ENERGY EFFICIENCY OF INDUSTRIALLY MADE BUILDINGS INFLUENCED BY THERMAL PROPERTIES OF FAÇADES

by

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The main objective of this paper is to evaluate the thermal properties of existing residential buildings built in industrial manner in Novi Sad, Serbia, from 1960 to 1990 based on building typology. Each of three analyzed building types has its characteristic façade, with thermal performances divided into periods according to the development of domestic thermal protection building codes. The necessary layer of subsequent insulation is determined by calculations in order to comply with European standards, also applied in Serbia from 2012. The proposed method of periodization simplifies the process of thermal performance assessment and it was checked through the case studies. Evaluation of energy consumption rationalization has been done through comparative analysis of energy losses. Based on the most common energy rehabilitation measures applied in Serbia, it was estimated that it was possible to reduce the energy losses in heating up to 60%.

Key words: *prefabricated residential buildings typology, facade composition, thermal properties, periodization, comparative analysis, energy efficiency*

Introduction

Numerous residential buildings (RB) were industrially built in the second half of 20th century, at the time of intense urban development and migration into urban areas in Europe. These buildings need retrofitting to comply with contemporary demands of building performances. The directive [1], among other requirements for the planned maintenance of essential properties during the service life, sets for thermal comfort and energy savings. During RB service life, it is necessary to monitor the structure's performance through regular inspection of deterioration and other defects, investigate and detect the emerging problems and control the appropriate maintenance works [2]. The service life depends on the physical deterioration of materials and limitation of applied solutions, as well. The energy efficiency, especially thermal protection of buildings is a problem whose solution may also include the issues of technological, economic, social, legal, and moral obsolescence [3] of the existing residential buildings that were built in an industrial manner. Therefore, it has to be primary assessed so the energy rehabilitation measures could be set as compatible to the other building renewal activities.

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The thermal protection of buildings in Serbia was mostly regulated by the standards of SRPS U.J5. series [4-7]. New codes on energy efficiency and certification of buildings were adopted, in accordance with [8], whose implementation is mandatory since October 2012 [9, 10]. These regulations limit the maximum allowed annual energy consumption for heating to 60 kWh/m^2 per year for new buildings and to 70 kWh/m^2 per year for existing buildings subjected to major renovation. The building is considered energy efficient if the annual energy consumption meets the codes while the minimum requirements of thermal comfort are fulfilled. The average annual energy consumption in residential buildings in Serbia exceeds 150 kWh/m^2 per year, while in developed European countries it is approximately 50 kWh/m^2 per year. Major renovations of existing buildings, regardless of their size, provide an opportunity to take cost-effective measures to enhance energy performance [8]. Prefabricated residential blocks, characterized by the multiplication of Facade design solutions, are predominant building types of the existing housing stock that needs retrofitting [11]. A thematic research and typology approach in structuring residential buildings by the same structure/type of facades and periodization according to current codes of thermal protection at the time of construction simplify the preliminary energy assessment of the building stock. Building typology and model buildings could be used for assessment of the building stock of the country, comparison of the building stock between different countries [12] and development of the strategic plan for energy rehabilitation of entire city areas.

In order to analyze the current situation and find solutions for prefabricated buildings' energy efficiency and a sustainable European city and housing, many research projects were initiated in Europe in recent decades [13-17]. In our country, there is insufficient number of thematically oriented researches in the area of RB that were constructed in the industrial way.

Three types of prefabricated dwellings constructed from 1960 to 1990 in Novi Sad were divided into periods by decades and intervals of application of regulations on the building's thermal protection. This was followed by the calculation and comparative analysis of thermal properties of the existing Façade walls, based on the building's design documentation and catalogues of the studied industrial building systems, in accordance with [9]. The thickness of the additional layer of external insulation is determined in order to enable the achievement of required overall heat transfer coefficient U [Wm^{-2}K^{-1}], according to the latest standards. Furthermore, based on the calculation of transmission heat losses in the façade wall, a comparative analysis has been performed on alternative solutions for the energy rehabilitation of façades (an additional outer layer of thermal insulation and the replacement of façade woodwork). Comparative calculations were made for the winter project temperature for Novi Sad according to actual standard (–18 °C) [5], as well as the temperature specified by the new standard (–14.8 °C) [9].

Industrial residential building systems used in Novi Sad

According to data on the structure of urban settlements and population from Serbian Census 2011, our cities are similar to West European urban quality. On the other hand, regarding the share of prefabricated dwellings in the existing housing stocks, Novi Sad can be compared with the countries of Central and Eastern Europe (approximately 30%) [11]. Approximately 55% of housing units in Serbia were built from 1960 to 1990. About 41,220 dwellings were built in Novi Sad in the same period. The prefabricated façade panels are in poor condition due to the intense process of deterioration and lack of maintenance [18].

Three systems of industrial RB were used: the prestressed framed industrial prefabricated IMS system, the large-panel prefabricated Montastan system and the skeletal semi-prefabricated NS 71 system. Façades were designed as panels of the building's bearing structure, except for the gable walls in the Montastan system. In all systems, those are multilayer prefabricated or semi-prefabricated elements, with the exception of the IMS system, where façades were both prefabricated and traditionally built walls made of bricks and concrete [19].

Multi-layer façades in the IMS system

Facades of the IMS system are non-bearing panel elements, hanging on or leaning against the edge beams or slabs. Regarding their structure, those are multilayer, heterogeneous elements, made in accordance with the current codes at the time of their design. The composition of the façades in the IMS system is described in fig. 1.

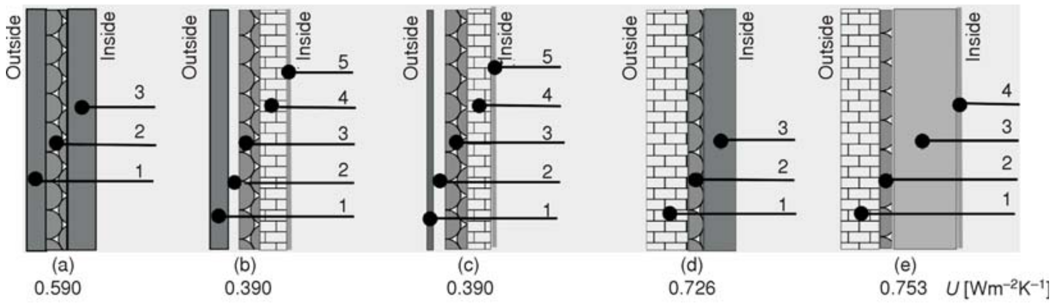

Figure 1. IMS façade panel types, composition [20] and thermal properties
(a) Prefabricated panel and parapet: 1. Concrete 6 cm; 2. EPS (expanded polystyrene) 6 cm, 3. Concrete 8 cm; (b) Semi-prefabricated ventilated façade: 1. Prefabricated concrete casing 6 cm; 2. Layer of air 2 cm; 3. EPS 6 cm; 4. Brick 6.5 cm; 5. Compo mortar 1.5 cm; (c) Lightweight ventilated façade: 1. Asbestos cement sheeting 1 cm; 2. Layer of air 2 cm; 3. EPS 6 cm; 4. Brick 6.5 cm; 5. Compo mortar 1.5 cm; (d) Semi-prefabricated façade with face brick casing: 1. Perforated face bricks 12 cm; 2. EPS 4 cm; 3. Reinforced concrete 8 cm; (e) Traditionally built façade: 1. Perforated face bricks 12 cm; 2. EPS 2 cm; 3. Perforated concrete block 20 cm; 4. Compo mortar 1.5 cm

In the first IMS design solution the building's façade is formed by parapet elements with a row of windows, with or without lightweight posts between them (usually asbestos cement sheeting and wood chipboard with EPS or mineral wool between them). Within the same building, prefabricated parapets are mostly of the same structure and finish as the storey-high panel fig. 1(a). Such design solutions adversely affect the building's thermal performance and the years of poor maintenance additionally extend the damage to joints and poor sealing. In some cases panels were clad with various clay based plates, which improved the thermal protection of façades.

Semi-prefabricated ventilated façade, fig. 1(b), provide indoor air quality and thermal comfort, because the ventilated layer prevents the structure from overheating during the summer, allowing the evacuation of water vapour and preventing condensation in the wall. These are also the properties of (e) façades built of lightweight materials, fig. 1(c). Semi-prefabricated façade with brickwork cladding, fig. 1(d), is more susceptible to damage due to temperature expansion of material and frost-sensitivity of the face brick and the development of the deterioration process adversely affect the thermal performance of the wall. Traditionally made façades in the IMS system are multilayered structures, fig. 1(e); with the supporting basic layer of bricks or blocks, with insulating layer and outer final covering of face bricks.

Clay block façades in the MONTASTAN system

Façade panels in the Montastan system are non-bearing elements of the building structure, supported by the floor panels, except for gables and partition panels, which are transversal bearing walls [21]. They are made of perforated clay blocks strengthened with concealed reinforced concrete grid with total thickness of 30 cm (fig. 2). The façade woodwork was factory-incorporated (timber, double glazed sashes) along with shutters. The building façade is fully formed by the panels. Vertical ties are covered with thermally insulated precast RC planks (fig. 2), while thermal protection of horizontal tie beams is made at the construction site, before finishing (fig. 3).

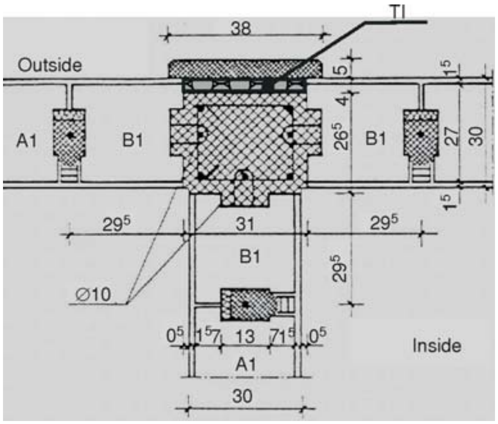

Figure 2. Detail of the Montastan façade: Horizontal butt joint of the façade and supporting panels with thermal insulation (TI) [22]

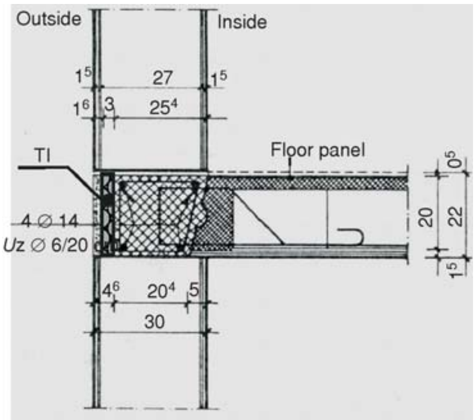

Figure 3. Detail of the Montastan façade: Vertical joint of façade panels with the floor panel with thermal insulation (TI) [22]

The production of panels was initiated in accordance with the 1970 code of thermal protection (U = 1.25 W/m^{2}K). After changing the codes in 1980 (U = 0.93 W/m^{2}K), the improvement of thermal properties of the monolayer panel structure was in trial by combining clay blocks with insulating material, fig. 4(a)-(c). Some higher-quality façades were achieved as

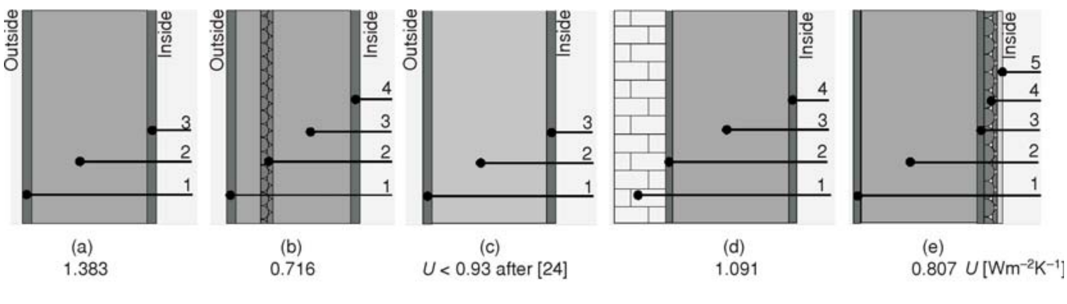

Figure 4. Montastan façade panel types, compositions and thermal properties

(a) 1. Cement mortar (CM) 1.5 cm, 2. Ordinary clay block (CB) 27 cm, Lime mortar (LM) 1.5 cm; (b) CM 1.5 cm, 2. EPS 3 cm, 3. Integrated CB 24 cm, LM 1.5 cm; (c) 1. CM 1.5 cm, 2. Aerated CB 27 cm, 3. LM 1.5 cm; (d) 1. Face brick 12 cm, 2. CM 1.5 cm, 3. Perforated CB 27 cm, 4. LM 1.5 cm; (e) 1. CM 1.5 cm, 2. Perforated CB 27 cm, 3. LM 1.5 cm, 4. EPS 2 cm, 5. Gypsum board 1 cm

double-layer, semi-prefabricated structures, enclosed by face bricks, after the panels were built in fig. 4(d). Except for better thermal performances, these façades are more favourable in terms of durability and aesthetics of the finishing layer. Another solution was to insulate the inward side subsequently, fig. 4(e). The poor thermal characteristics of Montastan RB were largely caused by the application of outdated codes: although the improved standards were already in use at the time of application of this system (from 1980 onwards), codes were understood as not binding, so the designers applied also the DIN 4701/1947 standard [23]. In this case, limitations regarding the coefficient U for the outer wall were not mandatory, but it was necessary to provide the amount of heat to meet the requirements of thermal comfort in rooms no matter how high the energy looses were.

Lightweight concrete façades in the NS 71 system

Application of the NS-71 system started before the system was fully developed. Although it was planned to produce several varieties of prefabricated façade panels [25], only the full-height wall elements and façade membranes (and the single-layer elements of lodge and attic enclosing) were in use, while all the other elements were made in the traditional way, at the construction site (fig. 5). Due to the short period of use, the system was not further industrialized nor improved.

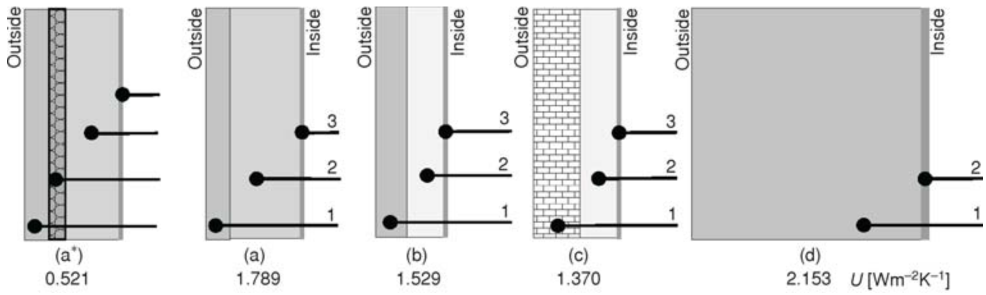

Figure 5. NS 71 façade panel types, composition and thermal properties
(a) 1. Concrete 6 cm, 2. EPS 6 cm, Ceramsite concrete 20 cm, 3. Lime mortar 1.5 cm; (a) 1. Concrete 6 cm, Ceramsite concrete 20 cm, 3. Mortar 1.5 cm; (b) 1. Natural or pebble dashing concrete 8 cm, 2. Aerated light weight concrete blocks 12.5 cm, 3. Lime mortar 1.5 cm; (c) 1. Perforated face brick 12 cm, 2. Aerated light weight concrete blocks 10 cm, 3. Mortar 1.5 cm; (d) 1. Concrete 60 cm, 2. Thermal mortar 3 cm*

Lightweight concrete façade panels, fig. 5(a) were manufactured for the construction of one city block [26]. The designed model of prefabricated wall with 6 cm thermal insulation (EPS) is not listed in the original design documentation – type NS-71 a*, fig. 5(a*). Kitchen lodges were closed with a curtain type wall, fig. 5(b). The parapets are masonry, built of bricks or blocks, fig. 5(c). Because of their dimensions (61×61 cm), facade columns also significantly affect the thermal properties of the façade, fig. 5(d). Façade woodwork is wooden, double glazed sashes, with wooden shutters. The lightweight ceramsite concrete is a conglomerate of cement and a multi-fractional ceramsite aggregate, with good insulating properties (both thermal and acoustic), it is resistant to frost and fire; there is no capillary movement of water, and meets the structural requirements up to CC 20 (cube strength) [27]. Despite the good thermal properties of this material, today, its environmental characteristics are considered as poor due to the large amount of energy needed for the extraction and production of ceramsite [28].

Thermal protection of industrially constructed residential buildings

The dwellings constructed from 1960 to 1990 in Novi Sad and industrial building systems are classified by decades and also by the method of calculation of buildings' thermal protection (tab. 1). Industrial residential building systems were designed for wide application. Thus, although Novi Sad belongs to II climate zone, the façade thermal properties were set to meet the requirements for all climate zones and all dwelling orientations, according to the current codes [4-7, 29-31].

Table 1. Periodization of built dwellings in Novi Sad regarding the applied regulations on thermal protection of buildings (outer wall) and type of construction

Period of application of regulations	Calculation of the building's thermal protection Value of the coefficient U for the external wall			Number of finished dwellings	Industrial building systems in use
Climate zone	I	II (Novi Sad)	III		
1961 through 1967	No limitation, calculation according to DIN 4701/1947, 1958			10.452	IMS
1967 through 1970	Overall thermal transmittance coefficient U values defined [$Wm^{-2}K^{-1}$]			3.869	IMS
	1.54	1.33	1.18		
1970 through 1980	Reduced maximum value for the coefficient U [$Wm^{-2}K^{-1}$]			14.228	IMS NS-71
	1.45	1.25	1.10		
1980 through 1987	Reduced maximum value for the coefficient U [$Wm^{-2}K^{-1}$] and included the summer mode into the calculation			9.110	IMS MONTASTAN
	1.225	0.930	0.830		
1987 through 1990	Coefficient U without changes, the building's specific heat losses defined			3.534	IMS MONTASTAN
1990 through 1998	1.225	0.930	0.830		
1998 through 2012	Reduced maximum values for U			The industrial building systems are no longer in use; except the IMS bearing structure in few residential buildings	
	1.10	0.90	0.80		
From the October 2012	For existing buildings U_{max} = 0.40 1 [W/m^2K] For new buildings U_{max} = 0.30 [Wm^2K]				

IMS façades in RB dating before 1967 are of poor thermal performance because they were designed according to DIN 4701/1947. The consequences are various values of coefficient U which could be defined either based on design documentation or more precisely by experimental measurement. The design values were checked for two RB and it was found that overall thermal transmittance coefficient *U* for both prefabricated and traditionally built outer multi-layer panels varies significantly: 1.91 W/m^{2}K (RB 1) [32] or 1.37 and 1.39 W/m^{2}K (RB 2) [33]. Parapet wall's *U* values also vary and they are different from panels in the same building: 0.96 W/m^{2}K (RB 1) and 1.73 W/m^{2}K (RB 2). The façades in the IMS building system since 1967 and later were designed and attested according to corresponding codes [34]. The calculated values of the overall thermal transmittance coefficient (*U*) of IMS catalogued façades (fig. 1) were less than 0.83 W/m^{2}K, which is the maximum allowable value for the climate zone III, as defined by the valid code at time the catalogue was made JUS U.J5.600 (1980).

Thermal properties of prefabricated panels in the Montastan system were reviewed constantly from the very beginning of implementation of the system [35, 36] and especially after the adoption of 1987 standards, when the problem was reviewed in the IMS system as well [37]. The category of specific heat loss of the building has been introduced, the value of which is significantly affected by the shape of the building. As opposed to the previous partial approach to the calculation of the thermal protection of individual structures, the consideration of thermal insulation has covered the building in its whole, which improved the standard thermal protection for 30%, without changing the values of coefficient *U*. This standard enabled designers to select the most convenient way of insulation in accordance with the building's surface area/volume ratio.

The introduction of a new category of transmission heat losses, expressed through the coefficients of heat transfer in edge and connecting elements, had particular importance for the revision of thermal properties of prefabricated elements. The notable structural heterogeneity results with numerous irregularities which are reflected also in the development of surface condensation. Thermal bridges in prefabricated concrete structures are all atypical parts of the façade fabrics, such as the linear joints and reinforcement connections between the external and internal layers of concrete, mutual connections and connections with the load bearing structure. The thermal characteristics of the prefabricated concrete façade, calculated without taking into account the influence of thermal bridges, significantly deviate from the actual values which is significantly degraded due to their adverse effects. Depending on the type of thermal bridge and the total number of such connections in the façade element, the ratio of the thermal transmittance coefficient of a characteristic section and the mean heat transfer coefficient may be even greater than 1:3 [37].

Comparative analysis of the improvement of façade thermal characteristics

Although some of the existing prefabricated façades fail to comply with the actual standard [4] for thermal protection of outer walls the required thickness of additional thermal insulation was calculated in order to meet the new standard [9]. The most common additional insulation type in Serbia is an EPS with a protective layer of mortar with plaster lath, so it was used in calculations for further comparison.

All the analyzed IMS façade elements meet the current codes: $U < 0.90$ W/m^{2}K for II climate zone (tab. 2). In the Montastan system, current standards of thermal protection are only met by the Montastan type B façade panel, while none of the elements of the NS 71 system meet any of the required characteristics (except for the NS-71 A* type panel, the application of which is not even confirmed) (tab. 2).

Table 2. Overall thermal transmittance coefficients of industrially built façades: current values, a necessary extra layer of insulation and the enhanced values (comparative review)

Type of element	IMS (a) (fig. 1)	IMS (b) (fig. 1)	IMS (c) (fig. 1)	IMS (d) (fig. 1)	IMS (e) (fig. 1)
U [Wm^{-2}K^{-1}] < 0.90	0.590	0.390	0.390	0.726	0.753
Necessary TI layer	5 cm	not necessary	not necessary	5 cm	5 cm
U [Wm^{-2}K^{-1}] < 0.40	0.343	0.390	0.390	0.385	0.393
Type of element	Montastan (a) (fig. 4)	Montastan (b) (fig. 4)	Montastan (d) (fig. 4)	Montastan (e) (fig. 4)	
U [Wm^{-2}K^{-1}] < 0.90	1.383	0.716	1.091	0.807	
Necessary TI layer	8 cm	5 cm	7 cm	7 cm	
U [Wm^{-2}K^{-1}] < 0.40	0.374	0.382	0.381	0.339	
Type of element	NS-71 (a) (fig. 5)	NS-71 (a*) (fig. 5)	NS-71 (b) (fig. 5)	NS-71 (c) (fig. 5)	NS-71 (d) (fig. 5)
U [Wm^{-2}K^{-1}] < 0.90	1.789	0.521	1.529	1.370	2.153
Necessary TI layer	8 cm	3 cm	8 cm	8 cm	10 cm
U [Wm^{-2}K^{-1}] < 0.40	0.398	0.377	0.384	0.373	0.344

Table 3. Dumping factor of temperature oscillations ν and water vapour diffusion parameters of industrially built façades: mass moisture content and draining period (comparative review)

Type of element	IMS (a) (fig. 1)	IMS (b) (fig. 1)	IMS (c) (fig. 1)	IMS (d) (fig. 1)	IMS (e) (fig. 1)
ν [–]; ν_{min} = 15	51.65	57.93	32.35	49.98	72.67
$X'_{total} < X'_{max}$ [%]	16.83 < 24.00	20.00 < 24.00	–	–	51.59 > 24.00
Draining period [days] Max allowed 90 days	30.9	36.0	–	–	11.8
Type of element	Montastan (a) (fig. 4)	Montastan (b) (fig. 4)	Montastan (d) (fig. 4)	Montastan (e) (fig. 4)	–
ν [–]; ν_{min} = 15	15.38	45.11	39.67	40.20	–
X' [%] $X'_{total} < X'_{max}$	3.14 < 5.80	32.37 > 24.00	3.68 < 5.70	–	–
Draining period [days] Max allowed 90 days	14.5	6.1	20.6	–	–
Type of element	NS-71 (a) (fig. 5)	NS-71 (a*) (fig. 5)	NS-71 (b) (fig. 5)	NS-71 (c) (fig. 5)	NS-71 (d) (fig. 5)
ν [–]; ν_{min} = 15	15.77	74.36	12.36	13.45	86.47
X' [%] $X'_{total} < X'_{max}$	5.35 < 7.50	23.93 < 24.00	7.56 < 12.40	–	–
Draining period [days] Max allowed 90 days	64.1	53.5	82.6	–	–

The best thermal performances are those of ventilated façade structures – IMS (a) and (b), which meet the latest standards (U < 0.40 W/m^{2}K) and do not require additional insulation to meet the code for 2012. The worst thermal performances are those of the NS-71 (d) facade column, which requires installing a thermal insulating layer of thickness as much as 10 cm. Other façade panels in NS-71 system are slightly better – there is 8 cm insulating layer to meet the demands.

Calculations of water vapour diffusion in buildings (tab. 3) meet both the current [6] and new standards [9] for all analyzed structures, with exception of mass moisture content percent X' [%] for IMS (e) and Montastan (b) façade, but in both cases the draining period is less than 90 days, which is maximum allowed for outer walls in Climatic zone II. Calculation of dumping factor ν [–] and temperature oscillations delay in summer period through the exterior building partitions (tab. 3) is not met by NS-71 (b) and NS-71 (c) type façade elements according to both standards [7, 9], where η is lower than minimal allowed value of 15.

Comparative analysis of energy rationalization of façades

In the case of the investigated multi-storey, industrially built RB, energy consumption is the key motivation and indicator of rehabilitation. Based on the values of overall thermal transmittance coefficients U (tab. 2), adequately unfavourable results in terms of energy consumption and losses can be expected. As opposed to the IMS system, where all the catalogued panels were applied (along with many others), it has been found that in the Montastan system the type (a) panel was mostly in use (fig. 6), while in the NS 71 system there was no significant application of other panels, except for the type NS-71A (fig. 5). Therefore, further calculations were made for those panels.

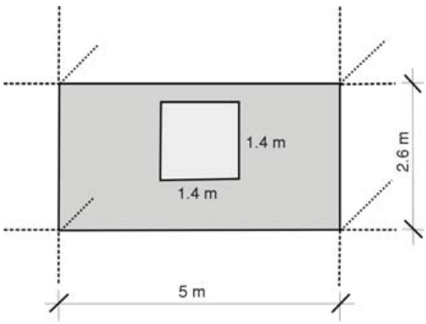

Figure 6. The model panel with the window

To make the calculation results comparable, a model of the external wall with the window (fig. 6) has been adopted and the model room is surrounded with heated rooms on all of its sides. The energy losses of the existing walls and losses in walls with improved thermal insulation and replacement windows (tab. 4) were calculated in accordance with the current and future winter project temperatures. The quality of windows in the calculation also varies as follows: existing window, wooden window, double glazed sashes (U_w = 3.5 W/m^{2}K), three-chamber PVC window with 4 + 12 + 4 isopane glass (U_w = 3.0 W/m^{2}K), and a window with certified Class A energy efficiency: U_w = 0.73 W/m^{2}K (fig. 7). The adopted values for the parameter U_w also comply with the new standard criteria [9].

Figure 7. Class A energy eff. window [38]

Table 4. Transmission heat losses of alternative solutions for precast façade

No.	Façade properties	Q [W] Et = –18 °C	Loss reduction [%]	Q [W] Et = –14.8 °C	Loss reduction [%]
1	IMS (a) with wooden windows with double glass	1210	–	1120	–
2	IMS (a) with 4 + 12 + 4 isopane glass PVC window	1110	8.3	1020	8.93
3	IMS (a) + 5 cm TI, with wooden windows with double glass	1090	9.9	1000	10.71
4	IMS (a) + 5 cm TI, with 4 + 12 + 4 isopane glass PVC window	980	19.0	900	19.64
5	IMS (a) + 5 cm TI, with class A energy efficiency window	690	43.0	630	43.75
6	Montastan (a) with wooden windows with double glass	1610	-	1480	-
7	Montastan (a) with 4 + 12 + 4 isopane glass PVC window	1500	6.8	1390	6.08
8	Montastan (a) + 8 cm TI, with wooden windows with double glass	1100	31.7	1010	31.76
9	Montastan (a) + 8 cm TI, with 4+12+4 isopane glass PVC window	1000	37.9	920	37.84
10	Montastan (a) + 8 cm TI, with class A energy efficiency window	700	56.5	650	56.08
11	NS-71 (a) with wooden windows with double glass	1820	–	1670	–
12	NS-71 (a) with 4 + 12 + 4 isopane glass PVC window	1710	6.04	1580	5.39
13	NS-71 (a) + 8cm TI, with wooden windows with double glass	1120	38.46	1030	38.32
14	NS-71 (a) + 8cm TI, with 4 + 12 + 4 isopane glass PVC window	1010	44.51	930	44.31
15	NS-71 (a) + 8cm TI, with class A energy efficiency window	720	60.44	660	60.48

The lack or insufficiency of thermal insulation result with high coefficients U values and low temperature of the internal wall surfaces, as well as the presence of thermal bridges leading to condensation. Any damage caused during the process of deterioration also allows the penetration of moisture through the façade, which further threatens the thermal comfort and indoor climate.

High heat losses during the winter result in increased energy consumption. As indicated by calculations and comparative analysis of heat losses (tab. 4) in characteristic type from each system of prefabricated façades, approximately the same reduction in energy consumption can be achieved in all systems by replacing the windows (savings of 5-9%). Significant savings can be achieved by subsequent thermal insulation of walls of poor thermal performances, even without replacing the windows (as much as 38%). Energy-saving of 60% can be achieved by installing windows of class A energy efficiency in combination with the required extra thermal insulation. The decreased winter design temperatures have minimal effect on the energy loss calculations.

Subsequent installations of external or internal thermal insulation on façade facilitate the reduction of the coefficients *U* values, the increase of temperature of interior walls and prevention of condensation. A better solution is external insulation since it allows continuous thermal protection of the façade, thereby avoiding the formation of thermal bridges and further deterioration process. External thermal insulation – EPS with a protective layer of mortar with plaster lath is usually applied in renovation in Serbia, due to its favourable price, satisfactory thermal insulating properties and simple installation. Internal thermal insulation is the most common solution in case of individual flats renovation (due to the usual lack of technical possibilities for partial installation of external insulation on the façade), but it should always be used with caution due to the danger of condensation in material. The highest-quality solution is the installation of external thermal insulation with ventilated cladding structure.

As confirmed by the recent studies [39, 40] that were carried out in RB in Belgrade, Serbia, it is important to rationalize the energy consumption by upgrading the thermal performance of façades for improving the energy efficiency. All alternative solutions could be tested using modern software packages [41] in order to optimize the solutions for façade, both from the financial aspect and the aspect of thermal energy loss. After the implementation of passive measures, more advanced solutions that lead to energy efficiency at the highest level of EU standards can be achieved by installing photovoltaic panels or by other methods of integrated renovation of RB [42].

Case studies

Based on data obtained from comparative research of listed literature and final design documentation of buildings that were selected for case studies, it has been tested whether it is possible, based on the method of periodization, to approximate the value of the overall thermal transmittance coefficient *U* for prefabricated and semi-prefabricated façades in the study period. Three buildings were selected for the calculation data analysis. Each one typically represent specific building system: RB 1 (Montastan), RB 2 (NS-71), and RB 3 (IMS).

After examining the design documentation for RB 1 (fig. 8) [23] and RB 2 (fig. 9) [43], it was found that the composition of façade panels matches the description and characteristics of Montastan (a) (fig. 4a) and NS-71 (a) (fig. 5a) panels, for which the values of the coefficient *U* are given in tab. 2, while the loss reduction can be achieved in accordance with the data presented in tab. 3. Based on this research, the general conclusion is that the method of periodization for determination of the coefficient *U* is unsuitable for RB built in the NS-71 system. The precise composition of facade panels of individual structures could be determined by examining the original design documentation. On the other hand, it was found that there was in-significant application of other panels in the NS-71 system, except for the type NS-71(a). Therefore, it is recommended to adopt the properties of the NS-71 (a) – type panel (fig. 5a) as a starting point in any future consideration of energy renovation of buildings built based on this system.

The examination of the design documentation for RB 3 (fig. 10) [44] resulted with conclusion that the method of periodization could be applied for approximation of coefficient U values for RB built in IMS system. The longest period of application (over 30 years), dynamism and diver-

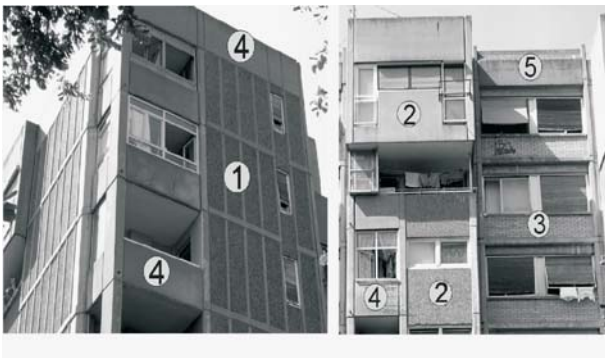

Figure 8. Recognizable NS-1 façade elements – RB 1
1 – Full story wall panel; 2 – Façade membrane; 3 – Parapet; 4 – Lodge and balcony enclosing; 5 – Roof attic

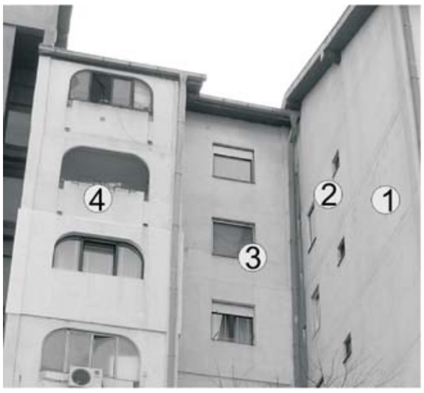

Figure 9. Montastan façade elements – RB 2
1 – Gable wall panel (GWP) without window openings (WO); 2 – GWP with WO; 3 – Façade panel with WO; 4 – Prefabricated concrete lodge panel

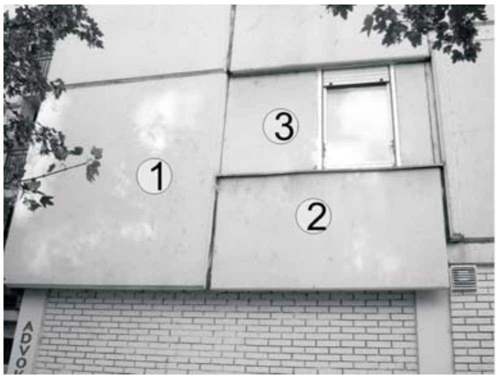

Figure 10. IMS façade elements – RB 3
1 – Storey-height façade panel; 2 – Façade parapet; 3 – Lightweight panel with insulation.

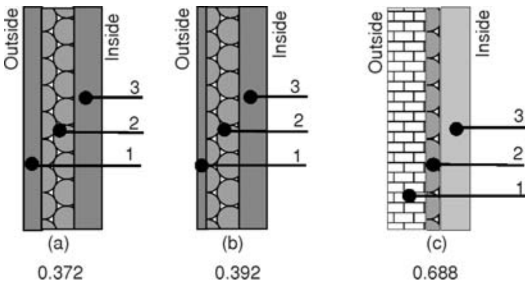

Figure 11. Composition of layers and the *U* values for the RB 3 IMS façade
(a): A story-height panel: 1 – concrete 6 cm, 2 – EPS 10 cm, 3 – concrete 8 cm; (b): Façade parapet: 1 – Concrete 3 cm, 2 – EPS 10 cm, 3 – Concrete 8 cm; (c): Brickwork façade wall: 1 – face brick 12 cm, 2 – Mineral wool 4 cm, 3 – Gypsum wall 10 cm; U [$Wm^{-2}K^{-1}$]

sity of development of the IMS system, as well as its application in a variety of civil engineering companies and the involvement of a number of designers contributed to the variations in the composition and properties of the buildings' façade panels. It was found that the composition of the façade varies and differs, but the values of the overall thermal transmittance coefficient U are in accordance with the current codes applied at the time of constructing (tab. 1), as well as the calculation of water vapour diffusion and the calculation of damping factor and temperature oscillations delay in summer period through the exterior building partitions. The calculated values for overall thermal transmittance coefficient U for all façade panels of the RB 3 also correspond to the previous finds (fig. 11).

The RB N5 was designed (1979) [44] and constructed in accordance with the current code at the time of building ($U < 0.93$ W/m^{2}K). The prefabricated concrete panels meet even the latest requirements ($U < 0.4$ W/m^{2}K), while the multi-layer brickwork façade needs additional insulation. The composition of lightweight filling with thermal insulation (fig. 10) is determined by observation in situ – it consists of an outward asbestos cement sheeting and wooden chipboard, with a 5 cm mineral wool layer in between. Only this small part of the façade, in conjunction with wooden windows represents a façade envelope of poor thermal properties, inevitably causing significant energy losses. Previously it was found that all the catalogued elements of the IMS system meet the standards of thermal protection, applicable at the time when designed. Thus, for RB that was constructed in this building system, the method of periodization may be accepted as suitable for the approximation of U values for the exterior walls.

During inspection of the buildings, it was found that there are ongoing works on renewal of façades on several buildings of the same type in this block. An additional 5-8 cm layer of EPS was installed with a protective layer of mortar and plaster lath. On some dwellings the external woodwork is under replacement – wooden windows are replaced with PVC or aluminium windows with isopane glass. Based on interviews with several residents, it was found that all of them are sharing the same subjective feeling of improved living comfort; the temperature in rooms that are insulated has increased 2-4 °C, and the level of noise that reaches from the streets is significantly reduced. Subsequent calculations revealed that the additional layer of the 8 cm EPS contributes to the reduction of the coefficient U of the façade, wall, fig. 11(a) from 0.372 to 0.216 W/m^{2}K. The works are funded by the owners of apartments. Unfortunately, there is no design documentation based on which the works were performed; instead, the work was treated as maintenance work, resulting in an insulating layer of arbitrary thickness. Also, brickwork façade at balconies is not insulated subsequently fig. 11(c), as these walls are not "perceived as cold" by residents and they agreed that they will further insulate only the concrete walls, figs. 11(a) and 11(b), usually with a 10 cm EPS layer. Adequate design documentation would insignificantly affect the price of works, but certainly would provide the savings in material. Also, it would be possible to plan the work in phases and identify the most efficient investments [45].

Conclusions

Based on the research above, in accordance with the presented methodology, it was found that the method of periodization is suitable to estimate the value of the overall thermal transmittance coefficient U of façades of multi-storey RB built in the IMS system. It was also found that there are many variations of multi-layer walls and U values are in accordance with the current regulations at the time of design and construction of the buildings. Façade panels in RB constructed in the Montastan, as well as the NS-71 system, generally fail to meet even the standards that were relevant at the time of design and construction, making the method of periodization unsuitable for the identification of thermal performances of façades. For each construction system (building type) the prevailing type of façade was determined, and it may be adopted as a starting point for determining the thermal properties of façade, when considering the energy renovation of buildings.

Comparative analysis of current condition of thermal protection (tab. 2) showed that the best properties are those of ventilated IMS façades, while performances are the weakest in Montastan and NS-71 façade. To achieve the required quality of the latest codes, insulation cover of 5-10 cm needs to be installed. According to the comparative analysis of heat losses (tab. 4) in the case studies approximately the same reduction in energy consumption by 5-9% can be achieved in all systems by replacing the windows. Subsequent thermal insulation of walls of poor thermal performances, even without replacing the windows, results with energy savings as high as 38%. Energy saving of 60% can be achieved by installing windows of class A energy efficiency in combination with the required extra thermal insulation. In order to improve the energy efficiency of existing multi-storey RB, in addition to adopting and implementing new standards in line with European directives and recommendations, it is also necessary to develop instruments for institutional, technical and financial support to the owners.

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