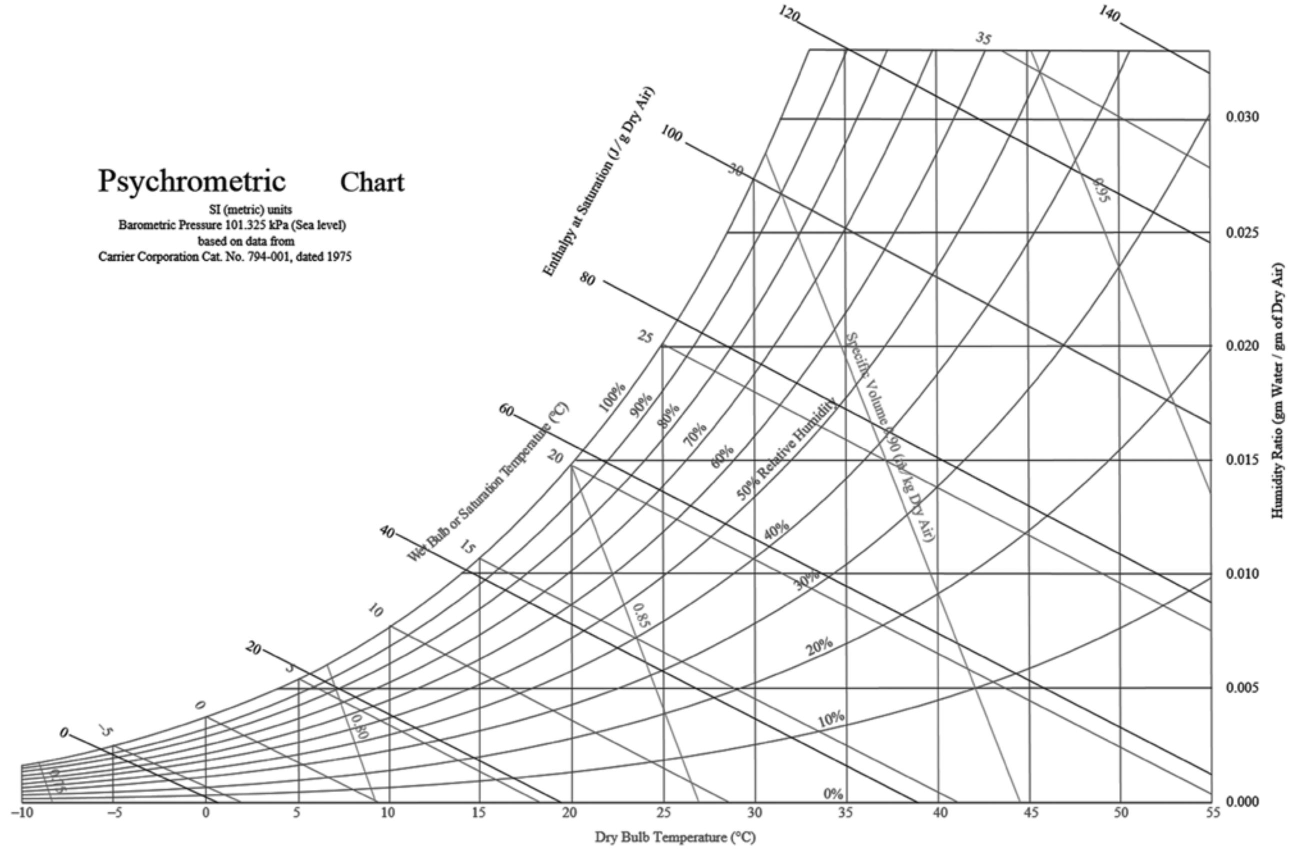

FIG. 2.1 Psychrometric chart
(©-2009-Creative Commons; retrieved from: https://commons.wikimedia.org/wiki/File:PsychrometricChart.SeaLevel.SI.svg)

In general, a good understanding of thermal comfort requires different types of representation of various combinations of simultaneous actions of thermal parameters. Based on a correlation between the temperature and humidity of the air, which is important for a perception of a thermal environment, a psychrometric chart could be understood as the most commonly used way of displaying the limits of comfort (Fig. 2.1).

An individual perception of the thermal environment, as well as not only the fact that "a person is different to other person, but he or she changes over time" (Hauslanden et al., 2005), influences the fact that today, the analytical determination and interpretation of thermal comfort is usually based on the calculation of the PMV and PPD indices that indicate the rate of thermal discomfort (EN ISO 7730, 2005; EN 15251, 2007).

Nowadays, efforts to reduce the use of resources in general, in the context of achievement of sustainability, result in the notion of sustainable thermal comfort. Although there is no simple answer to the question of what exactly sustainable thermal comfort is, the provision of thermal comfort is closely related to the problem of the heating and cooling of a building, i.e. of its energy consumption. In that sense, it could be assumed that suggestions and measures for good housekeeping contribute to the reduction of energy use. Bearing in mind that there are many combinations of relevant parameters that result in the achievement of thermal comfort, different rates of clothing and/or activity in combination with lower environmental temperatures and other objective thermal parameters could still result in an adequate level of thermal comfort which is, certainly, more sustainable in terms of energy consumption (Parsons, 2010).

3 Mechanisms of Behaviour of a Thermal Envelope in the Service of Thermal Comfort

The thermal envelope of a building is an element that separates the external from the conditioned, heated, or cooled internal environment and predetermines the quality of achieved comfort. It could be also considered as an interface between the exterior and the user inside the building (Hauslanden et al., 2005). Combined with the spatial design of a building, the design of a building fabric has a direct impact on the building's energy consumption. Hence, a proper envelope design is considered one of the passive design measures that should be applied in order to achieve energy conservation (Oral, Yener, & Bayazit, 2004; Sassi, 2006). Research on today's principles of building envelope design, conducted by Oral et al. (2004), determines that there are several types of parameters that affect the behaviour of a building envelope. They are primarily grouped as those related to the outdoor (external) environment, and those related to the indoor or built environment (Table 3.1).

The parameters related to the outdoors are a result of climate conditions and, therefore, are understood as natural factors that should be considered with their given values. On the other hand, those that relate to the indoor environment are the result of a designer's decision and include problems and decisions on different scales: immediate surroundings, a building, a room, or an element.

Accordingly, modern regulations in the field of thermal protection anticipate the verification of the energy performance of the building on two levels: 1) the individual building construction and 2) the whole building. With respect to this, in the case of Serbian thermal regulations (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and

Spatial Planning of the Republic of Serbia), 2011), the required verification is defined in the following way:

- on the level of the individual building construction by means of the identification of the U-value, i.e. the coefficient of heat transmission or thermal transmittance, by checking the mechanism of water vapour diffusion that occurs through the construction and by checking the so-called mass effect in the summer period;
- on the level of the whole building by means of the heat transmission loss coefficient $H_{T,}$ which considers the effects of thermal bridges, ventilation loss coefficient H_V, specific heat transmission loss H'_T and total volume heat losses q_V;

POS.	OUTDOOR	INDOOR				
scale		surroundings	building	room	element	
					opaque	transparent
parameters	***air temperature***	***dimensions and orientation of external obstacles***	***orientation***	***position within building***	***thickness of materials***	***dimensions of transparent components***
	solar radiation	***solar radiation reflectivity of surrounding surfaces***	position relative to the noise source	***dimensions and shape factor***	***density of material***	***number of layers of glazing***
	humidity	light reflectivity of surrounding surfaces	position relative to other buildings and the noise source	***orientation***	***specific heat of the materials***	***heat transmission coefficient of glazing***
	wind velocity	***soil cover and the nature of the ground***	***form***	***absorption coefficient for solar radiation entering through the transparent component***	***heat conduction coefficients of the materials***	***absorption, reflection and transmission coefficient of glazing (solar)***
	illumination level			sound absorption coefficient of the internal surfaces	light absorption and reflection coefficients of the surfaces	transmission coefficient of glazing for diffuse sunlight
	sound level			total sound absorption coefficient	sound transmission coefficient	transmission coefficient of glazing for direct sunlight
				light reflection coefficients of the internal surfaces	porosity and roughness of the surface	transmission coefficient of glazing for sound
					sound absorption coefficient of the surface	***type of frame***
					construction of the surface	maintenance factor of glazing
					layered structure	
					depth of the cavity between the layers	
					thickness and sound absorption of the insulating material inside the cavity	
					type and number of connections between layers	

TABLE 3.1 Parameters that influence the envelope design* *(after Oral et al., 2004)*

**italicised text represents parameters that have a direct impact on thermal comfort*

In general, the verification of the thermal characteristics of a building is carried out on the elements of its thermal envelope, i.e. all of the building elements that separate either the unheated from the heated parts of the building, or that separate parts of the building that have different comfort conditions.

3.1 Heat and Mass Transport Through a Building's Fabric

A building's fabric is a mediator through which heat and mass transport occur as a result of typical mechanisms of action. Acting on certain mechanisms of heat and mass transfer through the envelope contributes to the reduction of the energy requirements of the building (Sassi, 2006). These actions could be defined as the need for:

– minimising heat loss through appropriate insulation and making a building airtight;
– minimising unwanted heat gains with solar shading, insulation and reflective finishes;
– considering the use of thermal mass in order to moderate daily temperature variations or as heat storage.

Thus, the heat flow through the building's fabric could be explained by the mechanisms of heat reflection, heat transmission resistance that depends on the mechanisms of conduction and convection of the heat on its way through the element of the envelope (Fig. 3.1), and heat capacity, which can have significant effects on heat transfer (Hall & Allison, 2010). Conduction, as a mechanism for transmitting heat, is a result of direct contact. It is characteristic of solid bodies and stationary fluids and is transferred from one molecule to another or, in the case of metals, by the movement of free electrons. On the other hand, convection is characteristic of fluids (liquids and gases) and is achieved by the movement of the fluid's molecules. The third method of heat transfer - radiation, occurs when the heat of the radiation source is transmitted by the transformation of the internal heat into energy in the form of electromagnetic radiation (infrared radiation), which can be reflected or absorbed by a solid body. Each of the heat transfer modes is a complex function of the size, shape, composition (types of materials) and the orientation of the construction component.

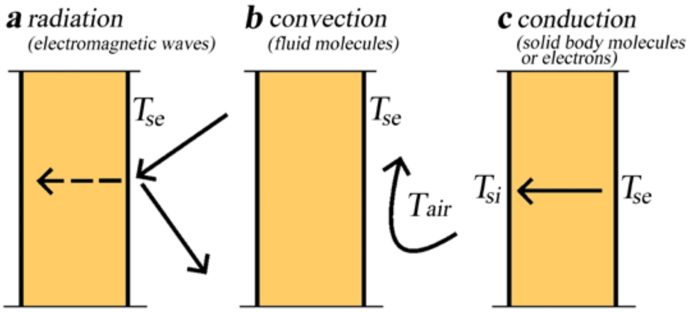

FIG. 3.1 Methods of heat transfer

When it comes to heat flow through architectural objects, the important issue is the transfer of heat from a fluid to a solid body, i.e. from the air to the building and vice versa, due to a temperature difference, as well as the transfer of heat through the construction itself. It is determined on the basis of thermal resistance (R value), which includes resistance to heat transfer at the boundary surface between the structure and the air (R_{si} and R_{se}), as well as resistance to heat conduction through the structure (R_T), which is dependent on the thermal conductivity (λ) and thickness (d) of each layer of material within the structure in question. The overall thermal transmittance (U value) of a building's fabric, which is the subject of thermal regulation, represents the reciprocal of the thermal resistance:

$$U = \frac{1}{R_{si} + R_T + R_{se}} = \frac{1}{R_{se} + \sum_n \frac{d_n}{\lambda_n} + R_{se}} = \left[\frac{W}{m^2K}\right]$$

The building structures that are commonly used today can be very complex, consisting of homogeneous or inhomogeneous layers, containing different types of air layers, air spaces etc. Such circumstances might additionally complicate the calculation of their thermal performance (EN ISO 6946, 2007; Vilems, Šild, & Dinter, 2008; Medved, 2011), as well as the determination of the mechanism of heat transfer through them.

However, the mass flow through a building's fabric refers to a mechanism of diffusion wetting, i.e. the transport of water vapour. This natural process of water vapour transmission should be carried out in such a way that two requirements are met: 1) there is no surface condensation on the inner surface of the thermal envelope of the construction; and 2) during the diffusion transfer of water vapour in the construction structure, there is no condensation of water vapour, to the extent that the increase in humidity affects the durability and bearing capacity of the building constructions (Medved, 2011).

Generally speaking, both heat and mass transport are results of the imbalance that exists in the environment with regard to temperature and relative humidity. In the case of heat transfer, it is explained as the transport of energy that results from temperature difference, while mass transport is a result of the difference in the concentration of matter (Hall & Allison, 2010). The directions of heat and thermal mass movement are generally synonymous but, under specific conditions, may be different (Vilems et al., 2008). Depending on the specific direction – towards the exterior or the interior of the occupied space, we can discuss the heat losses or heat gains, both of which could be either desirable or undesirable, depending on the particular situation. Therefore, it is important to properly understand the mechanisms of the transport, as well as the methods of quantification (Hall & Allison, 2010; Künzel & Karagiozis, 2010).

Certain assumptions are adopted when calculating the thermal characteristics of the thermal envelope, such as a stationary method of heat transfer a one-dimensional heat transfer, that is, the assumption that the heat flux is perpendicular to the observed barrier, as well as the postulation that all the relevant physical properties of the material are constant (Todorović, Bogner, & Denić, 2012). Bearing in mind the complexity of the problem of heat transfer, such assumptions and simplifications are justified and the calculated values are, in the majority of cases, sufficiently accurate. However, we should be aware of the fact that in reality there is a constant variability of certain parameters such as temperature and relative humidity; hence, instead of a steady state environment and stationary heat transfer, they are moisture-dependent and time variable (Hall & Allison, 2010). This fact affects both the characteristics of the material within the thermal envelope and, consequently, the mechanism of heat transfer.

3.2 Relevant Characteristics of Building Materials and Principles of Structuring a Building's Fabric

On their way through the thermal envelope, both heat and moisture might be stored or transmitted, depending on the hygrothermal properties of the applied building materials. In principle, the control of heat flow through a material or construction is based on three characteristic mechanisms of action: first, heat reflection, which is a characteristic of metals, i.e. the material in which the radiation prevails as a way of transferring heat. The principle is related to the correct installation of metal foils within the structure; the resistance of heat transmission, which is the principle of operation of thermal insulation materials; and the storage or accumulation of heat as a characteristic of solid constructions, which is time variable (Hall & Allison, 2010) and significant for the adequate thermal stability of the structure. The way in which the natural process of water vapour diffusion through the envelope takes place is directly related to the permeability of a building material, and porous building materials are especially sensitive to any change in moisture content. Consequently, the measured values of the thermal conductivity of a built-in porous material and its design values can vary to a certain extent, so this fact should be taken into consideration when designing an element of a thermal envelope (Hall & Allison, 2010).

Depending on the dominance of relevant hygrothermal properties, materials can be classified into several particular groups. Regarding their basic thermal properties, one can distinguish the following types of materials:

- those having good thermal accumulation and bad insulating properties, like the so-called structural materials;
- those having bad thermal accumulation and good insulating properties, such as thermal insulation;

- glass as a unique building material that is specific for its transparency and exhibits specific behaviour in relation to different electromagnetic/ solar radiation ranges - visible, ultraviolet and infrared; and
- innovative insulating materials which could be understood as a new generation of building materials that are the result of the increasing need for better energy efficiency in buildings;

On the other hand, regarding their vapour permeability and the role in the structure, there are two specific types of materials:

- those that act as an impermeable film or a vapour barrier that retards vapour movement but does not totally prevent its transmission; and
- vapour permeable foils, i.e. layers of thin material that allow the passage of water vapour in one direction, but prevent it in the other;

The proper functioning of the physical process of water vapour diffusion, the accomplishment of which is important, depends on the climatic conditions, the type and properties of the applied materials, the thickness and vapour permeability of the individual layers of the material, as well as their order in the assembly. Otherwise, an undesired increase in the humidity of a material within a thermal envelope may occur as a result of an uncontrolled diffusion flow, which, over time, can cause changes in its thermal, mechanical and other properties, that is, various forms of construction damage and the premature aging of materials and constructions (Künzel & Karagiozis, 2010).

Contemporary thermal requirements impose specific problems in building practice due to the increased thickness of conventional building materials. Therefore, there is a need for a more efficient use of building materials and structures, due to an increased awareness of their relevant properties and rules of behaviour. The provision of comfort and efficiency in a building construction in terms of energy can be achieved when several aspects are taken into account simultaneously: the insulation properties of materials and constructions, their behaviour regarding the water vapour diffusion that is dependent on a material's permeability, and adequate application of thermal inertia that is relevant for better thermal storage and enables thermal phase or time lag. In that sense, the basic principles to be respected are as follows:

- In the case of layered constructions, the resistance to heat transfer of all layers should increase from the inside out, and at the same time, their water vapour diffusion resistance should decrease from the inside to the outside;

- In order to take advantage of the thermal inertia of walls, thermal insulation should be on the outside of the construction - exceptions are rooms that are occasionally heated in which rapid warming of the air in the room is needed (theatre and concert halls, sports halls, etc.);

- When creating the concept of a building and structuring the assemblies one should strive for an adequate combination of thermal inertia and good thermal insulation;

- Ventilated air layers can contribute to better characteristics of structures in relation to the diffusion of water vapour through the structure (by omitting a vapour barrier), as well as to the summer stability of the structure (by increasing the temperature oscillation damping factor).

4 Comfort in Buildings and the Interdependence of Comfort Requirements – Case Studies

In practical terms, the achieved comfort in buildings is a direct result of the way we build buildings; specifically, the applied materials, the design and construction rules that change over time as a result of technical and technological innovation, the development of building regulations, social, economic, and other circumstances. An estimation of the achieved living comfort might be a starting point for understanding the quality of the building stock, as well as its potential for further energy improvements.

Bearing this in mind, the housing stock of Belgrade was analysed from the perspective of thermal comfort but with a reflection on its effects on other types of comfort (Đukanović, 2015). The assumption was made that the erected buildings, through their structure, volumetrics, and shaping, create the most important preconditions for achieving thermal comfort, in which a decisive role is played by the façade envelope, as the boundary between the most expressive temperature differences. In both thermal conditions to which the façade is exposed (winter and summer), the structure of the envelope (exterior walls, windows, roofs, etc.) is crucial for the achievement of thermal comfort, while in the summer, additional protection at the window level together with natural ventilation also play an important role and contribution.

As part of the conducted research, constitutive structures of thermal envelopes of typical residential buildings were determined and used as a basis for the creation of representative models of the residential architecture of Belgrade. These models were the subject of further analyses, conducted according to the determined comfort parameters, in order to examine the overall quality of the analysed housing stock.

4.1 Determination and Characteristics of Representative Models

Three theoretical models that reflect different periods of construction of the housing stock are selected and analysed: 1) the oldest buildings (built before the First World War); 2) those built during the mass housing construction of the sixties and seventies; and 3) buildings built in the 1990s (Table 4.1). Regarding the existence of regulations in the field of thermal protection (Radivojević, 2003; Radivojević & Jovanović Popović, 2013), the selected construction periods correspond with the following times: 1) before the adoption of the first regulations in this area; 2) the time that corresponds to the first regulations on thermal protection in Serbia; and 3) the period preceding the adoption of the

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Rulebook on energy efficiency of buildings (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and Spatial Planning of the Republic of Serbia), 2011), which introduced an obligation in Serbia to build energy efficient buildings. The analysis of the three selected models focuses on the façade envelope and the effects it has on the realisation of thermal, air, acoustic, and visual comfort.

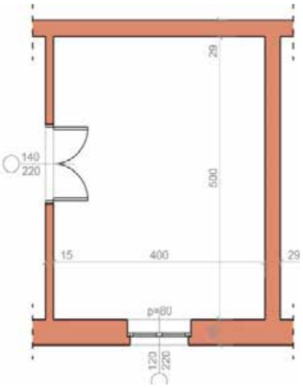
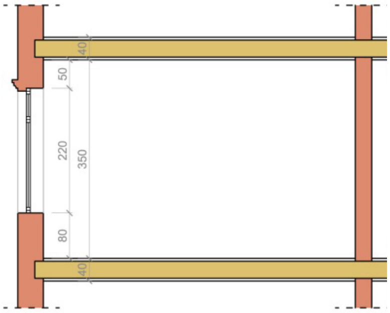
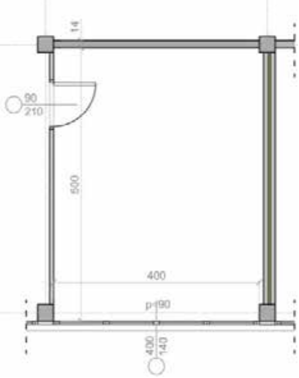
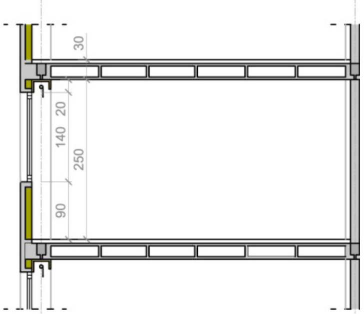
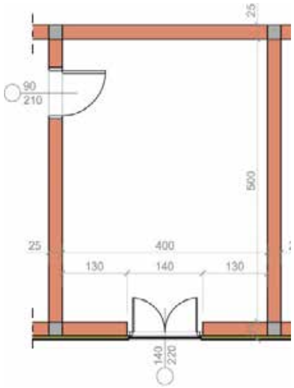
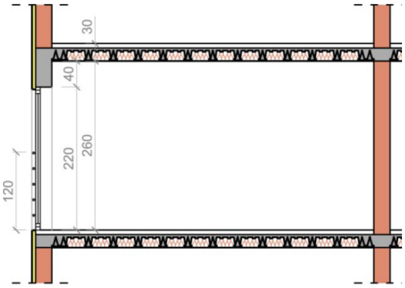
	TYPICAL HOUSE / ROLE MODEL	FLOOR PLAN	CROSS SECTION
Model 1 (before 1919)			
Model 2 (1960-1975)			
Model 3 (post 1990)			

TABLE 4.1 Basic characteristics of the analysed theoretical models

The models were created with all the relevant elements that represent a typical living room from the analysed period. The living room is selected as a place where daily activities take place. Therefore, it can be considered relevant for assessing the extent to which housing comfort was achieved. The analysis of the Belgrade housing stock indicated that the length and width of the room might be the same for all models (5 x 4 m), corresponding to a constructive and functional grid found both in massive and skeletal systems. However, the height of the room is variable depending on the period that the model represents. The analysed room occupies a central position in the organisational scheme, having peripheral walls that are determined as follows: one wall of the room is defined as a façade wall, another is a barrier to the neighbouring apartment, and the other two as partition walls between the other rooms of the apartment. Viewed vertically, the spatial unit is installed in the central part of the building, so that above and below there is a neighbouring residential area. This is the most common position in multi-storey residential buildings. A southern orientation of the room was adopted, which is a desirable position for this spatial purpose.

Peripheral structures of analysed models (walls, floor structures and windows), as well as the applied structural system (massive or skeletal) correspond to those typical for the observed construction period. The window dimensions, their position, number, height of the parapet, applied frame material and structure, glazing, as well as the type of window protection, vary depending on the current modes of construction and architectural styles. The influence of window features is perceived in all forms of housing comfort (visual comfort), and in some it plays a decisive role.

For model 1, which represents the oldest buildings in Belgrade, massive, brick masonry is the characteristic basic material of construction. The earliest construction period was marked by the use of wooden windows with a double frame and a single glazed sash, which were built into a brick wall (Đukanović, Radivojević & Rajčić, 2016). According to the set criteria, in accordance with the standards and architectural volumetrics of the time, high individual windows were installed.

Model 2 represents objects formed during the period when prefabricated systems, based on reinforced concrete, were applied. The model was created in the skeletal, IMS system, which prevailed in the residential construction of Belgrade at the time, with a parapet structured from a combination of regular and foam concrete. In accordance with the recognisable form of facades of multi-storey residential buildings of the time, the model has strips of horizontal windows and parapet-shaped panels of a multi-layered structure. Due to the reduced thickness of the parapet walls and the propagated savings in construction, single frame, wooden windows with a connected double sash and single glazing were used. Therefore, an assembly with a canvas roller blind was adopted in model 2.

Model 3 reflects the period after 1990, which is characterised by the abandonment of prefabricated reinforced concrete systems and the return to traditional building methods. The load-bearing walls were most often made of cavity clay blocks, which became the dominant material in the construction of residential buildings, replacing bricks in

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constructive positions. Façade walls are coated with plastered insulation material (usually polystyrene). During the 1990s, the production of PVC windows started, which eventually suppressed the use of wooden ones, primarily because of simple maintenance, good thermal properties and low prices (Table 4.1).

4.2 Indicators of Achieved Thermal Comfort

In accordance with the requirements derived from the relevant regulations in Serbia, the selected parameters for evaluating thermal comfort are: heat transfer coefficient (U), water vapour diffusion parameters - condensation check, summer thermal stability check by calculating the temperature oscillation damping factor (ν) and the temperature oscillation delay (η), as well as transmission losses through the façade elements. In Table 4.2, the structure of the façade envelope is shown for each model: the percentage distribution of the surfaces of opaque and transparent parts, as well as the ratio of transmission losses through the window and façade wall on the observed segment. This approach is a consequence of the way in which the research model is formed, where the dimensions of the windows are variable and reflect the characteristics of the selected construction period. In this sense, a model has been designed so that its thermal envelope consists only of a façade wall with a window. Thus, changes in the dimensions of windows and the height of the storey would be seen independent of other influences.

In the case of the non-transparent parts of the façade, heat transfer coefficients of exterior walls do not meet current regulations in any of the models, which, according to Serbian regulations, for existing buildings should be less than 0.4 W/m^2K (Ministarstvo za zaštitu životne sredine, rudarstvo i prostorno planiranje Republike Srbije (Ministry of Environmental Protection, Mining and Spatial Planning of the Republic of Serbia), 2011). By comparing the results shown in Table 4.2, the worst results for the heat transfer coefficient are for the concrete prefabricated wall (model 2), which is due to the poor thermal characteristics of reinforced concrete as the basic material in the assembly. Summer thermal stability parameters do not meet the prescribed values for this particular façade wall, which can result in a variation of air temperature in the interior of the room, depending on the temperature of the outside space. In the layers of the façade walls in models 2 and 3, condensation occurs, which dries within the allowed time limit. However, the drying time for model 2 is significantly longer, indicating the more unfavourable characteristics of this wall as it relates to water vapour diffusion.

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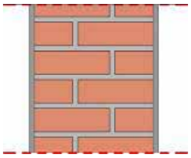
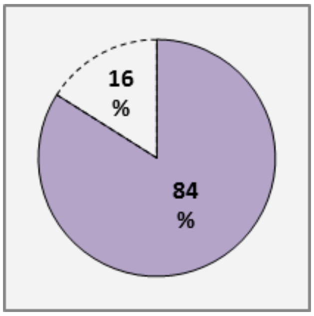
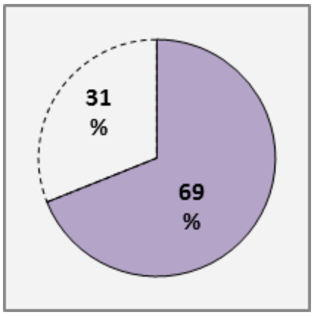
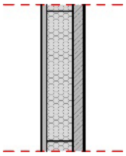
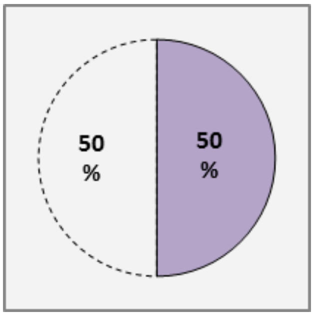
MODEL 1 FAÇADE ENVELOPE

Façade wall	Window	Opaque/transparent representation	Transmission losses
			
brick wall 45cm, both sides plastered	wooden, double frame, double sash (wide box); single glazed interior curtains		
U=1.1 W/m^{2}K U > U_{max}	**U= 2.6 W/m²K,** U > U_{max}	**surface of façade envelope: 16.46** m^2	**total transmission losses of the façade envelope: 22.08 W/K**
v=131.0 > v_{min}= 15			
η=16.8 > $η_{min}$= 7		façade wall: 13.82 m²	façade wall: 15.22 W/K
condensation: none		window: 2.64 m²	window: 6.86 W/K

MODEL 2 FAÇADE ENVELOPE

Façade wall	Window	Opaque/transparent representation	Transmission losses
			
parapet element with a combination of regular concrete and foam concrete	wooden, double frame, connected sash; single glazed canvas roller blind		
U=1.46 W/m^{2}K U > U_{max}	**U= 2.8 W/m²K** U > U_{max}	**surface of façade envelope: 11.76** m^2	**total transmission losses of the façade envelope: 25.04 W/K**
v=10.4 < v_{min}= 15			
η=5.9 < $η_{min}$= 7		façade wall: 5.88 m²	façade wall: 8.58 W/K
condensation: in layer 2; 25.6 days drying time		window: 5.88 m²	window: 16.46 W/K

MODEL 3 FAÇADE ENVELOPE

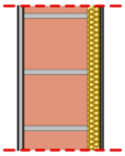
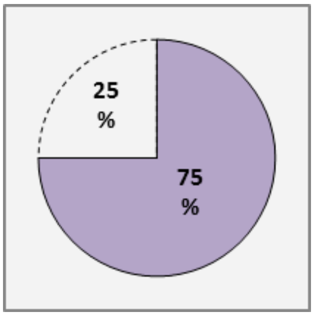
Façade wall	**Window**	**Opaque/transparent representation**	**Transmission losses**
			
cavity clay block wall with plastered thermal insulation	single three-chamber plastic window, double glazed external roller blind		
U=0.53 W/m^{2}K U > U_{max}	**U= 3.0 W/m²K** U > U_{max}	**surface of façade envelope: 12.33** m^2	**total transmission losses of the façade envelope: 14.15 W/K**
v=109.7 > v_{min}= 15			
η=9.3 > $η_{min}$= 7		façade wall: 9.25 m²	façade wall: 4.91 W/K
condensation: in layer 3; 1.5 days drying time		window: 3.08 m²	window: 9.24 W/K

TABLE 4.2 Indicators of thermal comfort of analysed models

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Different windows are built into the models, resulting in differences in heat transfer coefficients. The best features are seen in the wooden double window with a wide box, and the worst in the single three-chamber plastic window with double thermal insulating glass. For model 1, the transparent parts are less represented in relation to the façade wall (16%), but due to the poorer thermal characteristics ofthe window compared to the wall, the redistribution of transmission losses through the envelope changes.

The graph representing the transparent and non-transparent façade parts in model 3 shows a slightly higher window presence (25%) compared to model 1, but the ratio of transmission losses through the façade elements is completely different, due to the large differences in heat transfer coefficients between the two elements of the thermal envelope. Although in model 3, the façade wall contains thermal insulation so the value of the coefficient of heat transfer through the wall is more favourable than in the case of model 1, thermal characteristics of the window are assessed as the worst among the three model buildings, resulting with a high percentage representation in total transmission losses of this model.

The specificity of model 2 in relation to the other examples is the structure of the envelope, in which the surface of the façade wall is equal to the surface of the window, which is informed by the design characteristics of the first prefabricated buildings in Belgrade. Alternating horizontal window and concrete parapet elements is a feature of this construction period, and demonstrates certain specificities in the results of the thermal calculation. The unfavourable heat transfer coefficient of the applied window, combined with a 50% representation of the window surface in the façade envelope, contributes to the high value of heat losses through the window. The heat loss through the window consists of 66% of the total generated heat, which represents the largest share taken by any window in the conducted research. At the same time, among the analysed models, transmission losses through the façade have the highest value in the case of model 2.

4.3 Indicators of Achieved Air Comfort

For the assessment of air comfort, ventilation through infiltration is important, and is determined by the applied façade materials, the type and quality of the joinery, and the way it is incorporated. Since energy efficient architecture aims to achieve energy savings and reduce heat losses, minimising uncontrolled infiltration by sealing the fissures and couplings is a way to achieve large energy savings for heating and cooling. However, doing this may create spaces in which air quality is not at a satisfactory level.

The infiltration of air through the façade wall is of low intensity and, in most cases, it cannot provide a minimum number of air changes to achieve the hygienic minimum. Air infiltration through façade joinery is several times more intense than the flow through the exterior walls, which contributes to the focus of the analysis of the air comfort of existing residential buildings in Belgrade on this parameter which, on the one hand, contributes to the quality of indoor air, and on the other, increases the ventilation losses and the energy needed for heating. The amount of air infiltrated through the joints of the window is calculated according to a general formula, which includes the length of the coupling, the permeability of the joints and the pressure difference.

The air flow by infiltration through the couplings has been calculated for the analysed models and the obtained results are shown in Table 4.4. For model 1, double wooden windows with a spaced double sash were applied, in which the elements of the frame and sash were made with folds, and without any means of sealing. The doubled window frames and sashes, the formation of ridges in the bricks on which the window bears, and the buffer layer of air between the outer and inner elements, all contributed to the better insulating properties of this type of window. The windows are divided into two-pieces in width and height, which increases the length of the couplings that are relevant for the airflow calculation and, with a pressure difference of 25Pa, the hygienic minimum is reached, i.e. the half-volume flow of the total volume of the room achieved for one hour, according to the standard EN 12831 (2003).

On model 2, wooden windows with a connected double sash were applied, which correspond to the concept of thin walls comprising reinforced concrete, typical of the multi-family buildings of the analysed period. The couplings between the window elements are formed with folds and without seals, and since the window frame is single, this set shows higher air permeability than a double window with a spaced double sash. The windows are continuous, forming horizontal strips that extend along the entire length of the façade, which significantly increases the length of the overlap and additionally contributes to a higher air flow. In Table 4.3, it can be seen that at a minimum pressure difference of 5 Pa, a hygienic minimum is achieved, while in the case where the difference between the external and internal pressure is 50 Pa, achieved only by infiltration through the joints, i.e. without opening the window, almost three changes of air are performed per hour.

	WINDOW TYPE	VOLUME OF THE SPACE [m^3]	LENGTH OF THE OVERLAP L [m]	PERMEABILITY a [m^3/hmPa$^{2/3}$]	AIR FLOW [m^3/h] $V=\Sigma a_l \cdot l_l \cdot \Delta p_{E-I}^N$									
					Δp_{E-I}									
					5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Model 1	double wooden with a spaced double sash	70	11.4	0.4	13	21	28	34	39	44	49	53	58	62
Model 2	wooden with a connected double sash	50	16.4	0.6	29	46	60	73	84	95	105	115	125	134
Model 3	PVC single with a double glazed unit	52	11.2	0.2	7	10	14	17	19	22	24	26	28	30

TABLE 4.3 Air flow through window couplings on analysed models

Favourable thermal and sound performance, affordable price, and easy maintenance, have all contributed to the fact that plastic windows have become the most commonly used in domestic housing construction since the 1990s, as was adopted in model 3. The results show that the best air tightness is achieved in this model due to the low coefficient of permeability and a coupling length approximately equal to model 1 and significantly shorter than model 2. The minimum airflow through the window couplings by the mechanism of infiltration is achieved at a pressure difference of 40 Pa, as shown in Table 4.3.

4.4 Indicators of Achieved Sound Comfort

The consideration of the façade barrier in the context of sound comfort is largely conditioned by the window opening, which represents the weakest segment in the overall façade wall assembly and the potential place where sound impulses are transferred. As various window assemblies applied on the façades of residential buildings in Belgrade are analysed in this study, one should bear in mind the fact that the insulating properties of the applied window (Fasold & Sonntag, 1971 and database in the software *Ursa Fragmat Akustika RS*) greatly contribute to the total sound insulation of the barrier (Table 4.4).

The new system of standards in the field of sound protection has introduced significant changes in the method of calculating the acoustic properties of the premises. Unlike the previous calculation method in which the partitions are viewed as individual, separated elements, the current method of calculating involves a complex view of all the surrounding structures and their interconnections, which directly affect the isolation power of the observed partition. In this way, the overall complexity of sound transmission through the construction is considered.

	TYPE OF WINDOW	WINDOW SOUND INSULATION	FAÇADE WALL ASSEMBLY	SOUND INSULATION $D_{2m,nT}$
Model 1	double wooden with a spaced double sash (12cm)	39 dB	massive brick masonry	45 dB
Model 2	wooden with a connected double sash	31 dB	concrete prefabricated parapets	31 dB
Model 3	PVC single with a double glazed unit	31 dB	massive block masonry	34 dB

TABLE 4.4 Sound insulation properties of façade wall assemblies

The sound insulation ($D_{2m,nT}$) of a façade wall is defined as the difference in the sound levels between the two spaces separated by the façade partition and, as such, is determined by the limit values of noise in the open space and indoors. Depending on the location of the object in relation to the acoustic zones, the sound insulation values were determined, and for the purposes of this study a minimum value of $D_{2m,nT}$=20 dB was adopted. All the analysed façade walls satisfy these conditions, but the best results were achieved with model 1, because the sound insulation of the barrier is in direct proportion to its surface mass, and the application of a solid brickwork structure shows its good insulation characteristics (Table 4.4). On the other hand, the use of wide-box windows, which have a high level of insulation properties compared to other types of windows applied, affects the insulation of the façade far beyond the prescribed minimum values.

4.5 Indicators of Achieved Visual Comfort

The research of light comfort, for natural lighting conditions, resets the focus to the façade wall and its role in the realisation of this form of comfort. The achievement of the given conditions by using daylight provides incomparable health benefits to the users of the space and at the same time contributes to the rational use of energy and the improvement of the overall energy efficiency of the building. The maximum use of natural light in order to achieve optimal conditions of light comfort, while reducing the use of artificial light, is a recommendation of all standards that deal with this issue.

The research of light comfort of the Belgrade housing stock was done for daylight conditions. The selected models illustrated the typical ways of forming transparent parts of the envelope in Belgrade residential buildings. In addition to the dimensions of the window opening, other elements of the envelope structure that affect the level of illumination of the room are the dimensions of the illuminated room (width, depth, and clear height), the height of the parapet, and the existence and depth of a terrace or a loggia.

In order to examine the established models, identical environmental conditions (location, orientation, and conditions of the sky) are set. A southern orientation is selected, which is recommended for the living space, although in the summer months it may be unfavourable due to the occurrence of glare. In the middle of a room, a table was placed to monitor the brightness and flash in the work area. The parameters on which the assessment of the quality of lighting of residential buildings was carried out are the ratio of daylight and glare. The analysis of the light comfort of the analysed models was done using a computer tool, which allows a simple, spatial view of the parameters of light comfort (Velux Daylight Visualizer 2).

In the case of Model 1, the use of windows that were taller than usual in relation to the width is characteristic, with the ratio of their dimensions being approximately 1:2 (w/h). The average daily illumination ratio is 1.89% (Table 4.5), which fits into the average requirements that are prescribed for living rooms (1.6-3%), though it is close to the lower limit. In the central part of the room, where daily activities are performed most frequently, the daily illumination ratio is about 1.5%, which is between the median and low requirements according to the current domestic regulations (SRPS U.C9.100, 1963; Jugoslovenski komitet za osvetljenje (Yugoslav Committee for Lighting), 1974).

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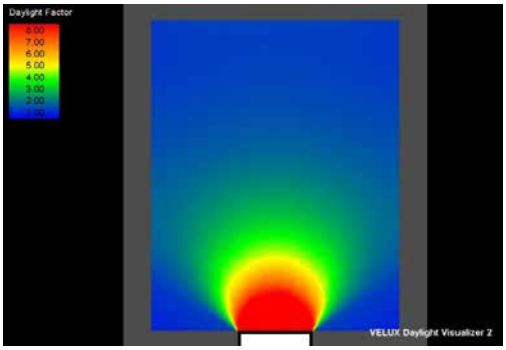
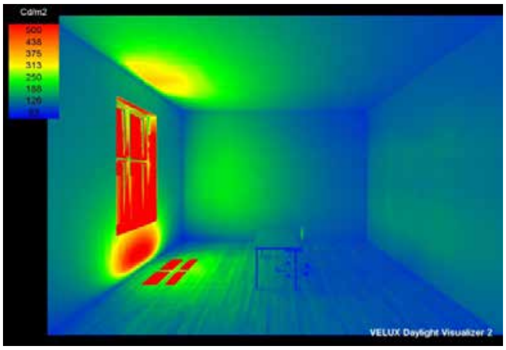
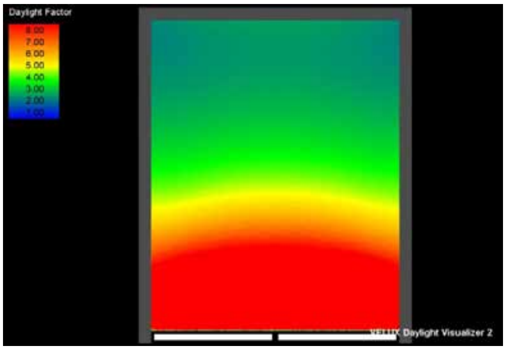
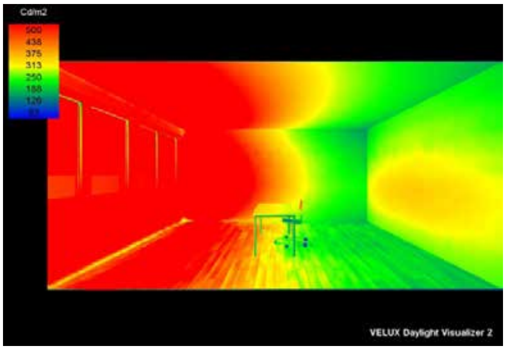
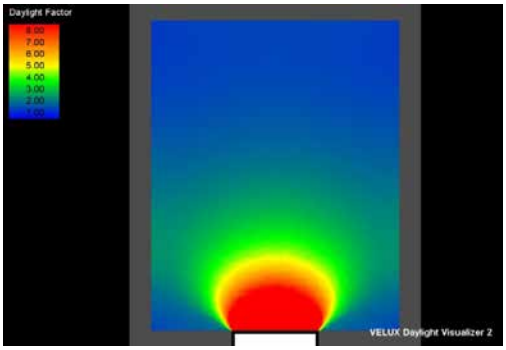
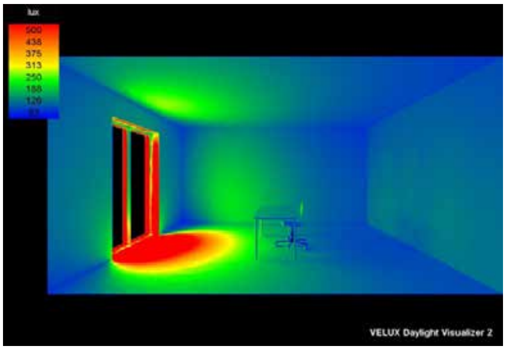
	DAILY ILLUMINATION RATIO [%]	GLARE [cd/m2]
Model 1: window 120/220cm	average value: 1.89	
		
Model 2: window 400/140cm	average value : 5.17	
		
Model 3: window 140/220cm	average value : 2.05%	
		

TABLE 4.5 The representation and values of the parameters of light comfort as a result of the use of Velux Daylight Visualizer 2

The accentuated height of the window opening allows the penetration of light deep into the room, but its insufficient width results in poorly illuminated parts in the corners of the room next to the façade wall, resulting in an unevenly illuminated space. Glare appears on a small surface next to the façade wall, and the brightness of the wall and ceiling surfaces is, with minor deviations, at optimum limits. However, the brightness of the visible task on the set work table is 100 cd/m^2, which is on the lower scale of the recommended values (100- 300 cd/m^2).

For model 2, the daily illumination ratio is 5.17% and this value is in the category of large requirements prescribed for the living room, in which tasks such as reading and studying are envisaged. The value of this parameter varies from 1.74 to 16.99% and ranges from the level of medium requirements to extremely large (over 12%). A uniform distribution of light in the room is evident as a result of the installation of window strips along the entire length of the façade wall. It is equally distributed across the width of the room with uniform attenuation in the depth of the room.

The walls have a surface gloss of more than 200 cd/m^2 and in the zone next to the window it increases to 1000 cd/m^2, which is a multiple of the recommended value. The brightness of the ceiling also exceeds the optimal values (250-1000 cd/m^2). In addition, in the first third of the depth of the room, a glare phenomenon with values exceeding 6.000 cd/m^2 is recorded. In order to achieve optimum levels of illumination and prevent the appearance of glare, the obtained results suggest that protection in the form of curtains or blinds in the summer months is necessary.

On the facades of residential buildings built after 1990, represented by model 3, there are elongated window openings with or without a low parapet, and with one-leaf or two-leaf doors with an outer railing of an appropriate height (a so-called French balcony). The average daily illumination ratio is 2.3%, which fits into the category of median requirements prescribed for living rooms (1.6-3%). In the central part of the room, the daily illumination ratio is approximately 2%.

The walls of the room have a surface gloss of greater than 100 cd/m^2, and the glare phenomenon is registered in the lower zone around the façade opening. The brightness of the ceiling surface is largely within the recommended limits (100-300 cd/m^2), while the glare phenomenon is registered only in the area of the floor or work surfaces that are placed directly next to the door opening.

It has been shown that the similarities in the design of the window openings in models 1 and 3 have affected the results of the study of the illumination of the living room, showing only slight differences. On the other hand, model 2 is specific and completely different, so that the parameters of visual comfort show diametric differences in relation to the other two models, both in terms of the means of distribution of light in the room, and in relation to the values of the parameters of illumination that determine the extent of the achieved light comfort.

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5 Conclusions

There are different reasons and methods in which the choice of materials affects both the living comfort and energy efficiency of a building. As has been explained, this refers especially to the design and structure of a building envelope, which is the main interface between man and his environment, on one hand, and the most relevant factor for the achievement of living comfort and simultaneous energy consumption of a building on the other. Our knowledge of the behaviour and role of materials in a construction enables us to predict the behaviour of a building as a whole and to understand the effects of a design on the building's operation and function.

The presented analyses of selected models of Belgrade housing stock have pointed out how different structures of building fabric, building techniques and technologies, together with the applied design principles that were typical for the time represented by a model, affected the achievement of comfort conditions and energy consumption. It is characteristic that the various parameters and their combination, which relate primarily to the characteristics of the façade envelope (such as the wall and window structure and the wall to window ratio), influence the realisation of the various types of comfort:

- **thermal comfort** is dependent on a combination of the characteristics of the wall structure and the quality and structure of the window but, due to the significant difference in transmission losses of these elements, it is also highly dependent on the wall to window ratio;
- achievement of **air comfort** is, to a great extent, a result of the air tightness of the façade, as a consequence of the quality and size of the window, but also from the junction of the window with the wall;
- **sound comfort** depends on the surface mass of the wall and on the properties of the window frame and glazing structure; while
- quality of **visual comfort** is, to a large extent, conditioned by the wall to window ratio.

Although the models represented situations that were in accordance with the standards of the time, from today's perspective, regarding the majority of the analysed parameters, certain enhancements are needed in order to adjust to current demands (Đukanović et al., 2016), which confirms the evolution of our understanding of living comfort.

The emphasised need to reduce energy use is imperative today, putting into focus the issue of thermal comfort, although other forms of comfort are monitored simultaneously. The high demand for minimal energy consumption in buildings, among other things, imposes the need for the use of thicker insulating materials, which often jeopardises the feasibility of such complex and often bulky constructions. On the one hand, solutions for such problems are sought in the application of new types of advanced materials that will be more adaptable to the set requirements, and on the other hand, there is the question of the need to re-examine the high demands of thermal comfort in so-called sustainable comfort. However, it is certain that, in time, in the light of sustainable development, besides the problem of energy, other issues will be included in current doctrines of design and construction, bringing a new perspective to the selection and use of building materials.

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