





## Article

# Energy Refurbishment of Serbian School Building Stock—A Typology Tool Methodology Development

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**Abstract:** Energy refurbishment of school buildings is a priority regarding both energy consumption in buildings and improving comfort conditions for sensitive young occupants. During 2016–18, a group of teachers and associates from the Faculty of Architecture, Mechanical Engineering, and Electrical Engineering from the University in Belgrade participated in the project “Energy efficiency in public buildings” in cooperation with GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), University of Belgrade, Faculty of Architecture and Ministry of Mining and Energy of the Republic of Serbia. During 2016 and 2017, a comprehensive survey and database of public buildings were conducted by the local community. The focus of the research was the facilities of children’s institutions, and detailed data were collected to determine the current building stock conditions, energy consumption, and possible improvements. This paper presents the methodology of the project based on defining the typology of buildings, determining the representatives of the characteristic periods of construction, and analyzing their energy performance. Five possible scenarios were considered: designed condition, existing state, and three levels of a building improvement. The main goal of this project was to ascertain the entire fund for school buildings, indicate the potential for energy savings of this type of public building at the national level, and use this as a starting point for developing strategic decisions and further energy efficiency policies. This paper presents the complete results of the research on school buildings in Serbia, their energy performance, and possible energy savings. Key findings show that a great majority of schools are in a poor state in terms of their energy efficiency, but at the same time, there is a large potential for improvement of building envelope, HVAC, and lighting systems, which can cut the current energy need for heating to up to 80%.



**Citation:** Đukanović, L.; Ignjatović, D.; Ćuković Ignjatović, N.; Rajčić, A.; Lukić, N.; Zeković, B. Energy Refurbishment of Serbian School Building Stock—A Typology Tool Methodology Development. *Sustainability* **2022**, *14*, 4074. <https://doi.org/10.3390/su14074074>

Academic Editors: Oriol Pons-Valladares and Jelena Nikolic

Received: 18 February 2022

Accepted: 17 March 2022

Published: 30 March 2022

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**Keywords:** school buildings; typology; energy efficiency; energy improvements

## 1. Introduction

Renovation of the existing building stock is a key strategy for achieving energy savings on a global level. However, the slow pace of energy renovation of the existing building stock has led to the adoption of the latest European strategy—A Renovation Wave for Europe [1] published in October 2020, with the main goal of doubling the building stock renovation rate in the next 10 years and adopting an ambitious level of decarbonization of the buildings by 2050. Since the European building stock is extremely heterogeneous and old, it is emphasized that 85–95% of the buildings that exist today will still be in use in 2050, even though 75% of the existing EU buildings are not energy efficient. One way to encourage refurbishment at the EU level is to uniformly certify existing buildings and make that data more apparent, transparent, and useful, as it is proved that it boosts improvements in the energy performance of public buildings [2]. Current requests for the refurbishment of public buildings in Serbia apply only to buildings owned by the central government,

which makes up only 4.5% of public buildings. That number is very low, regarding the fact that it should provide an example and guide for further building energy renovation [3]. Even greater potential can be recognized in the refurbishment of school buildings because in addition to improving the comfort of young occupants in the facilities, learning by doing can be an exceptional educational tool for the younger generations to adopt the right attitude towards their environment, and energy conservations and resources [4]. The European Commission also has recognized the importance and benefit of the renovation of educational facilities and financed several projects that deal with this matter [5,6].

As a state accession state of the European Union, Serbia has undertaken the obligation to harmonize its regulations in the field of energy efficiency with the regulations in power in the European Union. By signing the agreement on accession to the Energy Community on 1 July 2006, all regulations adopted by the Energy Community have become binding. A significant step forward in this field was the adoption of two rulebooks in 2011–2012 that more tightly determined the matters regarding energy consumption in buildings, and introduced the obligation to issue energy certificates: Rulebook on the Energy Efficiency of Buildings and the Rulebook on Conditions, Content, and Manner of Issuing Energy Performance Certificates [7,8]. During 2010–2014, a scientific research project, the “Energy Efficiency of Buildings Assessment of Energy Performances of the Serbian Building Stock” was launched as part of the international Tabula project (Typology Approach for Building Stock Energy Assessment) [9] in cooperation and with support from GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). Researchers from the Faculty of Architecture in Belgrade participated in this project, which completely and comprehensively researched the characteristics of the existing residential buildings’ fund from the point of view of energy consumption. Results were published in several monographs [10–12]. The next significant research project “Energy Efficiency in Public Buildings—Schools and Kindergartens” was done during 2016–2018, and was also in cooperation with GIZ, and the University of Belgrade—Faculty of Architecture and Ministry of Mining and Energy of the Republic of Serbia, by a group of teachers and associates from the Faculty of Architecture, Mechanical Engineering, and Electrical Engineering from the University of Belgrade. Results were also published in several monographs and scientific papers [13–16]. The problematic creation of the typology of school buildings and their specific features will be presented in this paper.

## 2. Methodological Approach

The focus of the research was building characteristics that significantly affect the energy efficiency of school buildings. The study was based on the typology of buildings that were developed to classify and define the differences within this type of public building. The fund of public buildings includes an extreme variety of buildings, with different functional and organizational matrices and typological, constructive, material, and technological characteristics of buildings. School buildings have their characteristics in the systematization and typology of public buildings based on which the analysis of energy performance should be done. Given that there was no adequate database for public buildings in Serbia to provide relevant information needed for analysis, it was necessary to conduct sampling for data collection through a specially designed survey of public buildings in the entire territory of the Republic of Serbia.

The methodological procedure carried out on the project can be divided into several phases that proved necessary for this type of analysis:

- Survey of public buildings in Serbia: conducting the survey and a formation of questionnaires;
- Database formation: verification, processing, and cluster analysis;
- Determining the relevant parameters and forming the typology of school buildings;
- Adoption of the typology of school buildings and selection of model buildings/representatives;
- Calculating the energy performance of model buildings/representatives;

- Defining the methodology for improving the energy performance of model buildings;
- Calculating the energy performance of improved models;
- Conclusions on achieved energy savings.

### 2.1. Survey of Public Buildings and Formation of a Database

The problem encountered at the very beginning of the project was the lack of necessary data on public buildings. To obtain relevant data for further analysis, a survey was defined with a dedicated questionnaire defining all the necessary information about the public buildings. For the needs of the project, during 2016 and 2017, data about buildings were collected by the local community according to questionnaires formed by researchers on the project. The questionnaire was designed at three independent levels through the gradation of data collection according to the needs of the survey.

The first level of the questionnaire listed all public buildings, the second level was intended for the survey of administrative buildings and all types of childcare institutions, while the third level implied detailed analysis of school and preschool buildings. The first level of the questionnaire contained basic data on public facilities and served primarily to identify institutions. It included five key questions: name and type of public institution, number of buildings, the location—the municipality on which it was located, the address of the institution, and the institution's source of funding. The second level of the questionnaire further investigated administrative buildings and all types of children's institutions. It included 14 questions that were primarily focused on defining the basic characteristics of buildings. The first group of questions included information on the exact position of the building; the address, the cadastral municipality, the number of the cadastral plot, and the number of the building on the site. The second group of questions referred to information on the year of construction, the method of construction, and the use of the building: if it was purposely built for today's purpose, whether it was built with a building/use permit, if it had an energy certificate or it had undergone an energy audit, as well as whether and to what extent it had undergone any interventions. The third level of the questionnaire was the most detailed, and it was completed only for preschool and school facilities. This level contained 48 questions that can be grouped into three distinct parts. In the first, questions were formed about the architectural and construction characteristics of the building: dimensions, the number of floors, volumetric characteristics, and compactness, occupancy and usage of the building, characteristics of the building envelope (facade finishings and wall materials, window, and roof type), age of windows, condition of the building, etc.

The second data group referred to mechanical systems in the building, the determination of energy sources, and the distribution of the installations for heating, ventilation, and air conditioning (HVAC) and DHW preparation in the building, as well as questions on the user's satisfaction with the achieved thermal comfort. The third group of questions referred to electrical installations and lighting systems. This set of questions further explained electricity consumption in the building and the method of domestic hot water preparation, as well as the type of lighting systems in the building, the use of air conditioning, and annual electricity consumption.

For the needs of the research, a software tool for database analysis was developed. The database contained data for 1857 school buildings in the Republic of Serbia. The developed software allowed an easy search through the data for all building parameters defined through questionnaires and allowed for the further addition of new data updating the building information (Figure 1).

The screenshot shows the 'GIZ - Public Buildings v6' software interface. The main window displays a data table with columns for building ID, name, address, location, and various technical parameters. A detailed view for building ID 2000259 is shown below the table, including fields for construction year, floor area, and roof type. On the right, a 'Upis' (Registration) panel contains dropdown menus for selecting building type, location, and other attributes. At the bottom, a 'Slike' (Images) section shows several photographs of school buildings.

Figure 1. Software tool illustration.

## 2.2. Determining the Parameters for Forming the Typology and Adopting the Matrix of School Buildings

The survey on the field has been conducted by an alternative approach to data collection that included relying on local community cooperation instead of hiring a professional organization. This approach did not ensure even distribution and responsiveness, as some municipalities were very responsive, some did not respond at all, and some provided incomplete or invalid data. The additional step of validation of collected data was needed to provide uniform quality of information on buildings, which caused delays in the research process and proved the need to primarily rely on professionals to collect and process information to obtain quality data. Further data analysis was performed by the statistical tool of cluster analysis based on the recognition of homogeneous groups and defining building types that had similar characteristics and performance. This method was explained in detail in previous publications [17]. The main characteristics analyzed were the age of the building and the volumetry and the materialization of the facade. The obtained characteristics of individual types, according to the periods of construction and gross floor area, are shown in Table 1.

Based on the results of the cluster analysis, a search of the database was performed to find buildings that best match the characteristics of the model building types. The basic parameters, according to which the typological matrix of buildings was formed, were the particular type and period of construction and the gross floor area of buildings. The systematization of the building stock was defined based on four characteristic periods describing typical building design and construction characteristics: the period up to 1945 (period A), the period 1946–1970 (period B), the period 1970–1990 (period C) and the period after 1990 (period D). This periodization was defined respecting historical development and architectural styles defining each period, as well as the development of techniques and technologies of the construction and construction industry. The second parameter is the gross floor area of buildings where the classification is made defining: small schools (up to 500 m<sup>2</sup>—mark 1), medium-sized schools (from 500 to 2000 m<sup>2</sup>—mark 2), and large schools (over 2000 m<sup>2</sup>—mark 3). The typological matrix of the selected representatives of school buildings is shown in Table 2. Since the cluster analysis showed that for certain periods and

types, two homogeneous groups of objects with the same performance are shown, both types are included in the final table as type and subtype.

**Table 1.** The description of the model of school buildings.

Type	Period	Analysis Parameters	Gross Floor Area		
			Type 1 Smaller than 500 m <sup>2</sup>	Type 2 from 500 to 2000 m <sup>2</sup> Type/Subtype	Type 3 Larger than 2000 m <sup>2</sup> Type/Subtype
A	before 1945	gross floor area	235 m <sup>2</sup>	810–1310 m <sup>2</sup>	2890 m <sup>2</sup> /3185 m <sup>2</sup>
		floors	GF	GF/GF + 1	GF + 1/GF + 2
		compactness	compact	compact/ partially complex	partially complex/ complex
		roof type	pitched roof	pitched roof	pitched roof
		facade	brick	brick	brick
B	1946–1970	gross floor area	145 m <sup>2</sup>	1160 m <sup>2</sup>	3010 m <sup>2</sup>
		floors	GF	GF + 1	GF + 2
		compactness	compact	compact	complex
		roof type	pitched roof	pitched roof	
		facade	brick	brick	
C	1971–1990	gross floor area	255 m <sup>2</sup>	1610 m <sup>2</sup>	2660/5045 m <sup>2</sup>
		floors	GF	GF + 1	GF + 1/GF + 2
		compactness	compact	compact or complex	complex/partially complex
		roof type	pitched roof	pitched roof	
		facade	brick	brick/ concrete	
D	After 1991	gross floor area	230 m <sup>2</sup>	995 m <sup>2</sup>	6200 m <sup>2</sup>
		floors	GF	GF + 1	GF + 2
		compactness	compact or complex	compact	complex
		roof type	pitched roof	pitched roof	
		facade	clay block	clay block or concrete	

**Table 2.** The typological matrix of the selected representative school buildings.













Type	Period	Gross Floor Area		
		Type 1 Smaller than 500 m <sup>2</sup>	Type 2 from 500 to 2000 m <sup>2</sup> Type/Subtype	Type 3 Larger than 2000 m <sup>2</sup> Type/Subtype
A	before 1945			
				

Table 2. Cont.

Type	Period	Gross Floor Area		
		Type 1	Type 2	Type 3
		Smaller than 500 m <sup>2</sup>	from 500 to 2000 m <sup>2</sup> Type/Subtype	Larger than 2000 m <sup>2</sup> Type/Subtype
B	1946–1970			
C	1971–1990			
D	After 1991			

The distribution of school buildings in building stock according to the adopted characteristic periods is shown in Figure 2.

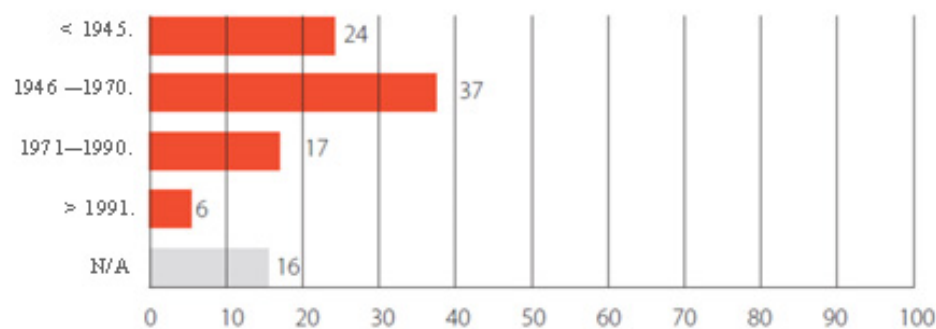


Figure 2. The distribution of school buildings according to the periodization used to form the typology [%].

Figure 2 shows that 24% of school facilities were built by 1945, while the most intensive period of construction of this type of building was after World War II until 1970 (37%). School buildings constructed in the period of socialism in Serbia represent the most numerous buildings and the highest quality buildings in the whole school building stock in terms of their architectural value, spatial organization, and functionality. In the period 1971–1990, 17% of school buildings were built, while after 1990 the intensity of school construction dropped significantly to only 6%. The data from the survey showed that in that period, a negligible number (below 1.5%) of small and medium-size school facilities were built, so in the final typology, these facilities were not even considered. Moreover, cluster analysis showed that some varieties are recognized within one group, and in that case, in addition

to the basic type, subtypes were included to insist on data accuracy (period up to 1945: medium and large buildings, and 1971–1990: large schools (Table 2).

Taking into account that the first thermal building regulations in Serbia appeared in the 1970s, the figures show that about 60% of school buildings, which still exist today, were already built and consequently were not subject to any obligations regarding thermal protection. Since the adoption of current regulations on energy efficiency in 2011 [7,8], only a few buildings have been built and a small number of schools have been energy refurbished [18]. On that account, we can conclude that most of the school buildings are not in line with modern thermal building regulation requirements. The research showed that in only 14% of buildings there is thermal insulation in the facade, from which in 60% of the buildings, the applied thickness of thermal insulation is less than or equal to 5 cm.

The list of schools showed, that in Serbia, in terms of gross floor area, small schools up to 500 m<sup>2</sup> predominate, making up 34% of the total building stock. Large schools (over 2000 m<sup>2</sup>) are represented with 27% while middle-sized schools (500–2000 m<sup>2</sup>) make up 21% of total school buildings. This percentage corresponds to the socio-political conditions in the state. In the post-war period, the idea of industrial development and concentration of population in urban centers was propagated, leading to the rapid development of cities due to the large migration of populations from rural areas. The change in the housing policy in the cities, and the increased number of inhabitants demanded new school facilities that were larger and with a higher capacity of students. In rural areas, corresponding to the needs of the reduced number of inhabitants, the concept of building smaller school facilities was perceived.

The basic characteristics of the adopted periods of construction of school buildings, obtained by the survey, can be briefly defined through the following descriptions.

#### 2.2.1. Period A—To 1945

The period before 1945 was the period of the formation of the education system in Serbia. The emphasis was on the development of primary school education and the establishment of a network of school facilities. The predominant type of school building, more than 50%, were small buildings (up to 500 m<sup>2</sup>), usually compact in form, organized in a single block, with a pitched roof and basement and attic floors not used for school activities (Table 1). The construction system of the building was massive, with load-bearing walls of full brick, with single window openings, usually wooden, single or double framed with single glazing. In addition to the predominant small buildings, medium-sized schools (25%) and large schools (21%) were built in urban areas as two-story buildings in a complex form with a central main block and additional side wings. These buildings, besides primary educational function, had a significant symbolic function, usually having facades with features and decorative plasterwork of current architectural styles of the places in which they were built. Because of the age of buildings, as well as due to poor maintenance, over time, wooden window structures have deteriorated. In the majority of the school buildings (58%) these windows were replaced by PVC windows. A very small number of school buildings of this period (only 10%) have thermal insulation in the facade, usually added additionally during the building energy refurbishment process.

#### 2.2.2. Period B—1946–1970 Years

The post-war period is characterized by a significant increase in the total building stock, as well as the stock of school facilities. Post-war economic changes caused by the development of industrial production produced demographic migrations and population growth in cities. All this influenced the need for an accelerated construction of school buildings in urban areas, and also the formation of a network of smaller schools in rural areas. In addition to the predominantly compact form of the buildings, during this period, partially complex and complex objects are becoming more represented. The one-story school buildings make up half of the total school buildings stock from that period, while there were 25% of two-story buildings and 16 % of three-story buildings. The roofs of the

buildings were predominantly pitched, but the usage of flat roofs is noticeable in the period of modernism in the 60s (Table 1). Due to the poor maintenance and deterioration of the flat roofs, a large number of school buildings went through the additional rehabilitation of the existing flat roof, usually changing the building form by additional construction of pitched roofs. The construction systems of school buildings in this period were predominantly massive, with walls made of brick, but in the second half of this period, with the appearance of reinforced concrete, appeared also skeletal constructions. The shape and dimensions of the windows were influenced by current modernist architecture and instead of individual openings, larger openings or window ribbons were formed. The windows in the buildings were wooden, but until today, because of the process of energy rehabilitation in the significant number of the facilities, they were replaced with PVC windows (42%). Since thermal regulations were established later, in this period, thermal insulation was not applied to facades. This caused a large number of buildings (92%) to be without any thermal insulation, while with the other 8%, thermal insulation was installed additionally during the rehabilitation and reconstruction of the facade.

### 2.2.3. Period C—1971–1990 Years

A significant increase in urban population and intensive urbanization in the Republic of Serbia during this period caused a growing need for the construction of large school buildings. Larger schools became predominant (38%), changing the former trends of building, while medium and small school facilities were represented in a similar percentage (26% and 31%). This period represents a qualitative shift in the design of the building, exploring new concepts and different models of spatial organization that, over time became more demanding and complex. Compact, partially complex, and complex buildings are equally represented (about 30%). In this period, as a consequence of more complex requirements imposed by modern education, two-story buildings take precedence over one-story buildings (40%). Pitched roofs predominate in this period, and the dominant material of the construction is still brick (Table 1). Large window openings are often formed in the form of horizontal ribbons, and the use of PVC profiles is dominant, again as a result of the refurbishment of school buildings (44%). Although the first regulations in the field of thermal protection were introduced in the 70s, the survey showed that the use of thermal insulation on facades was sporadic in schools built in this period (only 18%).

### 2.2.4. Period D—After 1991

The period begins with the disintegration of SFR Yugoslavia, which resulted in the significant migration of the population to the Republic of Serbia, mainly to the periphery of urban areas, which led to the need to predominantly build larger schools. Small schools are represented by 28%, while medium-sized and large schools make up half of the total number of schools built in this period. As a consequence of rationality in construction and a need to build schools of larger scale, compact forms are again predominantly built (around 50%), with the increased number of floors (38% of three-story buildings). Most of the buildings have pitched roofs, but in this period, the activation of attic spaces is noticeable. The structure of buildings is most often built with a reinforced concrete skeletal construction with various masonry infills. Individual window openings of a smaller surface area were reintroduced in postmodernism, abandoning the ribbon window openings that were characteristic of modernist expression (Table 1). The leading materials for windows were wood and PVC profiles, equally represented (about 40%). Even though regulations in the field of thermal protection have been established during that period, the lack of control over the construction of the buildings and application of binding regulations resulted in the surprisingly small actual application of thermal insulation on buildings, around 50%.

## 2.3. Regulations concerning School Buildings and Energy Efficiency

The regulatory framework in the Republic of Serbia defining building characteristics, construction, and matters of comfort in school facilities has developed over a long period



of time. The first Rulebook, which regulated the building of schools in more detail, was adopted in 1881 under the title *Rules on building schools and on school furniture*. This rulebook clearly defines the position and structure of the school building, its form, size, position, and orientation of the classroom. It also specifies the building materials and elements from which the building should be built, indirectly for the first time in the history of Serbian education, determining the quality of comfort and thermal characteristics in the facilities. Newer regulations in Serbia have further defined the conditions for school buildings, especially conditions related to providing student comfort. One of the most important conditions is the need for thermal and sound insulation of the facilities that provide tuition and children's occupancy, but this aspect is not strictly defined or explained in detail.

The matters of energy efficiency in school buildings are treated in Serbian regulations only by general regulations that apply to all types of buildings, without any special recommendations given for school facilities. The adoption of the *Rulebook on the energy efficiency of buildings* [7] in 2011, determines in more detail the energy properties of buildings, as well as the methods for calculating them. The *Rulebook on conditions, content, and manner of issuing energy performance certificates* [8] determines the limit values of the energy required for heating for 10 categories of buildings, including buildings intended for education and culture. The specific requirements for school buildings in the terms of thermal regulation are expressed through the definition of the allowed annual final energy consumption and the definition of heat gains from occupants and electrical appliances. For this type of building, other parameters that affect the calculations of the energy performance of buildings are defined: projected temperature (for summer and winter), daytime occupancy, the amount of outdoor air per occupant or area. In addition, energy classes have been defined for school buildings based on the calculated heating energy demand (Table 3).

**Table 3.** Energy class ratings for buildings used for education and culture [7].

Education and Culture Buildings		New	Existing
Energy Class	$Q_{H,nd,rel}$ [%]	$Q_{H,nd}$ [kWh/(m <sup>2</sup> a)]	$Q_{H,nd}$ [kWh/(m <sup>2</sup> a)]
A+	≤15	≤10	≤12
A	≤25	≤17	≤20
B	≤50	≤33	≤38
C	≤100	≤65	≤75
D	≤150	≤98	≤113
E	≤200	≤130	≤150
F	≤250	≤163	≤188
G	>250	>163	>188

New facilities must have a Class C rating (which applies to all facilities) while existing buildings under reconstruction must improve existing energy classes by one energy class after the reconstruction [8].

#### 2.4. Applicable Thermal Regulations and Calculation Principles

In Serbia, the method of calculation of building energy performance differs from the method used in the EU. Following the basic principles, the most important difference is reflected in the way buildings' energy class is calculated in the energy certification process. In EU countries, the energy class of a building is expressed through the required amount of energy for heating, cooling, ventilation, lighting systems, domestic hot water preparation, building automation and control, etc. In Serbia, according to the current regulations [7,8], buildings are categorized upon the heating energy demand exclusively per unit of heated area, while other forms of energy are not included in the total calculation. These regulations were adopted in 2011 with a one-year delayed start of implementation and were treated as "temporary", with the idea of using this method of calculation until adopting the national software that would calculate all required forms of energy. At the time of this research,

even until today, ten years after the adoption of the new regulations, there are no changes made regarding this matter.

The national standard for calculation and certification of building energy performance is regulated by the Rulebook on energy efficiency in buildings [7]. This rulebook is entirely in line with EN ISO 13790, and the calculation procedure is based on the fully prescribed monthly quasi-steady-state calculation method. Currently, the calculation of energy need is based on the energy requirement for heating, which is also used for expressing a building energy level [7]. The energy need for heating is determined for a defined heating season for several locations in Serbia, based on a heating degree day method. Climate data, used in calculations, consists of the number of heating days and outside temperatures determined for representative locations in Serbia. Solar radiation is addressed based on the average values for the entire territory of Serbia [19].

Throughout this project, calculations were also carried out for other types of energy, but the certification of buildings was done only according to the regulations calculated for the energy required for heating. For other types of energy, the calculation was performed according to the relevant standards:

- SRPS EN ISO 13790:2010 Energy performance of buildings—Calculation of energy use for space heating and cooling: determining the annual energy needs for heating and cooling, the annual energy required to compensate for heat losses, transmission heat loss coefficient, heat gains utilization, and the contribution of internal and solar heat gains;
- SRPS EN ISO 13789:2017 Thermal performance of buildings—Transmission and ventilation heat transfer coefficients—Calculation method: determining ventilation heat loss coefficients;
- SRPS EN ISO 15316:2017 Energy performance of buildings—Method for calculation of system energy requirements and system efficiencies: determining required heat for heating domestic hot water, heat losses of systems for heating and preparation of domestic hot water;
- SRPS EN ISO 15243:2010 Ventilation for buildings—Calculation of room temperatures and of load and energy for buildings with room conditioning systems: determining the energy consumption of cooling generation systems and distribution losses;
- SRPS EN ISO 15193:2012 Energy performance of buildings—Energy requirements for lighting: determining energy requirements for lighting.

The highest allowed values of the heat transfer coefficients [ $U_{max}$ ] are defined in the Rulebook on the energy efficiency of buildings for all positions of the thermal envelope, separately for new and for the existing buildings. The same principle of analysis and calculation of the positions of the thermal envelope of the building was applied in this research.

Standards used to perform this type of calculations corresponding to the EU regulations are:

- SRPS EN ISO 6946:2017 Building components and building elements—Thermal resistance and thermal transmittance—Calculation methods: determining thermal transmittance of non-transparent elements of the building;
- SRPS EN ISO 13370:2017 Thermal performance of buildings—Heat transfer via the ground—Calculation methods: determining heat transfer through structures in contact with the ground;
- SRPS EN ISO 10077:2017 Thermal performance of windows, doors, and shutters—Calculation of thermal transmittance—Part 2: Numerical method for frames: determining thermal transmittance of transparent elements of the building.

All the calculations were performed in the *KnaufTerm2Pro* program—software developed in accordance with the applicable energy efficiency regulations in Serbia. *KnaufTerm* is one of the most widely used calculation tools in Serbian practice for the verification of the energy performance of buildings. The software is available for free use with registration on the website of the KnaufInsulation company. The method of calculation is

based on the determination of the annual energy requirement for heating, through energy balance calculation, which includes transmission and ventilation heat losses, and solar and internal energy gains. The influence of thermal mass is taken into account through the dimensionless gain utilization factor for heating ( $h_{H, gn}$ ). The method defined in standard EN ISO 13370 is used for the calculation of floors and walls in contact with the ground, and it takes into account the geometry of the floor, through the value of the characteristic floor dimension ( $B'$  [m]) and equivalent floor thickness, as well as the thermal properties of the soil. By using this method, the floors on the ground of the same structural composition can have significantly different U-values, depending on their shape and size.

Ventilation heat losses are determined according to the SRPS EN ISO 13789:2017 standard, taking into account the class of airtightness of the building, and the entire ventilated building volume.

Types of HVAC systems were taken into account when determining the final and primary energy consumption, based on the determined energy need for heating, according to the applied system's efficiency, taking into account the level of efficiency of the systems and heat losses, according to SRPS EN ISO 15316:2017. Energy need for DHW preparation was also determined according to this standard.

Internal gains from equipment, lighting, and occupants are taken into account through tabular values determined according to the building's type, according to the EN ISO 13790 standard.

A comprehensive overview of the methodology for energy performance calculations in Serbia, based on current legislation, is given in previous publications [19,20] with a comparison to simulation tools and a discussion about the limitations of the used methodology. Buildings were analyzed as single-zone models, determining the entire heated area, heated volume, and ventilated volume according to the geometrical 3D model. Constraints coming from this kind of thermal analysis are not taking into account the different occupancy regimes and heating regimes. Moreso, indoor environmental quality, which is becoming even more important in the post-COVID situation [21], is taken into account only through the determination of the class of airtightness of the building, and respective values of air changes per hour. Some research of indoor environmental quality in Serbian schools with natural ventilation [22] suggests that even with the building being in compliance with regulations in terms of the size of classrooms and windows, the indoor environmental quality is not satisfactory in the heating season. The research of this scope, taking into account many building types, and dealing with the entire typology, couldn't go into much detail about every aspect influencing the energy performance of buildings. However, it opens the possibility for further research of numerous topics, and as such, indoor environmental quality, infiltration rates, and the influence of ventilation on building energy performance are currently being investigated further in school buildings [23].

Although building actual energy consumption data can be valuable in calibrating results of energy performance simulations and calculations, they haven't been used in this research, although they have been collected in the process of data acquisition, due to inadequate provided data and insufficient information about the occupancy and heating regimes.

### *2.5. The Energy Performance Calculations and the Definition of the Methodology for Improvement of Typical School Buildings*

The next step in the research process was to determine the energy performance of selected representatives of model buildings and assess the possible improvements. For every type of model, buildings were illustrated with all architectural and structural characteristics (Figure 3). Further thermal envelope characteristics and heat transfer coefficients were analyzed as well as heating and lighting systems and domestic hot water preparation. Moreso, for each type of building, similar building type representatives for which energy consumption calculations and energy classification have been performed were defined.



Figure 3. Example of school building type representation—existing state (Reprinted with permission from ref. [14], pp. 160–165, Jovanović Popović et al., GIZ).

By the on-site observation, in many cases, the changes in the deviations from the original design of the buildings were noticed. Because of that, during the analysis of the model buildings, a variant of the current condition of the building was considered, including all changes made to the object compared to the original condition.

In the next step, different scenarios of building refurbishment were considered through three levels of improvements, where the intervention was graded from the minimum defined by the current regulations (improvement of the energy class of the building for one level) to the maximum possible (in line with current practice and technical and material specificities).

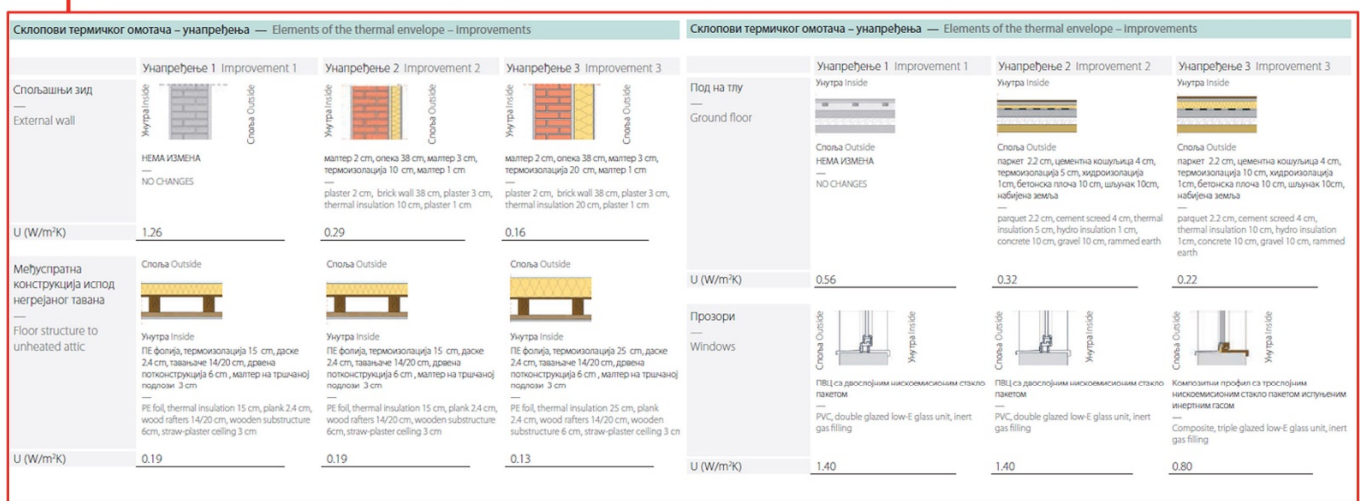
In order to provide a better overview of the current performance and the potential for improvement during all stages of the life cycle of the object, five scenarios were predicted:

- **As-designed:** Implies the original condition at the time when the facility was built according to the original project documentation, without any subsequent intervention on the elements of the thermal envelope or the existing heating system and the main energy source.
- **Current situation:** This includes subsequent interventions that have been done on the building until today, often being the replacement of windows, roofing, or the additional activation of the basement. This type of renovation was encouraged by the State and carried out on a large number of objects, mostly including the replacement of existing windows with PVC windows that do not meet current needs in terms of their thermal characteristics. Treating the impact of particular interventions that may have been undertaken on the selected buildings, the real condition of the building stock has been analyzed, taking into account all alterations made to the building's thermal envelope.
- **Improvement 1:** Implies energy refurbishment of the building in accordance with current regulations [7,8] to improve the energy class of the building for one level. This level of improvement is most often achieved by adequately installing windows of better quality (heat transfer coefficient  $U = 1.4 \text{ Wm}^2/\text{K}$ ). If the window replacement did not produce the desired results in achieving the desired energy class, further interventions were performed on the easily accessible elements of the thermal envelope, primarily the insulated floor and the unheated attic space. In this way, achieving the level defined by current regulations on thermal protection during the renovation of the existing buildings would be done. The existing heating system was retained, except in the case that local heating devices (stoves) were replaced by centralized heating or that liquid fuel was replaced by biomass. The existing lighting system at this level of improvement involved the replacement of the existing systems with LED luminaires.
- **Improvement 2:** Proposes intervention on all elements of the thermal envelope of the building so that the heat transfer coefficients meet individual requirements of the positions of the thermal envelope defined by current regulations [7]. This level of the intervention included adding thermal insulation at all necessary positions as well as replacing other deteriorated components of the envelope. In this way, all components of the building's thermal envelope would be in accordance with the necessary regulations that apply to the reconstruction of existing buildings. The heating system at this level was improved by using biomass (wood pellet in smaller buildings and wood chips in larger buildings), except for the facilities that are located in the urban areas already connected to a district heating system with natural gas as the most environmentally friendly fossil fuel. At this level of improvement, centralized lighting control and automatic lighting control are being introduced.
- **Improvement 3:** Implies a high level of energy efficiency improvement of the thermal envelope by performing maximum interventions in line with current practice and to the extent allowed by the assembly of the envelope and available materials and technologies. In this way, the maximum possible savings by improving the school buildings' stock were considered. Air to water heat pumps were used for space heating and domestic hot water preparation, and electricity was used as an additional energy

source for domestic hot water heating. At this level of improvement, the lighting automation system is further improved by the systems for presence detection and light level adjustment according to the time of day.

Presenting five possible scenarios of the school building’s life cycle contributes to a complete overview of energy consumption and possible energy savings of the existing school building stock and through several levels of improvement. Interventions on the thermal envelope were shown by sketches of components of the building thermal envelope with representations of all characteristic layers in five possible scenarios for each representative (as demonstrated in Figure 4). Only building D3, which represents the newest buildings, is shown through the existing condition (which are equal to the current one) and improvement 3, because it meets the requirements of thermal protection according to the current regulations.

Elements of the thermal envelope improvements - walls, floors, windows - for improvements 1,2,3



Heating system improvements - Heating system, Heat source efficiency, Domestic hot water preparation for improvements 1,2,3

Lighting system improvements - interior and exterior lighting and relative energy savings of lighting system for improvements 1,2,3

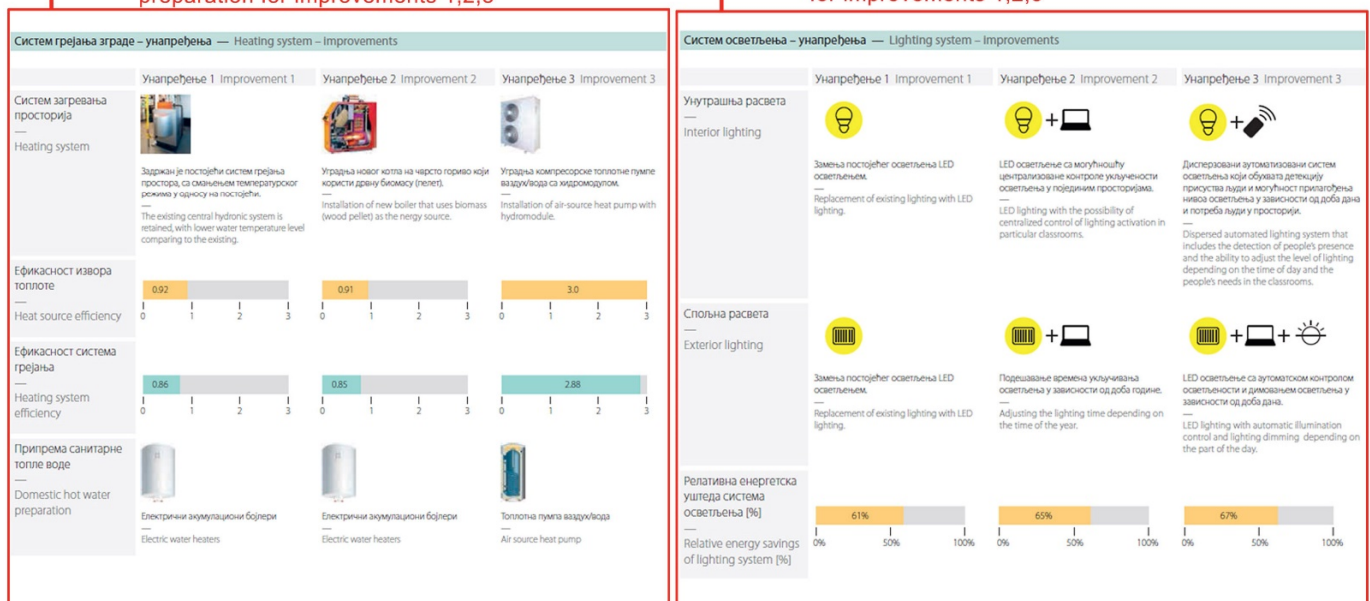


Figure 4. Example of school building type representation—improvements (Reprinted with permission from ref. [14], pp. 166–169, Jovanović Popović et al., GIZ).

All the improvements of individual components of the building thermal envelope were done to achieve maximum thermal protection, taking into account the real possibilities of the component itself and the implementation feasibility.

Thermal insulation layers in the components were placed on the outside in all situations possible, except in the buildings with a certain degree of protection, as cultural and historical monuments were treated differently and required special treatment [24]. The school facilities, with this type of protection, were predominantly built in the period until 1945 and can be found in urban areas. Special care was taken designing the improvements of the components in these school facilities, respecting the need to preserve the original appearance and architectural expression of this type of building. The authenticity of the facade and facade plastic was retained, and the thermal insulation was installed on the inside, being a less favorable solution from the point of view of thermal protection. For all buildings, technological procedures were planned to preserve the authenticity of the facade even when the final layer of the existing building was made of facade brick or concrete, even though these solutions affected the cost of intervention and complexity of the procedures. In such situations, the thermal insulation was placed on the outside wall, but the final layer was made of a material that corresponded to the original solution.

The energy performance of buildings is shown either through the improvement of the thermal envelope or the improvement of both the thermal envelope and heating system. Within the improvement of only the thermal envelope, calculations were performed for the original condition of the building and three levels of improvement, and the following are shown: heat losses, transmissive losses, and specific heating energy demands per year that also define the energy class level (Figure 4). Improving the energy efficiency of the school building was done in accordance with current regulations and is reflected in the reduction in energy required for heating while achieving the obligatory comfort conditions. Figure 4 shows the changes in achieved energy class levels depending on the level of improvement.

Since it was considered that the improvement of only HVAC systems, without the improvement of the thermal envelope, does not make logical sense, the next group of data referred to the combined interventions on both the thermal envelope and the heating system. Within these improvements, all types of energy consumed in buildings were presented: final and primary energy consumption, as well as CO<sub>2</sub> emissions after architectural and HVAC improvements and CO<sub>2</sub> emissions after improvements of lighting systems (Figure 5). Calculated CO<sub>2</sub> emissions are recognized in literature as an important measure of the value of the building stock and it must be considered in the process of refurbishing and improving the quality of the buildings [25,26].

### 2.6. Achieved Energy Savings

Based on the results of the calculations of the total energy required for heating ( $Q_{hnd}$ ) for the current condition of schools, it can be concluded that in most buildings (except D3) values range between 200–300 kWh/m<sup>2</sup>, corresponding to the lowest energy class level “G” (Table 4). The value of total heating energy required for building D3, which represents the most recently built school according to current thermal regulations, is many times lower (corresponding to energy class level “C”). This data shows that all school buildings, except for the most recently built, fewer in number, are in extremely poor condition in terms of energy consumption and in need of energy refurbishment. It can also be noticed that the highest values of total heating energy required were obtained in small schools (A1, B1, C1), which can be explained by the unfavorable influence of building compactness on total energy consumption [27]. In the consideration of the current condition of school buildings, subsequent structural interventions of the thermal envelope were taken into account. The most usual type of intervention was the replacement of original windows on the building with PVC windows of poorer thermal characteristics that usually do not meet the requirements of the current standard. Due to this change, the reduced energy required for heating is observed and buildings remain in the G energy class level (A1, A2, B1, C1, C2), or the energy class level is changed to F (A3) or E (B2, B3, C3).

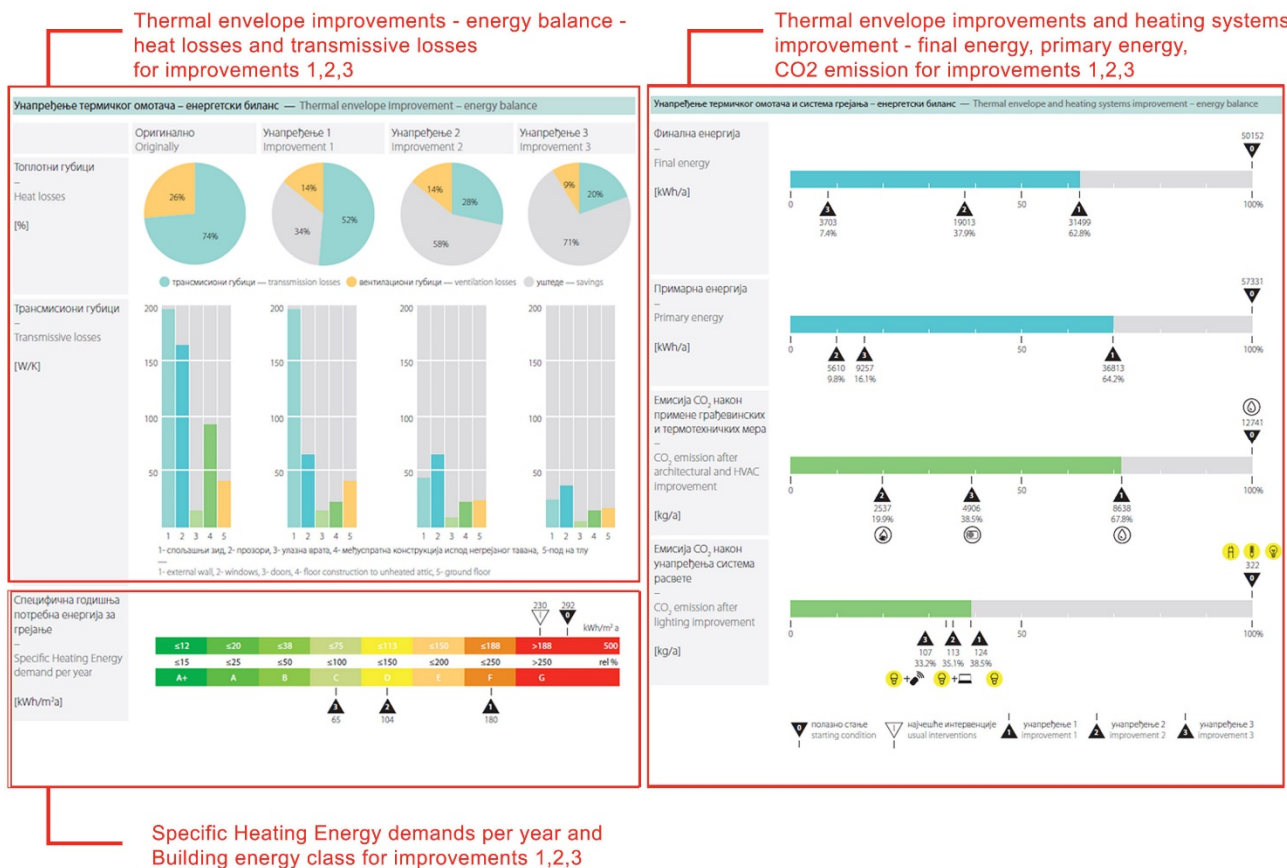


Figure 5. Example of school building type representation—improvements of HVAC and lighting system (Reprinted with permission from ref. [14], pp. 170–171, Jovanović Popović et al., GIZ).

Table 4. Total energy required for heating (Qhnd) of school buildings by type and level of improvement.

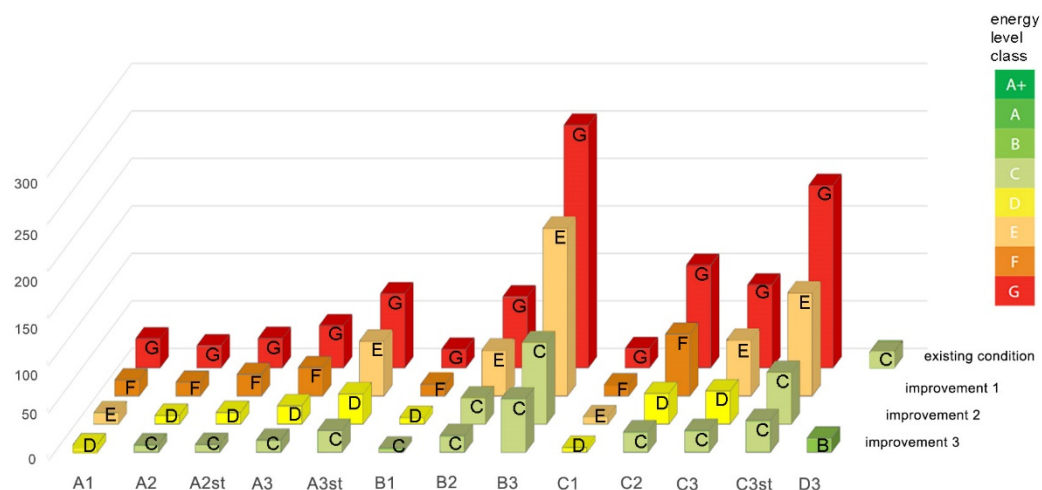
Type	Number of Buildings		Area		Current Energy Demands			Improvement 1		Improvement 2		Improvement 3		
			Typical School	Total	Typical School Qhnd	Total	Typical School Qhnd	Total	Typical School Qhnd	Total	Typical School Qhnd	Total		
	pcs	%	[m <sup>2</sup> ]	[m <sup>2</sup> ]	%	[kWh/m <sup>2</sup> a]	[GWh/a]	%	[kWh/m <sup>2</sup> a]	[GWh/a]	[kWh/m <sup>2</sup> a]	[GWh/a]		
A1	596	15.32	165	98,340	2.08	313.20	30.80	3.13	171.60	16.88	121.88	11.99	80.02	7.87
A2	165	4.24	567	93,555	1.98	249.71	23.36	2.38	155.44	14.54	99.08	9.27	68.89	7.87
A2 <sub>ST</sub>	135	3.47	917	123,795	2.61	251.43	31.12	3.16	184.69	22.86	100.13	12.39	66.58	8.24
A3	104	2.67	2168	225,472	4.76	197.69	44.57	4.53	132.60	29.89	85.93	19.37	56.59	12.76
A3 <sub>ST</sub>	138	3.55	2389	329,682	6.96	237.08	78.16	7.95	175.38	57.81	96.40	31.78	69.82	23.02
B1	664	17.07	102	67,728	1.43	292.29	19.8	2.01	180.13	12.20	103.90	7.04	64.92	4.40
B2	449	11.54	870	390,630	8.25	191.73	74.88	7.61	124.03	48.44	70.51	27.54	45.07	17.62
B3	538	13.83	2408	1,295,504	27.36	197.36	255.73	25.99	136.40	176.71	66.34	85.89	43.49	56.35
C1	337	8.66	191	64,367	1.36	318.06	20.48	2.08	184.25	11.86	120.74	7.77	80.30	5.17
C2	274	7.04	1288	352,912	7.45	306.65	108.20	11.00	184.48	65.11	91.90	32.43	60.97	21.53
C3	219	5.63	2080	455,520	9.62	191.91	87.42	8.89	129.57	59.02	77.13	35.13	50.45	22.98
C3 <sub>ST</sub>	194	4.99	4288	831,872	17.57	231.13	192.27	19.55	130.79	108.80	65.40	54.40	40.35	33.56
D3	77	1.98	5270	405,790	8.57	41.53	16.84	1.71	-	-	-	-	37.04	15.01
<b>Total</b>	<b>3890</b>	<b>100</b>		<b>4,735,167</b>	<b>100</b>		<b>959.67</b>	<b>100</b>		<b>629.19</b>		<b>346.97</b>		<b>246.54</b>

The national typology of school buildings showed that the highest number of facilities, 37%, were built in the period 1946–1970 (period B). This is a period of intensive building construction in Serbia in which a regulatory framework regarding thermal regulations had not yet been fully established. Within that period, the highest energy consumption was in the group of large schools over 2000 m<sup>2</sup> (B3), constituting around a quarter of the total number of school buildings (27.36%). Considering the number and condition of this type of school building, interventions on the facilities built in this period can be an opportunity to achieve great energy savings. Most of these buildings were built in the modernist style



in simple volumetrics with flat wall surfaces without any decorative plasterwork, making the process of energy renovation less demanding.

After the first level of improvement, with interventions made to improve the energy performance of building for one energy class level, there is a noticeable reduction in total heating energy required. In middle-sized and large schools, this reduction is 30–40%, and in small schools, up to 500 m<sup>2</sup>, greater savings were achieved, up to 45% (Figure 6). Energy class levels have been improved by one or even two levels, fulfilling the purpose of this level of improvement. The most recently built school (D3), as it meets the requirements of the current regulations, has not been improved at this level.



**Figure 6.** Energy class levels of school buildings by type and level of improvement.

The second level of improvement, where intervention has been done on both thermal envelope and HVAC and lighting systems, caused the total heating energy required to be reduced by 60%–70%, except in school D3, where no improvements were made (Figure 6). Energy class levels have been improved, achieving levels: C, D, and E.

After the third level of improvement, performing maximum interventions on the thermal envelope, and the HVAC system is improved by introducing air to water heat pumps, and with an improved lighting system, the total heating energy required was reduced by 70%–80%, compared to the current state. The only exception is school D3, where the reduction in total heating energy required is only 11% since the current state of the school was already at a satisfactory level and by the latest regulations (Figure 6). Energy class levels have also been improved and are mostly in level C, except for two buildings in level D and the newest school D3, which after the improvement is in level B.

### 3. Results

Results of the calculations of the total energy required for heating for representatives of the Serbian building stock of school buildings, for the present state, show that a great majority of schools are in a poor state in terms of their energy efficiency. At the same time, there is a large potential for improvement with building envelope, HVAC, and lighting systems. This research showed that even the first level of improvement, which tackles only the elements of the thermal envelope, cuts down the energy needed for heating by up to 45%, depending on the building type, which is about 330 GWh/a. After the second, more complex improvement level, dealing also with HVAC and lighting system improvements, energy needs were lowered by 60–70%, compared to the current state, which is about 612 GWh/a. The third improvement level, with the most ambitious interventions on the thermal envelope, HVAC, and lighting systems, cuts down current energy needs for heating by 70–80%, achieving annual savings of about 713 GWh/a.

However, these results should be interpreted as a resource in planning school building refurbishment, on both national and local levels, as well as an individual building level

in terms of possible refurbishment scenarios and savings that can be achieved. For the purpose of detail planning and decision making, especially on the level of a single building or smaller building stock (municipal), a more detailed analysis of improvement measures that are considered needs to be performed, taking into account not only energy savings that can be achieved, but also the needed investment and pay-back periods of each considered measure. These kinds of analyses were out of the scope of this research, but following the developed typology of school buildings, software for detailed calculation of refurbishment measures for school buildings and their economic implications were developed. Based on the collected data on school buildings' *Typology of School Buildings in Serbia*—software for the calculations was developed [28] to ensure that the decision-making process related to energy efficiency investments is based on transparent and understandable criteria that involve estimating investment costs and anticipated savings. The calculator for analyzing the application of EE measures at school facilities allows for a professional overview of proposed EE measures in school buildings that are optimized by the type of building, as well as financial aspects that include estimated costs and repayment periods.

#### 4. Conclusions

This research used a typology as a methodological tool for reviewing and classifying the total school buildings' stock in Serbia. In analyzing this type of public building, the total level of energy consumption in these buildings and possible energy savings due to their improvement were further investigated. Based on the survey of school buildings conducted to review their detailed performance, it was possible to implement cluster analysis and identify typical representations of buildings based on the characteristic construction periods and gross floor area. Based on the obtained data on each type of model building, real examples of school buildings were adopted, and further analysis of energy performance was performed. According to the analysis, and depending on their percentage in the total fund of school buildings, general energy consumption, and possible energy savings by the improvements were perceived for each representative type.

The main goal of this project was to ascertain the entire fund for school buildings, indicate the potential for energy savings of this type of public building at the national level, and use this as a starting point for developing strategic decisions and further energy efficiency policies. Furthermore, the data obtained by the survey represents a significant database that can be used for future research on school buildings, and their characteristics, in terms of building construction and potential and possible improvements, even outside the field of energy efficiency. The information summoned in this project could serve the local community as a tool for reviewing its fund of school buildings to realize the benefits achievable through the energy refurbishment of these types of buildings.

**Author Contributions:** Conceptualization, L.Đ.; Formal analysis, N.Ć.I. and N.L.; Investigation, N.Ć.I.; Methodology, D.I. and N.Ć.I.; Project administration, D.I.; Software, A.R.; Supervision, D.I.; Validation, A.R.; Writing—original draft, L.Đ.; Writing—review & editing, N.L. and B.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors would like to thank the GIZ organization and project Energy Efficiency in Buildings in Serbia, for their continuous support of the research of the Serbian building stock energy performance. Additionally, this paper is a part of the research funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia, under grant number 451-03-68/2020-14/200090. The research is done under research labs of the University of Belgrade Faculty of Architecture: building stock laboratory, SaRA (Sustainable and Resilient Architecture), the Innovation laboratory of sustainable development, and the laboratory for simulation of building energy performance.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

$Q_{H,nd}$	annual energy need for heating [kWh/m <sup>2</sup> ]
$Q_{H,nd,rel}$	percentual relation of building's actual annual energy need for heating ( $Q_{H,nd}$ ) and the maximal allowed value of annual energy need for heating
U <sub>max</sub>	maximal allowed value of thermal transmittance for thermal envelope components
$h_{H,gn}$	dimensionless gain utilization factor for heating
A1, A2, B1, B2, B3, C1, C2, C3, D3	school building types
A2 <sub>ST</sub> , A3 <sub>ST</sub> , C3 <sub>ST</sub>	sub-types of primary school building type

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