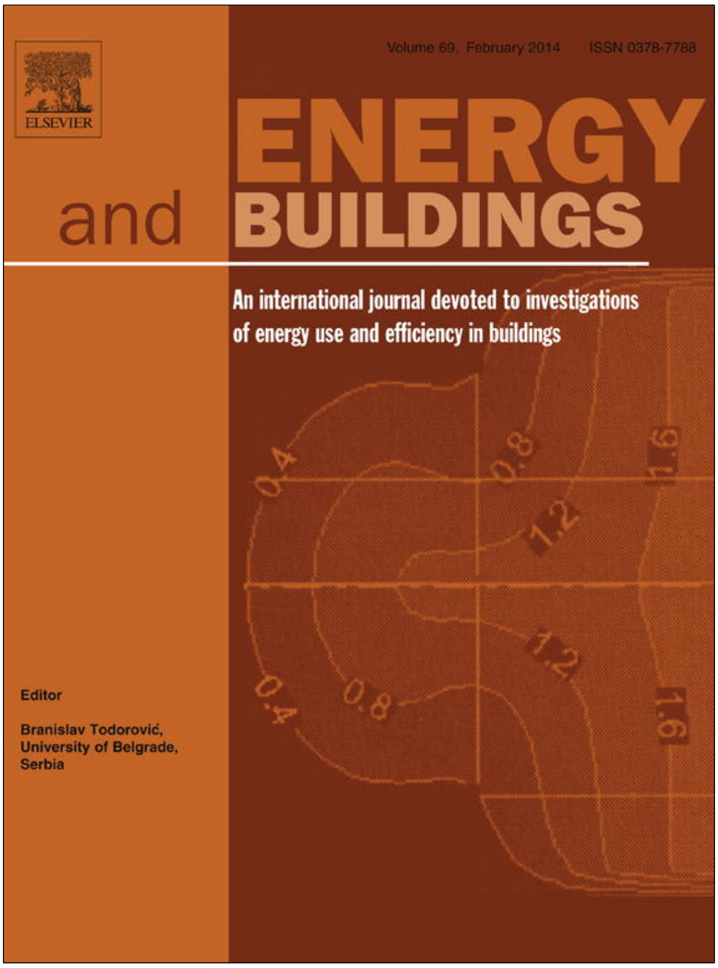
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Assessing the sustainability of the energy use of residential buildings in Belgrade through multi-criteria analysis

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ABSTRACT

The paper presents a method for selecting and calculation indicators of sustainable development, needed for determining the level of sustainable development, expressed through sustainability index of residential buildings. It is important to verify procedure for determining economic, social and environmental sub-indicators based on consumption of final energy (used to meet space heating, hot water generation and household cooking needs, as well as for operation of various household electrical appliances, indoor temperature and humidity). It was done for representative sample of Belgrade buildings stock. Different dwelling types constructed in two different periods and heated by electricity, district heating and fossil fuels were analysed. Multi-criteria analysis was used to evaluate residential buildings sustainability. The results showed that the best building options, constructed in the period 1981–2006, are: the apartment buildings and single family houses (electricity for space heating) when economy indicator has priority; the apartments connected to the district heating system when environmental indicator has priority; and single family houses connected to the district heating system when social indicator has priority. Implementation of proposed methodology is beneficial when evaluating and comparing sustainability of different residential buildings, enabling decision makers to more easily reach decisions on the issues related to energy policy and environmental protection.

1. Introduction

Modern energy systems exhibit features that are characteristic of unsustainable development: increased use of fossil fuels, increased energy consumption and significant emissions of environmental pollutants. Cities consumed about two-thirds of global energy consumption and 71% energy-related greenhouse gas emissions are attributed to energy use in urban areas [1,2]. The share of the final energy consumption by household and service sector is 27% and 13%, respectively in the total EU countries energy consumption [3]. The residential and commercial buildings account for more than half of the energy consumed in cities, where a large fraction of energy is utilised to meet lighting, cooking, heating, cooling and other human needs [4]. Recognizing this problem, the World Commission on Environment and Development has established a new method of measuring the progress of sustainability and defining sustainable energy systems [5]. Sustainable forms of energy production, distribution and use represent key goals of sustainable urban development and the essence of the Habitat II action plan [6]. A sustainable development strategy is perceived as a plan that promotes a balance between environmental, economic, social and institutional goals of the society. The most important issue in this strategy is proper sustainability measurement, which includes assessment, reporting and rating of energy system sustainability using standardized energy indicators of sustainable development (EISD) [7,8].

Numerous previous research investigations have examined building sustainability assessment methods based on quantitative and qualitative criteria (indicators). Kim and Todorovic presented review of sustainability criteria and indicators related to buildings. An illustration of practical procedure of screening selection of energy, ambient – outdoor environment, indoor environment and social indicator and sub-indicators determination for a residential buildings is given [9].

Several studies deal with sustainability assessment of different energy systems in buildings. Two studies present energy and exergy analyses and sustainability assessment of HVAC [10] and air cooling systems [11] for building applications. Sustainability assessments of the systems are conducted using a sustainability index method, related to exergy efficiency.

The following study described the differences in energy consumption and environmental impacts for two residential dwellings

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Nomenclature

ASPID	analysis and synthesis of parameters under information deficiency
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
EISD	energy indicator of sustainable development
EcI_{ec}	economic sub-indicator of electricity consumption
EcI_{tc}	economic sub-indicator of heat consumed for space-heating
EcI_{hwc}	economic sub-indicator of hot water consumption
EcI_{ecc}	economic sub-indicator of electricity consumed to meet household cooking needs
EnI_{at}	environmental sub-indicator of air temperature
EnI_{rh}	environmental sub-indicator of relative humidity
EnI_{CO_2}	environmental sub-indicator of CO_2 concentration
GHG	greenhouse gases
HVAC	heating, ventilating and air conditioning system
ISD	indicators of sustainable development
IS	index of sustainability
LCA	life cycle assessment
SD	standard deviation
SoI_{ls}	social sub-indicator of living space area per person
SoI_{ac}	social sub-indicator of air-conditioning use
SoI_{dw}	social sub-indicator of dishwasher use
SoI_{ic}	social sub-indicator of indoor comfort

located in Spain and Colombia. The assessment of the environmental impacts and final energy use needed for heating, ventilating, air conditioning (HVAC), domestic hot water, electrical appliances, cooking and illumination was performed using a life cycle assessment (LCA) [12]. Malmqvist and Glaumann [13] described methods for developing environmental performance indicators in energy management practice in the building sector. The results obtained in the analysis indicated that proposed energy use indicators, representative of four different impact categories, are suitable to be used in sustainability assessment. Study, made by Mwasha et al. [14], has shown that sustainable energy performance indicators are important in the model formation of the sustainable performance of residential building envelope and reduce building energy consumption. The following sustainable energy performance indicators were suggested for building envelope sustainable performance assessment: energy efficiency, environmental impact, affordability, social benefit, material efficiency and durability.

Different dimensions of sustainability were analysed in the methodology presented by Mateus and Braganca [15], with the goal of assessing the sustainability of residential buildings through various levels of indicator systems. The recommendations to enhance the sustainability level within the Saudi residential sector are demonstrated in the paper by Hanan and Sharples [16]. Next paper presents a multi-criteria decision-making model for energy efficiency, rating of intelligent buildings. The decision-making is developed using an analytic network process method and a set of lifespan performance indicators for intelligent buildings, selected by a new quantitative approach, called energy–time consumption index as a general approach to selecting indicators under the criteria of building sustainability [17]. Dall'O' [18] presented methodology for the energy performance ranking of residential buildings in urban area, important for sustainable energy planning strategies that accelerate the energy renovation process in existing buildings that are not energy efficient.

This paper presents an assessment of the sustainability of the energy use of building options in Belgrade city using ISD and a method of multi-criteria analysis. Investigated options in the process of sustainability calculation were formed by qualitative building characterisation based on the type of buildings, heating system and construction period in question. The method of stratified sampling was used in the selection process of objects that show the overall housing stock in the city of Belgrade. Different types of residential buildings (apartments and single-family houses) have been analysed. The considered building types were analysed with respect to criteria selection, the definition of sustainable goals, the selection of appropriate indicators (seen as a measure of adopted sustainability criteria), and the calculation of ISD through the final set of sub-indicators that provide essential information on building sector sustainability. In this paper, the general index of sustainability (IS) is calculated on the basis of a limited number of factors that take into account social, economic and environmental aspects.

2. Sustainable development and definition of ISD as a tool for sustainability assessment in the residential building sector

A building energy system produces, uses, converts and stores energy needed for building operation. The different forms of sustainable development of the residential building sector are primarily based on improving environmental and energy use of the building stock [19,20].

Indicators can provide essential information about sustainability of each energy subsystem in the frame of the complex energy system in the residential building sector. ISD represent a useful planning tool for determining different policy objectives and priorities. A properly defined set of ISD contribute to a better understanding of the different dimensions and aspects of sustainable development (economic, environmental, social, technological and political) and the complex mutual relations between the aspects [21,22]. However, neither one of the indicator sets is deemed final, because they can all be adapted and modified in accordance with new findings, scientific developments, political interests and the availability of basic data [23].

To achieve sustainable development goals, this paper presents EISD, which are classified under several categories, including economic, social and environmental categories. EISD show a measure of the criteria (categories) in the process of sustainability assessment.

Energy should be used in a manner that will not harmfully affect human health but will act positively through improved living conditions. When considering the economic aspect of sustainability, this paper illustrates the final energy use in the residential building sector, as an indicator of energy consumption. Increasing production and consumption of electricity and thermal energy from fossil fuels lead to environmental pollution (global warming and ozone depletion effects) and depletion of fossil energy resources. In decision making processes, deciding based on a single criterion (least cost energy supply) is not acceptable because sets of priorities, such as ecology requirements, energy use, and needed energy must be taken into consideration. From the economic aspect of building energy system sustainability, this paper defines EISD as the total electricity consumption per household, the electricity consumption for space-heating, hot water consumption and the electricity consumed to meet household cooking needs.

The social aspect of building energy system sustainability considers the required level of life conditions at reduced energy consumption. Using less energy is a requirement for an impact on climate change and reduces energy costs. Recently, the greatly increasing energy consumption of electrical appliances in households is evident. The number of air-condition units (due to longer and warmer summers) and dishwashers (an increase standard of living) in households increased in the city of Belgrade. The social aspect of building energy system sustainability could be defined through indicators that illustrate the living space area per person, the share of buildings where air-conditioning and dishwashers are used, and the share of households that are satisfied with indoor comfort [24].

A set of environmental indicators in the residential building sector is introduced to establish a connection between the energy consumed by the residential sector and the associated environmental impact, including all positive and negative effects resulting from different economic and political impacts. Additionally, a set of environmental indicators could illustrate the influence of environmental changes on the activities carried out in the residential sector. The impact of the indoor environment refers to the risks to which people in the building are exposed due to particular external conditions in the surroundings. These factors illustrate controllable environmental conditions that affect people living in the building, i.e., they describe the indoor climate. This paper presents parameters which are illustrative of indoor conditions as environmental indicators. The following sets of indicators were analysed: air temperature, humidity and concentration of CO_2 in the living room [25,26].

3. The selected target groups (buildings options) that represent the overall housing stock in the city of Belgrade

Modern cities are places where a significant amount of energy is both produced and consumed. Because this energy is produced through the utilisation of global energy resources, sustainability at the local level cannot be analysed separately from global sustainability. An increased standard of living has resulted in a significant increase in the energy demand of the urban residential and public sectors. Energy consumption in the considered sectors would increase further in the near future, especially with respect to the increased consumption of final energy used to satisfy the growing needs for space heating, air conditioning and refrigeration. Energy consumed in households is assumed to have a considerable impact on urban flow and this present's key element in considering the sustainability of complex urban systems [23,25]. Buildings represent the largest single energy consumer and a significant source of greenhouse gas emissions, especially CO_2.

The analysed building options represent different groups of residential buildings. Selected dwellings are located in the city of Belgrade, which occupies more than 3.6% of Serbian territory and has nearly 580,000 households and 1,700,000 inhabitants [27]. Belgrade is under the influence of the moderate continental climate with long cold winters which dictate the outdoor design temperature of −12.1 °C. The characteristics of the other seasons are hot summers, the short springs and the longer autumns. The coldest month is January and the warmest month is July. The mean annual air temperature in Belgrade is 11.9 °C. Much of Belgrade's building stock was built during the 1980s, when residential and office buildings were built without proper thermal insulation. In addition, fenestration systems installed in the considered buildings are in poor condition today. Therefore, large amounts of energy are needed to meet the space heating demand of residential and office buildings (200 kWh/m^2 in Serbia in contrast to 100 kWh/m^2 in Europe and 50 kWh/m^2 in Germany) [28,29].

Because Belgrade's citizen's account for 21% of the Serbian population, Belgrade's urban energy system has a complex structure and represents the largest national consumer of final energy. For example, 44% of all dwellings are connected to district heating systems, using the supplied heat for office space heating (4,300,000 m^2) and living space heating (16,200,000 m^2).An increasing environmental impact occurs as a result of constantly increasing energy generation and consumption. CO_{2eq} emissions originating from different

Table 1
Building options addressed in the analysis.

Building option			
Options	Type of buildings/ objects	Construction period	Space heating mode
I	Apartments	1946–1980	Electricity
II	Apartments	1946–1980	District heating
III	Apartments	1981–2006	Electricity
IV	Apartments	1981–2006	District heating
V	Single family house	1946–1980	Electricity
VI	Single family house	1946–1980	Fossil fuels
VII	Single family house	1981–2006	Electricity
VIII	Single family house	1981–2006	District heating
IX	Single family house	1981–2006	Fossil fuels

energy consuming sectors, as well as total CO_{2eq} emissions in the residential building sector resulting from the use of various fossil fuels, are presented in Fig. 1, based on 2006 data. However, more than 45% of the overall CO_{2eq} emissions discharged in 2006 were attributed to the residential and public sector [30]. According to the official data for Belgrade city, a precise consumption of different types of fossil fuels by sectors, as well as a GHG inventory, was calculated for 2006. Due to obligations under the Kyoto Protocol (non-Annex I country), it is assumed that the current values of CO_{2eq} slightly decrease compared to the CO_{2eq} values shown in Fig. 1.

To define the ISD and sustainability of different residential buildings using the multi-criteria analysis based on the economic, social and environmental sustainability aspects, the target group was determined. The target group serves as a basis for the analysis and identification of representative samples of buildings. The selected target group represented the overall housing stock in the city of Belgrade. The method of stratified sampling was used to determine the representative building sample. Qualitative characterization of the buildings (herein-after referred to as objects) was performed based on the building construction period, heating system and type of buildings in question. The total number of objects is sufficient to comprise a representative sample equal to 96 [31,32]. The analysis presented herein was carried out on a sample of 82 objects only, primarily due to the lack of information and difficulty in characterizing certain objects into defined building option groups.

Based on the results of the qualitative building characterisation, the representative sample was divided into nine sub-groups (I to IX options), as presented in Table 1. The adopted options included apartment buildings and single-family houses. Depending on the construction period, the buildings were split into two groups: those constructed in the period 1946–1980 and those constructed in the period 1981–2006. With respect to the space heating installation of the considered residential buildings, the following three options were analysed: district heating, combustion of fossil fuels and use of electricity for space-heating purposes.

4. Definition and calculation of ISD for various types of residential buildings in Belgrade

Following the selection of both representative types of residential buildings and energy indicators of sustainable development in Sections 2 and 3, the EISD were defined and calculated. Tables 2–4 show the basic sets of economic, social and environmental sub-indicators that are calculated based on the parameters obtained during the measurements and collected questionnaires (filled out by household members) [32].

As presented in Table 2, the following economic sub-indicators were taken into account: (a) Economic sub-indicators illustrative of electricity consumption (EcI_{ec}), obtained when the total electricity consumed by all of the objects representative of all building options was divided by the total number of objects; (b) Economic

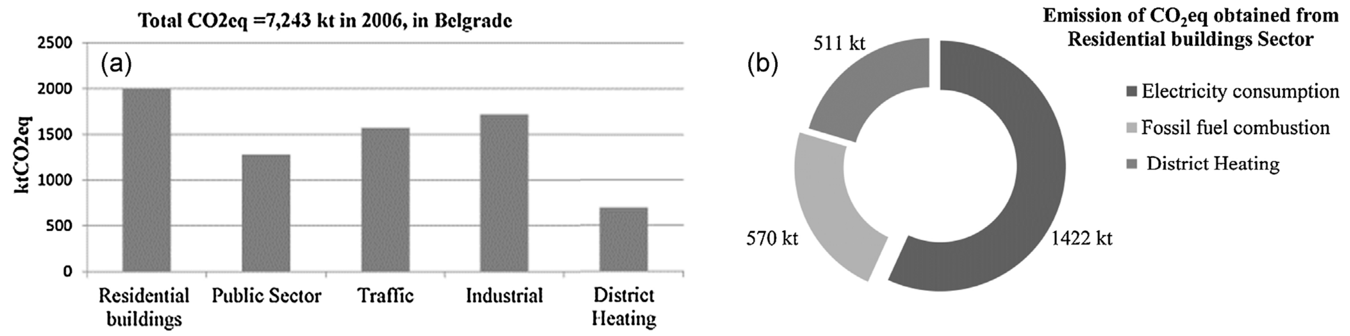

Fig. 1. (a and b) CO_{2eq} emissions originating from different energy consuming sectors in the city of Belgrade and emissions resulting from the use of various fossil fuels in residential building sector.

Table 2
Selected economic sub-indicators.

Energy indicators of sustainable development – economic sub-indicators			
Indicator	Name	Definition	Units
EcI_{ec}	Economic sub-indicators illustrative of electricity consumption	Total annual electricity consumption of the objects divided by the total number of objects	kWh/h/a
EcI_{tc}	Economic sub-indicators illustrative of heat consumed for space-heating	Total annual heat consumption of the objects divided by the total heated area	kWht/m^2/a
EcI_{hwc}	Economic sub-indicators illustrative of hot water consumption	Estimated consumption of hot water per person living in the household	m^3/person/a
EcI_{ecc}	Economic sub-indicators illustrative of electricity consumed to meet household cooking needs	Average specific annual consumption of electricity used to meet household cooking needs	kWh/h/a

Table 3
Selected social sub-indicators.

Energy indicators of sustainable development – social sub-indicators			
Indicator	Name	Definition	Units
SoI_{ls}	Social sub-indicators illustrative of living space area per person	Total area of a building divided by the total number of household members	m^2/person
SoI_{ac}	Social sub-indicators illustrative of air-conditioning use	Share of buildings where air-conditioning is used	(%)
SoI_{dw}	Social sub-indicators illustrative of dishwasher use	Share of buildings where dishwashers are used	(%)
SoI_{ic}	Social sub-indicators illustrative of indoor comfort	Share of households that are satisfied with indoor comfort	(%)

sub-indicators illustrative of heat consumed for space heating (EcI_{tc}), obtained when total annual amount of heat consumed by the objects was divided by the total heated area; (c) Economic sub-indicators illustrative of hot water consumption (EcI_{hwc}), taken as estimated values determined from the collected questionnaires; in the case of washing and dishwashing machines, the age of the machines and the number of cycles performed per week were taken into account; in addition, the consumption of hot water generated in household water heaters was estimated based on the electricity consumption data and was indicative of household water heating electricity use; (d) Economic sub-indicators illustrative of electricity used to meet household cooking needs (EcI_{ecc}), taken as estimated values determined from the collected questionnaires (type of stoves, how much time is used for cooking daily).

The following social sub-indicators, presented in Table 3, were taken into account: (a) Social sub-indicator illustrative of the living space area per person (SoI_{ls}), obtained when the total area of a building is divided by the overall number of household' members; This sub-indicator represents an average value for all objects included in one option; (b) Social sub-indicators illustrative of air-conditioning use (SoI_{ac}), representing the share of buildings using air-conditioning units; (c) Social sub-indicators illustrative of dishwasher use (SoI_{dw}), representing the share of buildings where dishwashers are used; (d) Social sub-indicators illustrative of indoor comfort (SoI_{ic}), estimated based on the collected questionnaires; Qualitative data were based on the indoor air quality, as estimated by household members, with obtained values representing the share of the optimal amount of fresh air as opposed to having little fresh air.

The following environmental sub-indicators, presented in Table 4, were taken into account: (a) Environmental sub-indicator illustrative of air temperature (EnI_{at}), representing the average

Table 4
Selected environmental sub-indicators.

Energy indicators of sustainable development – environmental			
Indicator	Name	Definition	Units
EnI_{at}	Environmental sub-indicator illustrative of air temperature	Average daily air temperature in the living room	°C
EnI_{rh}	Environmental sub-indicator illustrative of relative humidity	Average daily relative humidity in the living room	%
EnI_{CO_2}	Environmental sub-indicator illustrative of CO_2 concentration	Average daily concentration of CO_2 in the living room during the winter period	ppm

Table 5
Numerical values of selected sub-indicators.

Indicator	Ec				So				En		
Sub indicator Units	EcI_{ec} kWh/h/a	EcI_{tc} kWh/m^2/a	EcI_{hwc} m$^{3/}$person/a	EcI_{ecc} kWh/h/a	SoI_{ls} m^2/person	SoI_{ac} %	SoI_{dw} %	SoI_{ic} %	EnI_{at} °C	EnI_{rh} %	EnI_{CO_2} ppm
Option I	9318	102	11.3	396	15.4	53	75	75	22.0	50	1156
Option II	7271	132	16.8	768	22.3	40	70	78	22.7	41	901
Option III	6840	90	15.5	484	16.3	100	67	100	22.6	48	1556
Option IV	7199	119	16.4	728	22.8	57	45	73	22.9	45	739
Option V	12,293	160	18.9	533	23.9	18	50	75	20.8	54	462
Option VI	6822	179	13.0	376	26.0	36	36	64	21.5	43	1369
Option VII	10,118	99	11.9	432	27.1	47	25	50	21.6	51	772
Option VIII	10,518	133	17.4	528	28.3	41	100	80	22.0	40	902
Option IX	8154	190	15.5	435	26.6	30	44	33	21.7	52	1437

daily air temperature in the living room ; as determined from the measurements carried out during a period of one year in all buildings examined (apartment buildings and individual houses); (b) Environmental sub-indicator illustrative of relative humidity, indicating the average daily relative humidity in the living room (EnI_{rh}); (c) Environmental sub-indicator illustrative of CO_2 concentration (EnI_{CO_2}), presenting the average daily CO_2 concentration in the living room during the winter period.

Numerical values of the above described indicators and sub-indicators, used to analyse the quality of the examined building options, represented the input values loaded into the model utilised to calculate IS, Table 5.

The ISD are not quite suitable to be used as they are, because they are characterised by different units and range intervals. It is assumed that all of the specific criteria are normalised without a loss in generality. Normalisation of the specific criteria is done on the basis of the values of the sub-indicators. For each option $x(j) \in X$, quality estimation is performed by many criteria $q_i(j) = (q_1(j), \ldots, q_m(j))$, $0 \le q_i(j) \le 1$, that can be treated as a vector-criterion $q = (q_1, \ldots, q_m)$. This level means defining of monotonous of each normalised function type $q^j(x^j)$ (decreasing or increasing function).

The specific criteria are described by a power law function. If the value of q^j increases when the value of the indicator x^j increases, than the function $q^j(x^j)$ is defined by Eq. (1a) (for i = const, $j = 1, \ldots, k = 9$). However, the function $q^j(x^j)$is defined by Eq. (1b) if the value of q^j decreases when the value of argument x^j increases (for i = const, $j = 1, \ldots, k = 9$). MIN and MAX are used to indicate the upper and lower bounds of a given indicator.

$$q^j = \left\{ \begin{array}{ll} 0, & x^j \le \text{MIN} \\ \left(\dfrac{x^j - \text{MIN}}{\text{MAX} - \text{MIN}} \right)^{\Theta}, & \text{MIN} \le x^j \le \text{MAX} \\ 1, & x^j \ge \text{MAX} \end{array} \right\}_{j=1,k} \tag{1a}$$

$$q^j = \left\{ \begin{array}{ll} 1, & x^j \le \text{MIN} \\ \left(\dfrac{\text{MAX} - x^j}{\text{MAX} - \text{MIN}} \right)^{\Theta}, & \text{MIN} \le x^j \le \text{MAX} \\ 0, & x^j \ge \text{MAX} \end{array} \right\}_{j=1,k} \tag{1b}$$

In the practice the most popular normalised function is a linear function. As such, in this paper the following normalised function $q^j(x^j;\Theta)$, $\Theta = 1$ is adopted. In this way, normalised values of indicators are obtained by the linear normalisation. The set of numerical values for each sub-indicator for all considered options, is converted into a fuzzy set of normalised indicators, as presented in Table 6. After the normalisation process, the minimum value $q^j = 0$ indicates that the estimated 'j'-th option has a minimal preference from the 'i'-th specific criterion point of view. The maximum value $q_i(j) = 1$ indicates that the estimated 'j'-th option has a maximal preference from the 'i'-th specific criterion point of view.

4.1. Interrelation between the chosen sub-indicators

After selection of the EISD, independent criteria were chosen with the aim to eliminate their mutual correlation. The interrelation between criteria (selected indicators) was performed by correlation analysis. This method includes calculation of the correlation coefficient between the criteria M_i and criteria the M_j by the following equation.

$$r_{ij} = \frac{cov(M_i, M_j)}{\delta_{Mi}\delta_{Mj}} \tag{2}$$

where cov (M_i, M_j) is the covariance of M_i and M_j; and δ_{Mi} and δ_{Mj} represent the standard deviation of M_i and M_j respectively.

The correlation coefficient includes the influence of other criteria that are not constant. To accurately establish the mutual relation

Table 6
Normalised sub-indicator values.

Indicator	Ec				So				En		
Subindicator	EcI_{ec}	EcI_{tc}	EcI_{hwc}	EcI_{ecc}	SoI_{ls}	SoI_{ac}	SoI_{dw}	SoI_{ic}	EnI_{at}	EnI_{rh}	EnI_{CO_2}
Option I	0.153	0.923	0.100	0.000	0.000	0.640	0.916	0.645	0.518	0.197	0.322
Option II	0.813	0.583	0.234	0.021	0.398	0.342	0.801	0.728	1.000	1.000	0.690
Option III	0.740	1.000	0.476	0.000	0.000	1.000	0.732	1.000	0.992	0.407	0.000
Option IV	0.862	0.654	0.422	0.277	0.455	0.732	0.227	0.589	1.000	0.721	0.924
Option V	0.000	0.371	0.000	0.417	0.582	0.000	0.342	0.645	0.000	0.000	1.000
Option VI	0.982	0.000	1.000	1.000	0.823	0.250	0.020	0.340	0.122	0.931	0.014
Option VII	0.429	0.994	1.000	1.000	0.949	0.502	0.000	0.000	0.201	0.092	0.876
Option VIII	0.040	0.399	0.288	0.605	1.000	0.365	1.000	0.783	0.518	1.000	0.689
Option IX	1.000	0.000	1.000	1.000	0.892	0.113	0.204	0.000	0.280	0.000	0.000

Table 7
Correlations between economic sub-indicators.

	EcI_{ec}	EcI_{tc}	EcI_{hwc}	EcI_{ecc}
EcI_{ec}	−1			
EcI_{tc}	−0.289	−1		
EcI_{hwc}	0.523	−0.549	−1	
EcI_{ecc}	−0.507	−0.500	0.771	−1

Table 8
Correlations between social sub-indicators.

	SoI_{lc}	SoI_{ac}	SoI_{dw}	SoI_{ic}
SoI_{lc}	−1			
SoI_{ac}	−0.436	−1		
SoI_{dw}	0.025	−0.206	−1	
SoI_{ic}	−0.298	0.385	0.585	−1

Table 9
Correlations between environmental sub-indicators.

	EnI_{at}	EnI_{rh}	EnI_{CO_2}
EnI_{at}	−1		
EnI_{rh}	0.563	−1	
EnI_{CO_2}	−0.071	0.688	−1

of two criteria, the partial correlation coefficients are determined by Eq. (3).

$$\xi_{ij} = \frac{-r^*_{ij}}{\sqrt{r^*_{ii} r^*_{jj}}} \tag{3}$$

$$r^*_{ij} = (-1)^{i+j} \Delta_{ij} \tag{4}$$

where r^*_{ij}, r^*_{ii} and r^*_{jj} show the algebraic complement (cofactors) of the r^*_{ij}, r^*_{ii} and r^*_{jj} elements; Δ is the determinant of the matrix r_{ij}. When increasing the value of ξ_{ij} the correlation between two criteria is higher. In case of $\xi_{ij} = 1$, criteria M_i is completely connected with criteria M_j and one of them should be removed.

Each element of the symmetric matrices presented in Tables 7–9 and shows the mutual relation of the criteria M_i and M_j, as well as M_j and M_i, in the groups of economic, social and environmental sub-indicators. After applying this method investigate the relations between sub-indicators (from Table 5), the following results are obtained.

A correlation coefficient between 0.5 and 0.7 indicates a moderate correlation for almost all relations between the economic sub-indicators, besides the correlation coefficient of −0.289 as a low correlation between EcI_{ec} and EcI_{tc} and the correlation coefficient of 0.771 as a high correlation between EcI_{twc} and EcI_{ecc}. All correlations indicate a low and moderate correlation between the social and environmental criteria [33]. None of the analysed sub-indicators is not rejected because mutual correlation between the sub-indicators does not show a strong dependence ($\xi_{ij} = 0.8–1$).

4.2. Aggregation of indicators and weight coefficients used in the sustainability evaluation

The methods of the multi-criteria analysis are used in the methodology which applies in the planning of sustainable development of complex energy systems. The differences in the characteristics of complex energy systems point to the need for the development and improvement of the methods and procedures for assessing the sustainability of these systems. The common characteristics of the area where these methods applies have a high degree of uncertainty in determining the problem, immeasurable units and the need to introduce the socio-economic aspects in the planning of the energy systems. In this study the ASPID (analysis and synthesis of parameters under information deficiency) multi-criteria method was used.

This method presents a combination of the influence all of the criteria which were taken into consideration and final result was expressed in the form of the index of sustainability (IS). The index of sustainability is calculated from the normalised values of the sub-indicators and using the linear agglomerate function at pre-defined constraints (non-numerical information) which define apriority of indicator (economic, social or environmental). Finish the last level of aggregation Eq. (7), using the method of multi-criteria analyses, is getting the IS, which shows a measure of the validity or viability, or quality of the investigated options over the economic, social and environmental aspect. In this way, the mathematical and graphical synthesis of all the indicators was made in one complex index (IS). The accuracy in determining the mean of the IS was checked by calculating the standard deviation [34–37].

The importance of specific criteria (indicator) is illustrated through a respective weight coefficient, meaning that the quality assessment of the considered building options depends on the priority status given to individual weight coefficients before the overall evaluation is carried out. By changing the value of w_i, the influence of a specific criterion on IS is altered. Thus, w_i is proportional to the importance of the respective criteria evaluated by each indicator.

To be able to determine the impact of specific criteria, weights coefficients or the weight of specific criteria were introduced. In the process of determining the weight coefficients ($0 \le w_i \le 1$, for each $i = 1, \ldots, m$), it was assumed that $w_1 + w_2 + \ldots + w_i = 1$. The weight coefficients were measured with an inter-step accuracy of $h = 1/n$ (where $n = 100$ in the analysis presented herein). In this paper, the number of elements in the set of weight coefficients $N(n,m)$ is calculated in accordance with the following expression:

$$N(m,n) = \frac{(n+m-1)!}{n!(m-1)!} = \frac{(100+4-1)!}{100!(4-1)!} = 176851 \tag{5}$$

where n is a number of scales obtained when the segment from 0 to 1 is divided and m is a number of sub-indicators (criteria).

Boundaries within the values of the weight coefficients established in this manner enable the discrete nature of weighting

Table 10a
The values of the weight coefficients and the standard deviation at the first level of economic and social sub-indicators aggregation.

Conditions	Weight coefficients				Standard deviation			
	EcI_{tc}	EcI_{ec}	EcI_{hwc}	EcI_{ecc}	EcI_{tc}	EcI_{ec}	EcI_{hwc}	EcI_{ecc}
1. $EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$ 2. $SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$	0.53	0.27	0.14	0.06	0.129	0.080	0.066	0.045
1. $EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$ 2. $SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$	0.53	0.27	0.14	0.06	0.129	0.080	0.066	0.045
1. $EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$ 2. $SoI_{ic} > SoI_{dw} = SoI_{ls} = SoI_{ac}$	0.64	0.12	0.12	0.12	0.221	0.074	0.074	0.074
1. $EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$ 2. $SoI_{ls} > SoI_{ac} = SoI_{dw} = SoI_{ic}$	0.64	0.12	0.12	0.12	0.221	0.074	0.074	0.074

Table 10b
The values of the weight coefficients and the standard deviation at the first level of environmental sub-indicators aggregation.

Conditions	Weight coefficients			Standard deviation		
	EnI_{at}	EnI_{rh}	EnI_{CO_2}	EnI_{at}	EnI_{rh}	EnI_{CO_2}
$EnI_{at} > EnI_{CO_2} > EnI_{rh}$	0.616	0.278	0.106	0.142	0.104	0.079
$EnI_{at} > EnI_{CO_2} > EnI_{rh}$	0.616	0.106	0.278	0.142	0.104	0.079
$EnI_{CO_2} > EnI_{at} = EnI_{rh}$	0.165	0.165	0.670	0.098	0.098	0.196
$EnI_{rh} > EnI_{at} = EnI_{CO_2}$	0.165	0.670	0.165	0.098	0.098	0.196

Table 11
The values of the weight coefficients and the standard deviations at predefined constraints.

Constraints	Weight coefficients			Standard deviation		
	Ec	So	En	Ec	So	En
Ec > So > En	0.616	0.278	0.106	0.142	0.104	0.079
Ec > En > So	0.616	0.106	0.278	0.142	0.104	0.079
En > Ec = So	0.165	0.165	0.670	0.098	0.098	0.196
So > En = Ec	0.165	0.670	0.165	0.098	0.196	0.098

and the process of w_i normalisation to be taken into account. A finite set of weights were chosen from the set of all weight coefficients $W(m, n) = \{w = (w_1, w_2, \ldots, w_m)\}$, with the elements obtained from the set $\{0, 1/n, 2/n, \ldots 1, w_1^{(t)}, \ldots + w_m^{(t)}\}$, where $w_1^{(t)} + w_2^{(t)} + \cdots + w_m^{(t)} = 1$.

To be able to obtain an average value of the weight coefficients, non-numerical information (conditions) was introduced. Broadly accepted as the most suitable approach, non-numeric information was introduced when one of the sub-indicators was given priority, while other sub-indicators retained same weight coefficient values [38]. According to the defined conditions, subsets of w_i were formed that meet the defined conditions (non-numerical information). In Tables 10a and 10b, the values of the weight coefficients and the standard deviation which are obtained at predefined conditions when one of the sub-indicators has priority are shown. They were used in the first level of aggregation of the economic, social and environmental sub-indicators.

In this manner, all of the possible weight coefficients meeting the established conditions were defined. According to the constraints of the non-numerical (ordinal) and inexact (interval) information, a new set of weight coefficients, representing all combinations of w_i that meet the defined constraints, was obtained and further processed through the calculation of $W(I, m, n)$. Table 11 presents the values of the weight coefficients and their standard deviations at predefined constraints. In the process of the second level of aggregation priority is given to one of the indicators.

The weights indicate partial contribution of sub-indicators to criteria (economic, social and environmental indicator) at first level of agglomeration and partial contribution of indicators to IS of each option at second level of agglomeration.

The agglomerated values of the indicators are obtained at the first aggregation level, by multiplying the normalised values of the sub-indicators with the average values of the weigh coefficients, in accordance with the following expression:

$$Q_{agi}(q; w) = \sum_{i=1}^{m} w_i q_i = Q(q_1, q_2, \ldots, q_m; w_1, w_2, \ldots, w_m) = Q(q) \quad (6)$$

where w_i is an average value of the weight coefficient under defined condition at the first aggregation level (Tables 10a and 10b) and q_i is the normalised indicator value (Table 6).

A criteria-based estimation of the options was performed at the second aggregation level through an additive synthesis function, as follows:

$$IS(q; I) = \frac{1}{N(I; m, n)} \sum_{s=1}^{N(I;m,n)} Q(q; w) \quad (7)$$

where $N(I,m,n) \leq N(m,n)$ represents the number of vectors of the $W(I,m,n)$ set that meet the defined conditions.

5. Analysis of building sustainability based on the use of the ASPID method of multi-criteria analysis: Belgrade case study

The methods used to assess the sustainability of the residential building sector in Belgrade have been mainly based on local standards and regulations and local conventional building solutions. The paper presents a calculation that takes into account the aggregation of indicators representative of all levels preceding the final sustainability evaluation level. The multi-criteria analysis is used to facilitate the integration of multi-dimensional indicators in the index of sustainability (IS).

The work presented in this study is based on the use of ASPID multi-criteria analysis, which was utilised to assess the sustainability of nine selected building options in Belgrade's residential building sector [36,39–42]. The method enabled the ranking of the examined building options and the assembling of building option priority list determined based on economic, social and environmental criteria.

The utilised ASPID method is based on a stochastic model of weight coefficient uncertainty, leading to the randomization of weight coefficients and thus to the general IS [36]. The method is used for criteria analysis and synthesis, enabling options to be evaluated in terms of lacking information and the influence of individual indicators. When, under pre-defined constrain, priority is given to one of the indicators (criteria), it is possible to perform a ranking of the building options and obtain a related priority list of the analysed options.

A sustainability analysis of the options was performed for four different cases. Each case was representative of different indicator constraints and sub-indicator priorities, as shown in Table 12.

Fig. 2 shows Case no. 1 where priority was given to the economic indicator (weight coefficient of $w = 0.616$ and standard deviation of $SD = 0.142$) over the social indicator ($w = 0.278$, $SD = 0.104$) and the environmental indicator ($w = 0.106$, $SD = 0.079$). In the process of sub-indicator agglomeration, based on the pre-defined conditions, the following sub-indicators were given priority: the average specific annual heat consumption for space heating (EcI_{tc}); living space

Table 12
Different cases considered in the sustainability analysis performed.

Case no.	Condition 1	Condition 2	Condition 3	Constraint
Case no. 1	$EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$	$SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$	$EnI_{at} > EnI_{CO_2} > EnI_{rh}$	Ec > So > En
Case no. 2	$EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$	$SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$	$EnI_{at} > EnI_{CO_2} > EnI_{rh}$	Ec > En > So
Case no. 3	$EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$	$SoI_{ic} > SoI_{dw} = SoI_{ls} = SoI_{ac}$	$EnI_{CO_2} > EnI_{at} = EnI_{rh}$	En > Ec = So
Case no. 4	$EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$	$SoI_{ls} > SoI_{ac} = SoI_{dw} = SoI_{ic}$	$EnI_{rh} > EnI_{at} = EnI_{CO_2}$	So > En = Ec

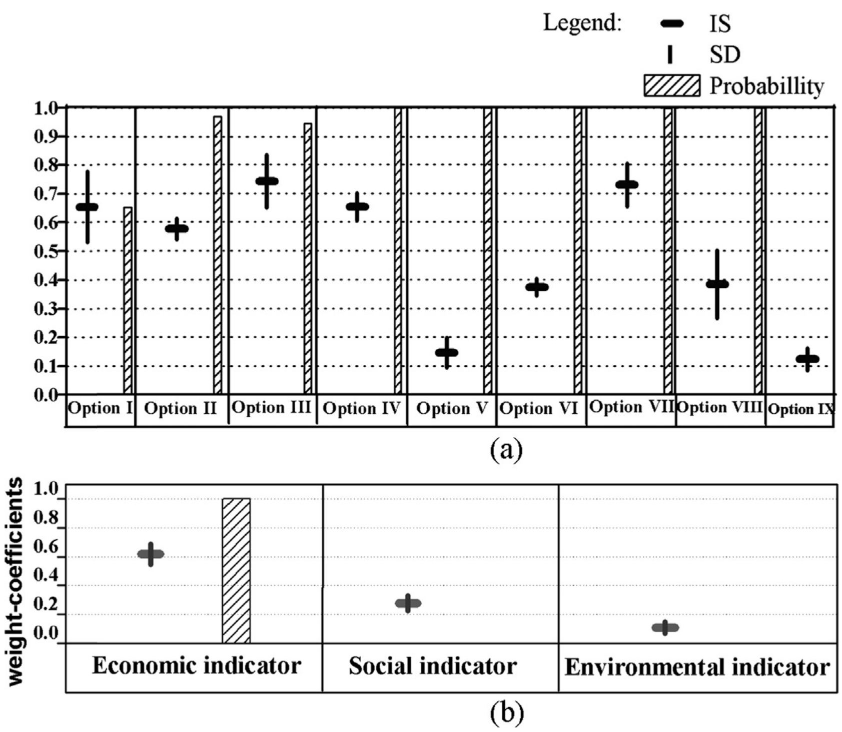

Fig. 2. IS for building options I–IX and Case no. 1, where priority was given to the economic indicator: (a) index of sustainability; (b) weight coefficients.

area per person (SoI_{ls}); and the average daily air temperature in the living room (EnI_{at}).

Case no. 1 Constraint: Ec (condition 1) > So (condition 2) > En (condition 3)
Condition 1: $EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$
Condition 2: $SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$
Condition 3: $EnI_{at} > EnI_{CO_2} > EnI_{rh}$

As seen in Fig. 2, at the predefined constraints adopted for Case no. 1, the best evaluated options were Option VII and Option III, with the indicative values of option quality being equal to 0.729 and 0.741, respectively. The groups of objects that included apartments and single family houses constructed in the period 1981–2006, where electricity is used to meet the space heating demand, exhibited good sustainability. Option V (single family houses constructed in the period 1946–1980, where electricity is used to meet the space heating demand) and Option IX (single family houses constructed in the period 1981–2006, where fossil fuels are used to meet the space heating demand) had ranked last, i.e., they were listed at the very bottom of the priority list.

Case no. 2 reflects the situation when priority was given to the economic indicator ($w = 0.616$; SD = 0.142) over the environmental indicator ($w = 0.278$; SD = 0.104) and social indicator ($w = 0.106$; SD = 0.079), as seen in Fig. 3. In the process of sub-indicator agglomeration, the calculations were performed for the same conditions as those used in the previously described Case no. 1.

Case no. 2 Constraint: Ec (condition 1) > En (condition 3) > So (condition 2)
Condition 1: $EcI_{tc} > EcI_{ec} > EcI_{hwc} > EcI_{ecc}$
Condition 2: $SoI_{ls} > SoI_{ic} > SoI_{dw} > SoI_{ac}$
Condition 3: $EnI_{at} > EnI_{CO_2} > EnI_{rh}$

The priority list of building options presented in Fig. 3 shows that the best level of sustainability was exhibited by Options III and IV, followed by Options I and VII, which were found to have good sustainability features. Options V and IX had again ranked last, as in the previous case. Case no. 2 reflects the situation when priority was given to the economic indicator, while all sub-indicators had been given the same priority, as in the previously examined case. Option IV (apartments constructed in the period 1981–2006 and connected to the district heating system) and Option III (apartments constructed in the period 1981–2006 where electricity is used to meet the space heating demand) were found to exhibit the best sustainability features, with the IS determined to be 0.774 and 0.845, respectively. When priority was given to the economic indicator over the environmental indicator, option III shows the best sustainability as in the previous case where the economic indicator had priority over the social indicator.

Fig. 4 illustrates Case no. 3 where priority was given to the environmental indicator (weight coefficient of $w = 0.670$, standard deviation of SD = 0.196); the social and the economic indicators were given the same weight coefficients ($w = 0.165$, standard deviation of SD = 0.098). In the process of sub-indicator agglomeration, based on the pre-defined conditions, the following sub-indicators were given priority: CO_2 concentration (EnI_{CO_2}); average annual specific electricity consumption (EcI_{ec}); and indoor comfort (SoI_{ic}).

Case no. 3 Constraint: En (condition 3) > Ec (condition 1) = So (condition 2)
Condition 1: $EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$
Condition 2: $SoI_{ic} > SoI_{dw} = SoI_{ls} = SoI_{ac}$
Condition 3: $EnI_{CO_2} > EnI_{at} = EnI_{rh}$

When priority was given to the environmental indicator, it was noticed that Option II (apartments constructed in the period 1946–1980 and connected to the district heating system) and Option IV ranked the best on the rating list, as seen in Fig. 4. The derived IS values indicating the quality of Option II and IV were found to be 0.918 and 0.895, respectively. Option IV was determined to be the best, as in Case no. 2 (when priority was given to the economic indicator), while Objects VI and IX ranked lower on the priority list.

Case no. 4 reflects the situation when priority was given to the social indicator (weight coefficient of $w = 0.670$, standard deviation of SD = 0.196); the environmental and the economic indicators

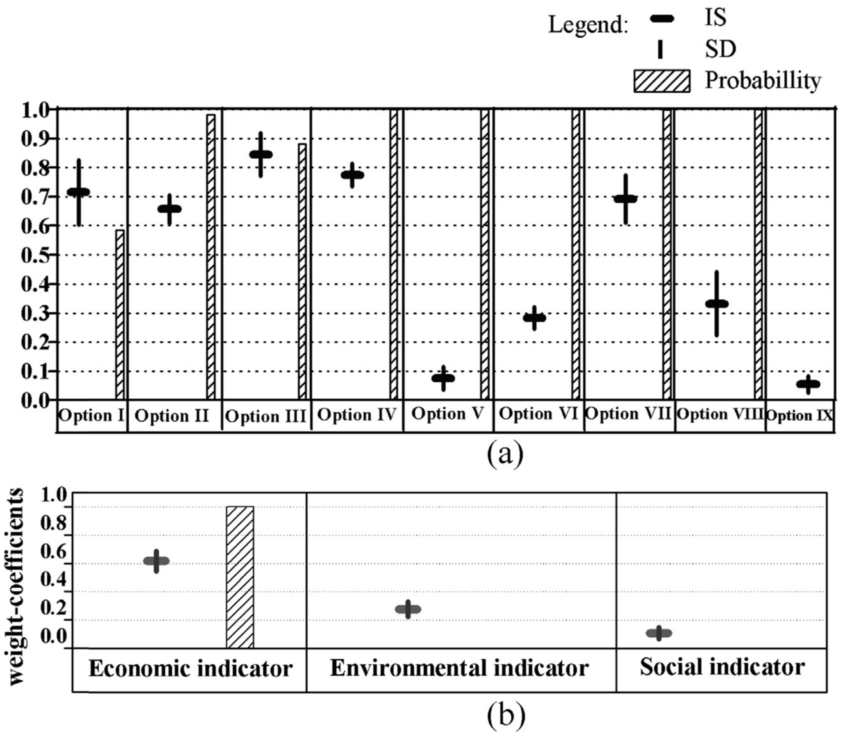

Fig. 3. IS for building options I–IX and Case no. 2, where priority was given to the economic indicator: (a) index of sustainability; (b) weight coefficients.

were given the same weight coefficients ($w = 0.165$, standard deviation of SD = 0.098). In the process of sub-indicator agglomeration, based on the pre-defined conditions, the following sub-indicators have been given priority: living space area per person (SoI_{ls}); average daily relative humidity in the living room(EnI_{rh}); and average annual specific electricity consumption(EcI_{ec}).

Case no. 4 Constraint: So(condition 2) > En(condition 3) = Ec (condition 1)
Condition 1: $EcI_{ec} > EcI_{tc} = EcI_{hwc} = EcI_{ecc}$
Condition 2: $SoI_{ls} > SoI_{ac} = SoI_{dw} = SoI_{ic}$
Condition 3: $EnI_{rh} > EnI_{at} = EnI_{CO_2}$

Fig. 5 illustrates the priority list obtained for Case no. 4, where the constraint was defined to give priority to the social indicator.

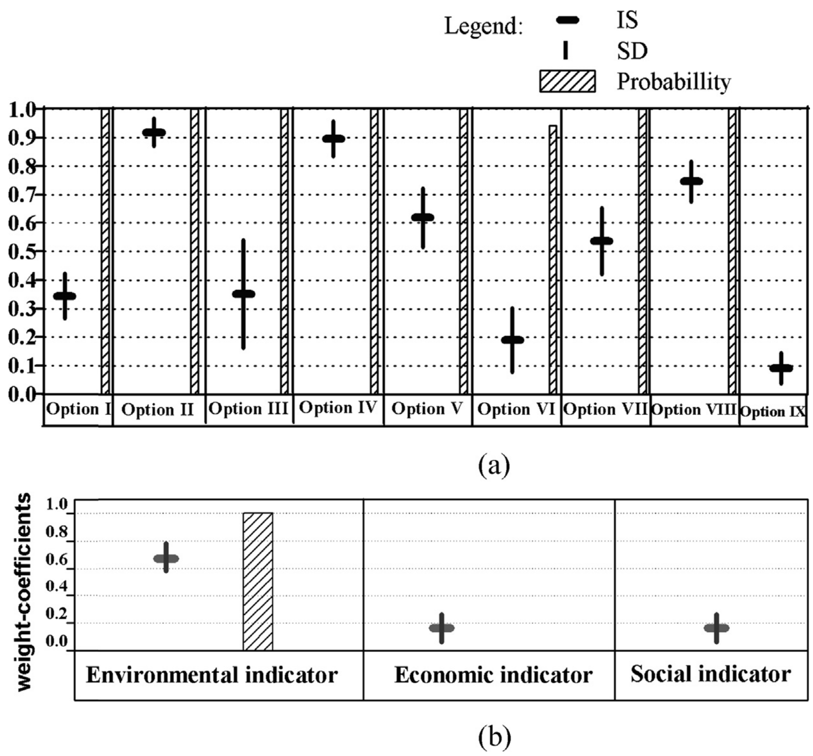

Fig. 4. IS for building options I–IX and Case no. 3, where priority was given to the environmental indicator: (a) index of sustainability; (b) weight coefficients.

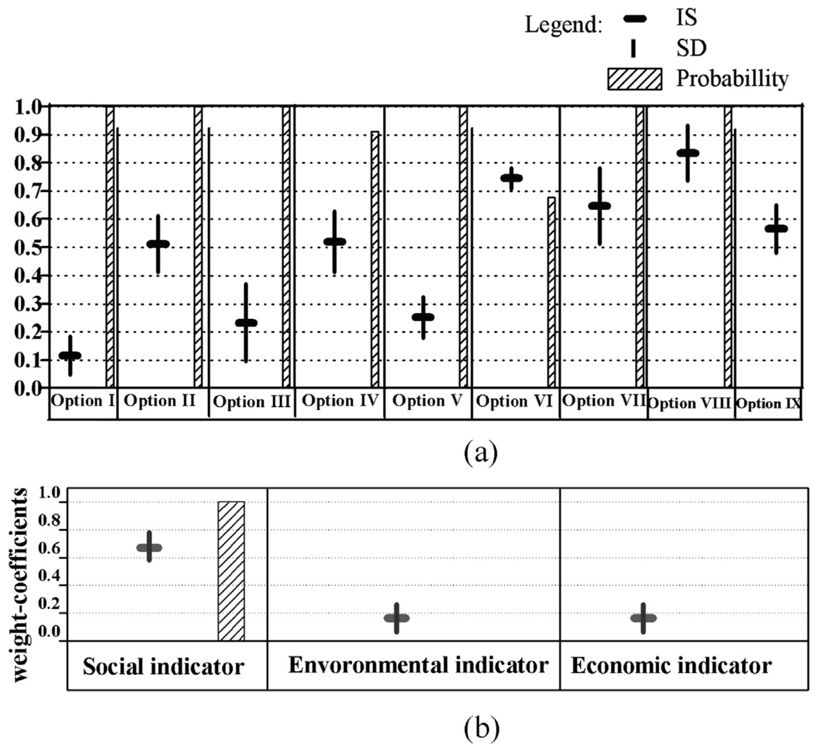

Fig. 5. IS for building options I–IX and Case no. 4, where priority was given to the social indicator: (a) index of sustainability; (b) weight coefficients.

The best level of sustainability was exhibited by Option VIII, i.e., single-family houses connected to the district heating system (the IS was found to be 0.835). The next options in line, Options VI, VII and IX, were determined to have good sustainability features, with IS values of 0.746, 0.647 and 0.566, respectively. Option I, i.e., apartments constructed in the period 1946–1980, where electricity is used to the meet space heating demand, ranked last on the priority list.

6. Conclusion

The conducted analysis included the selection, definition and calculation of ISD, shown to represent a useful tool in assessing the sustainability of various building structures (apartments and single family houses, herein referred to as building options). The sustainability analysis conducted for nine building options in the residential building sector was conducted using the selected indicators of sustainable development. The following indicator sets, representative of the different conditions of the examined building options, were calculated: economic, social and environmental. Each indicator set was in compliance with the number of sub-indicators that were defined, to describe the characteristics of the considered building option. The following sub-indicators were computed and loaded as input parameters into a mathematical model used to obtain the index of sustainability of the examined building options: economic sub-indicators illustrative of electricity consumption, heat consumed for space heating, hot water consumption, electricity consumed for household cooking needs; social sub-indicators illustrative of living space area per person, air-conditioning use, and dishwasher use; and environmental sub-indicators illustrative of indoor comfort, air temperature, relative humidity and CO_2 concentration.

The indicator quantification was performed based on the data obtained from measurements and collected questionnaires. As the next step, a procedure for obtaining the normalised and agglomerated sub-indicator values, representing the first level of the sustainability index calculation process, was proposed. A novel method of measuring the sustainability of complex energy system of the residential sector has been proposed. First, the technique of linear normalisation of the absolute criteria values was performed and later, in the agglomeration process, the analysis and synthesis of parameters under information's deficiency (ASPID method) was performed. The ASPID method of multi-criteria analysis was used to determine the quality of the examined building options. The method comprises non-numerical information in the form of relations established between different criteria used in the sustainability evaluation of the examined building options. The weights of the indicators (criteria) were determined mathematically, in contrast to the weight coefficients which were determined through expert estimates (subjectively). Finally, an appropriate mathematical tool was used to objectively assess the weights' (share in the final results), because the uncertainty of the weight coefficients vector was examined during the randomization process.

The paper presents results obtained for four different cases, with the ranking of the examined building options performed based on the related value of the index of sustainability. For a specific predefined constraint, in the case when the economic indicator was given priority over the social and environmental indicators, Options VII and III (apartment buildings and single family houses constructed in the period 1981–2006 and with electricity used to meet the space heating demand) were determined to exhibit the best behaviour with respect to the sustainability features. When priority was given to the environmental indicator the best building options were determined to be Options II and IV (apartments connected to the district heating system and constructed in the period 1946–1950 and 1981–2006, respectively). In the case when the social indicator was given priority over the environmental and economic indicators, which were given the same value of the weight coefficient, group of objects representative of single family houses constructed in the period 1981–2006 and connected to the district heating system were evaluated as the most sustainable building option.

The results of the proposed methodology are considered to be particularly beneficial in the policy-making process, where they can be used as a starting point in stakeholder discussions regarding measures to be adopted and the best energy scenario to be developed.

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