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Sustainability assessment of residential buildings by non-linear normalization procedure

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ABSTRACT

This paper presents the mathematical procedure for the determination of overall sustainability index of nine options for the agglomeration of economic, environmental and social indicators. Eleven sub-indicators were selected and calculated for all chosen options. In accordance to final energy consumption (for space heating, hot water production, cooking and the household electrical appliances) the selection, defining and determining the economic, social and environmental indicators was developed. It was done for all chosen options selected by qualitative characterization of residential objects in accordance with construction period, type of heating system and type of object (buildings or family houses).

Investigation of the influence of non-linear normalization on the sub-indicators' agglomeration was the aim of this paper. Normalized sub-indicators are obtained by selection of the appropriate linear ($\theta = 1$) or non-linear function ($\theta \neq 1$). Sustainability index and its standard deviation were calculated for different value of the parameter θ and each option in six different cases. The functional dependence between the sustainability index and the associated standard deviation of the θ parameter (characterizing the way of normalization) was obtained.

1. Introduction

In EU developed countries building sector consumes about 40% of final energy consumption [1]. According to some researches, building industry is a great consumer (about 40%) of global economy materials. During its' 'lifetime' (including building, maintaining and demolition) buildings are 'responsible' for 50% of total energy consumption and for CO_2 emission in the atmosphere (also 50%) [2]. Prediction that 60% of all human population will be inhabited in urban places by the end of 2030 [3] is based on fact that there is a global tendency of people migration from rural to urban places all round the world. Consequently, the main part of building stock will be placed there. Cities are places with very intense growth and fast development, but in structural point of view, very unbalanced also, what makes them complex energy systems. In order to comply with economic development, environmental protection and living standards, there is a strong need to implement the concept of sustainable development, containing a multi-criteria approach on these systems.

Serbian building stock is made of about 3.2 million homes. The average age of those facilities exceeds three and a half decades, and about 30% of buildings require serious reconstruction. During World War II City of Belgrade suffered extensive damage, and city's housing stock was mainly built after War along with a period of reconstruction and the large migration of rural population to the city. Extremely high demand for housing has led to a building boom. Usually, entire settlements' construction was based on a project of typical residential building without specific reference to the quality. There have been significant changes in the structure and size of settlements, fast and cheap construction was the basis of progress till the 70-ies of the last century, when energy balance of buildings for the first time came into focus as a consequence of energy crisis.

Unlike the period when they were built whole settlement in Belgrade suburbs, individual residential buildings has been dominated construction in last decade in the central city area. The high density of housing, narrow streets, a large number of building floors, pollution and so on have contributed to uncomfortable living in apartments that have been designed and built under the latest regulations [4]. For the sustainability assessment of different energy options with economic, environmental and social aspects based on variety of criteria, it is necessary to establish indicators for sustainable energy development and to calculate sustainability index as a

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measure of the quality of different options. This is important, not only from the viewpoint of new housing construction, but also from the point of aged building revitalization to meet needs of human living in modern society.

Decision making is one of the most important human activities. In everyday life we often have to make decisions by choosing one of the several possible alternatives. When the decision is based on a single criterion, the process is fairly simple. Traditional single criteria approach to the energy problem was mainly economic in nature and was aimed to identifying the most effective options at low price. However, focusing on environmental and social aspects beside economic one, MCDM methods find a place in different energy systems. The particular characteristic of MCDM methods is to employ more then one attribute to obtain an integrated decision result [5].

MCDM's method is a basic tool for the sustainability assessment in this paper. The main quality of this method is that could solve possible problems and find compromising solution between groups with different interests and that also could give rated options as a final result.

Priorities in this process are defined by various groups regarding its own interests and needs, considering weight coefficients influencing final result. Generally, there are two main models for the weighting coefficient determination. First one is the quality model, weight coefficients are determined subjectively for criteria, based on expert's opinion. They are not, very often, able to determine precise probability of some option. Usually, experts give verbal comparative statements that one option is more probable then the other, or those they occur with equal probability [6]. Second one is quantitative model based on use of mathematical tools giving as a result objective determination of weight coefficients. Quantitative model includes obtaining uncertainty of weight coefficient vector during the process of randomization. Weight coefficients are mathematically determined on a base of every option and criteria value interaction under predefined constrains. Using ASPID (Analysis and Synthesis of Parameters under Information Deficiency) method, the interaction of weight coefficients regarding different aspects of sustainability development could be considered in a way of giving advantage to some of criteria. Weight coefficients determination is done mathematically, by choosing them from weighting factors finite set, number of elements depends of a number of parts in [0–1] segment. This number of elements also depends of a starting specific criteria number in conditions of restrictions based on available set of non-numerical information. Also, application of ASPID method (unlike some other methods), as a result gives no information loss during the process of sustainability estimation by indicators standardization (normalization) of a complex energetic system. Looking from the multi-criteria methods practical use point of view, this ASPID method gives better understanding and results presentation.

2. Indicators of sustainable development for residential buildings

Sustainable development indicators have to be clearly defined, feasible, understandable and practical. Their selection and use is a difficult task since the result depends on the quality of indicators' selection [7]. Indicators of sustainable development are needed in decision-making processes that take place in all levels of society [8,9].

In order to assess sustainability of different options using multi-criteria method with economic, social and environmental aspects, sustainable development indicators for residential buildings were defined and total number of discussed objects was 83 from the Belgrade city and its suburbs [10]. Qualitative characterization of objects is done in compliance with: construction period, heating system by mode and objects by type.

Belgrade is characterized by moderate continental climate with four seasons and average annual temperature of 11.7 °C. Winter is cold, with about 21 days with negative temperature and therefore half of the building total energy consumption is used for heating. Belgrade's households are mainly connected to the district heating system. Heat accumulation electric heaters are mostly used as very reliable equipment for heating at the second place, while the combined system for heating and cooking on the basis of solid fuel combustion is at the third place. Other types of heating systems are based on burning oil and gas.

Buildings' geometry and spatial characteristics are very important in determining improvement capabilities. There is an opinion that certain technical standards are much better implemented in multi-residential buildings' than individual houses' construction. Building height and number of residential units are main elements for the object classification by type. Objects with not more than 3 floors and not more than 4 residential units are classified as individual houses and objects with more than 3 floors and more than 4 residential units as multi-residential buildings.

In order to determine the sample size which will present the population of all object in Belgrade city Cochran's formula was used [11].

$$n = \frac{Z^2 \cdot p \cdot q}{e^2} = \frac{(1.96)^2 \cdot 0.5 \cdot 0.5}{(0.108)^2} \approx 83 \tag{1}$$

where n is the sample size; Z is the abscissa of the normal curve that cuts off an area at the tails (value obtained from statistical tables equal to 1.96 for the confidence level of 95%); p is the estimated proportion of an attribute that is present in the population (the variability is unknown in the proportion, and therefore maximum variability of 0.5 is adopted); q is equal to $1 - p$ and e is the desired level of precision (Due to the limited number of measuring instruments and the high cost of research and limited campaign time, adopted value for precision is ±10.8%. Smaller margin of error "e" provides greater reliability of the obtained results, but in that case, the sample size would be greater.)

The final phase is the selection of the sampling units. Stratified sampling is used as a sampling technique in this paper [12]. The sample size of each stratum is proportionate to the population size of the stratum. This method enables division of Belgrade housing stock into subgroups called 'strata' according to the defined building characteristics and almost always leads to increase in survey precision. Using the following equation sample size within each 'strata' has been obtained.

$$n_h = \left(\frac{N_h}{N}\right) \cdot n \tag{2}$$

where n_h is the sample size for stratum h; N_h is the population size for stratum h; N is total population size and n is total sample size.

Variables N_h and N are obtained from Census 2002 [13], while n is 83 (see Eq. (1)). Housing units are selected utilizing the random sampling.

Based on the qualitative characterization the sample is divided into nine sub-groups (options) in accordance with construction period, type of heating system and type of object. There are two main groups of options made by type of objects. Options 1–4 are from a group of buildings and options 5–9 are from a group of single family houses.

First and second option are representing group of building apartments built in period 1946–1980 with a difference in heating system. Apartments in first option use electricity for heating and apartments in second option are connected to the district heating system. In third and fourth option are building apartments built in

Table 1
Description of selected sub-indicators.

Indicators	Sub-indicators	Selected sub-indicators
Economic	Ec_1	The average specific annual consumption of electricity in household
	Ec_2	The average spec. annual consumption of thermal energy for space heating
	Ec_3	The average specific annual consumption of hot water
	Ec_4	The average specific annual consumption of electricity needed for cooking
Environmental	En_1	The average daily air temperature in the living room
	En_2	The average daily relative humidity in living room
	En_3	The average daily concentration of CO_2 in living room in winter period
Social	Sc_1	Living space per person
	Sc_2	Share of total area of apartments and houses that use air-conditioning
	Sc_3	Share of apartments and houses that use dishwasher
	Sc_4	Share of households that are satisfied with the indoor comfort

period 1981–2006 respectively with electrical heating system and district heating system.

Fifth and Sixth option are representative of older houses built in period 1946–1980. Fifth option correspond to electrical heating system and sixth one to the heating system based on fossil fuel burning. Options 7–9 are all made of relatively new houses built in period 1981–2006 respectively with electrical heating, district heating and heating based on fossil fuel combustion.

Indicators of sustainable development were selected and formed for defined options [14]. Table 1 shows the basic set of sub-indicators of economic, environmental and social criteria. They were calculated on the basis of parameters obtained by measuring [15] and questionnaire (filled by household members) [16,17]. The numerical values of the indicators, needed to assess the quality of the options, presents the input values to the model used for calculating the general index of sustainability (Table 2).

3. Sustainability index calculation procedure

Sustainability index is agglomerated indicator for the measurement of an energy system's quality [18] based on the assumption that the energy system is a complex system. The quality of selected options are defined by energy indicators of sustainable development, which are represented by three sets of economical, environmental and social sub-indicators. The first step in sustainability index determination of an option is selection of m criteria $(a^1,\ldots,a^m)$ on the basis of which will be evaluated some of k considered options $(A(1),\ldots,A(k))$. Selected criteria constitute sub-sets of economical $(Ec^1,\ Ec^2,\ \ldots\ Ec^{m'})$, environmental $(En^1,\ En^2,\ \ldots\ En^{m''})$ and social $(Sc^1,\ Sc^2,\ \ldots\ Sc^{m'''})$ indicator sets while $m'+m''+m'''=m$ and m', m'', m''' represent number of selected criteria from the group of economic, ecological and social indicators. This selection is subjective and depends on the experts who form them. After establishing the criteria, each option is assigned the value of sub-indicators that are commonly obtained by measuring or calculation and represents the quality measure of an object (options) with observing criteria point of view. In other words, each of the energy system's considered options $A(i)$ $(i=1,k)$ is described by the vector a_i^j $(i=1,k;j=1,m)$ where the $a_i^j = Ec^j$ $(i=1,k;j=1,m')$, $a_i^{j+m'} = En^j$ $(i=1,k;\ j=1,m'')$ and $a_i^{j+m'+m''} = Sc^j$ $(i=1,k;\ j=1,m''')$ [19].

Sub-indicators of sustainable development are different physical values and they are not suitable for mutual comparison. In order to be comparable, normalization procedure is required. It converts their absolute value into the one with no units and without any generalization loss. This procedure involves finding the associated function $q_i^j = f(a_i^j)$ such that the following inequality $0 \le q_i^j \le 1$ is correct for each selected criterion individually, i.e. for $j=\text{const.}$ according to the formula:

a) For monotonically increasing sub-indicator values

$$q_i = \left\{ \begin{array}{ccc} 0 & , & a_i \le MIN \\ \left(\dfrac{a_i - MIN}{MAX - MIN}\right)^{\theta} & , & MIN < a_i < MAX \\ 1 & , & a_i \ge MAX \end{array} \right\}_{i=1,k} \quad (3)$$

b) For monotonically decreasing sub-indicator values

$$q_i = \left\{ \begin{array}{ccc} 1 & , & a_i \le MIN \\ \left(\dfrac{MAX - a_i}{MAX - MIN}\right)^{\theta} & , & MIN < a_i < MAX \\ 0 & , & a_i \ge MAX \end{array} \right\}_{i=1,k} \quad (4)$$

where MIN is the lower limit value of the observed sub-indicator $(j=\text{const.},\ i=1,k)$; MAX is the upper limit value of the observed sub-indicator $(j=\text{const.}, i=1,k)$; q_i is the normalized sub-indicators' values and θ is the power of normalization.

The most popular normalization function is linear, when $\theta=1$. The comparison of the sustainability index and the corresponding standard deviation for $\theta=1$ and $\theta \ne 1$ is presented in following section of this paper, regarding the case of calculating the sustainability index, based on realistic values of sub-indicators from the practice.

The normalization process converts absolute sub-indicator values into a fuzzy set of normalized sub-indicators. The maximum value $q_i^j = 1$ indicates that from the j-criteria point of view i-th object (or option) is the most sustainable and the minimum value $q_i^j = 0$ indicates that from the j-criteria point of view i-th option (or object) is the worst sustainable option.

The individual contribution of each sub-indicator to corresponding indicator is difficult to determine. In this respect the weighting coefficients are used to determine importance of individual sub-indicator to the corresponding indicator and agglomeration procedure is adopted as follows [20]:

$$EcI_i^{agg} = \sum_{j=1}^{m'} w_i^j \cdot q_i^j \quad (5)$$

$$EnI_i^{agg} = \sum_{j=m'+1}^{m'+m''} w_i^j \cdot q_i^j \quad (6)$$

$$ScI_i^{agg} = \sum_{i=m'+m''+1}^{m} w_i^j \cdot q_i^j \quad (7)$$

where q_i^j is the normalized values of sub-indicators; w_i^j is the weighting coefficients for sub-indicators' agglomeration into economical, environment and social indicators based on first level pre defined restriction; m', m'', m''' are the number of economical, environment and social sub-indicators, respectively; m is the total number of sub-indicators and EcI_{agg}, EnI_{agg}, ScI_{agg} are the agglomerated values of economical, environment and social indicators, respectively.

Table 2
Numerical values of sub-indicators.

Indicator	Ec				En			So			
Sub-indicator Units	Ec_1 kWh/hld	Ec_2 kWh/m^2	Ec_3 m^3/prs	Ec_4 kWh/prs	En_1 °C	En_2 %	En_3 ppm	Sc_1 m^2/prs	Sc_2 %	Sc_3 %	Sc_4 %
Option 1	9318	100	13.8	670	22.0	50	1156	15.4	53	75	75
Option 2	6540	124	13.3	619	22.7	41	901	22.3	40	70	78
Option 3	6840	82	12.4	660	22.6	48	1556	16.3	100	67	100
Option 4	6326	119	12.6	529	22.9	45	739	22.8	57	45	73
Option 5	12,293	139	15.6	480	20.8	54	462	23.9	18	50	75
Option 6	5816	179	9.5	242	21.5	43	1369	26.0	36	36	64
Option 7	8153	95	10.2	235	21.6	51	772	27.1	47	25	50
Option 8	9794	137	13.1	414	22.0	40	902	28.3	41	100	80
Option 9	5588	194	10.3	209	21.7	52	1437	26.6	30	44	33

Table 3
List of cases based on pre-defined constrains.

Case no.	I agglomeration level			II agglomeration level
Case1	$Ec_1 > Ec_2 = Ec_3 = Ec_4$	$En_1 > En_2 = En_3$	$Sc_1 > Sc_2 = Sc_3 = Sc_4$	$Ec > En = Sc$
Case2	$Ec_1 > Ec_2 = Ec_3 = Ec_4$	$En_1 > En_2 = En_3$	$Sc_1 > Sc_2 = Sc_3 = Sc_4$	$En > Ec = Sc$
Case3	$Ec_1 > Ec_2 = Ec_3 = Ec_4$	$En_1 > En_2 = En_3$	$Sc_1 > Sc_2 = Sc_3 = Sc_4$	$Sc > Ec = En$
Case4	$Ec_1 = Ec_2 > Ec_3 = Ec_4$	$En_1 > En_2 > En_3$	$Sc_1 = Sc_4 > Sc_2 = Sc_3$	$Ec > En = Sc$
Case5	$Ec_1 = Ec_2 > Ec_3 = Ec_4$	$En_1 > En_2 > En_3$	$Sc_1 = Sc_4 > Sc_2 = Sc_3$	$En > Ec = Sc$
Case6	$Ec_1 = Ec_2 > Ec_3 = Ec_4$	$En_1 > En_2 > En_3$	$Sc_1 = Sc_4 > Sc_2 = Sc_3$	$Sc > Ec = En$

At first agglomeration level the weight-coefficient w_i^j shows the importance of particular criteria q_i^j on indicators (economical, environment and social). In this paper mathematical way for weight-coefficients' calculation is performed. The weight-coefficients are chosen from the set [20]:

$$w(m,n) \in \left\{0, \frac{1}{n}, \frac{2}{n}, \ \ldots, \ \frac{n-1}{n}, 1\right\} \tag{8}$$

from all $N(m, n)$ possible weights, where:

$$N(m,n) = \frac{(n+m-1)!}{(n!(m-1)!)} \tag{9}$$

where n is the devisor of segment [0,1]; m is the number of initial specific criteria (m', m'', m'''); the condition $\Sigma w^j = 1$ ($j = 1, m$) is used for the reduction of the set of all possible weight-coefficients $w(m, n)$. On the other hand non-numeric, inexact and incomplete information is used in a form of equality or inequality to give priority to some criteria (criterias) among other (others). Calculated arithmetical mean value for all admissible weights (meeting all above mentioned restrictions) is used in Eqs. (5)–(7).

Sustainability index of i-th object is calculated at second level of agglomeration by equation [20,21]:

$$SI_i = w_{Ec} \cdot (EcI_i^{agg})_n + w_{En} \cdot (EnI_i^{agg})_n + w_{Sc} \cdot (ScI_i^{agg})_n \tag{10}$$

where w_{Ec}, w_{En}, w_{sc} are the weight-coefficients for economical, environment and social indicators' agglomeration into sustainability index based on second level pre-defined restrictions; $(EcI_{agg})_n$, $(EnI_{agg})_n$, $(ScI_{agg})_n$ are the agglomerated and normalized value of economical, environment and social indicators.

Weight-coefficients are calculated in the same way as at first agglomeration level.

4. Case study

ASPID methodology was used in this paper for the sustainability index assessment of examined options. For the demonstration of the procedure, introduced in the previous part of this paper, 9 different options described with initial values of 11 chosen sub-indicators from three different group of indicators (economical, environmental and social) were under investigation [22]. Selected option is representing group of objects distinguished by location (placed in city and suburbs), heating type and construction quality.

Six different cases (Cases 1–6) were included into analysis based on pre-defined constrains Table 3. In order to investigate the influence of nonlinearity in the normalization process to the final calculation of the sustainability index, the change in nonlinearity was introduced in the procedure. The agglomeration of normalized sub-indicators is obtained by selection of the appropriate linear ($\theta = 1$) or nonlinear function ($\theta \neq 1$) [23] in Eqs. (3) and (4). The overall Sustainability index and its standard deviation were calculated for different values of the parameter θ and for each option.

For the linear type of normalization, for each sub-indicator in Eqs. (3) and (4), the value of the power of normalization was equal to 1 ($\theta_1 = \theta_2 = \ldots = \theta_{11} = 1$). Series of eleven different powers of normalization were selected ($\theta_1, \theta_2, \ldots, \theta_{11}$) for the non-linear type of normalization. For each different sub-indicator's normalization process, θ-value was found from a graph representing the functional dependence between squared standard deviation and θ – parameter, in a way that standard deviation reaches a minimum. It is shown as an example for θ_1 selection for the Ec_1 sub-indicator normalization in Fig. 1

Sustainability index (SI) values and its' appropriate standard deviations (SD) are calculated for six different cases and each of nine

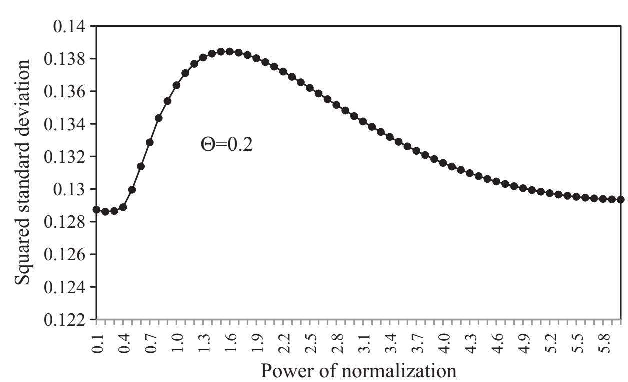

Fig. 1. The functional dependance between calculated standard deviation and power of normalization for Ec_1.

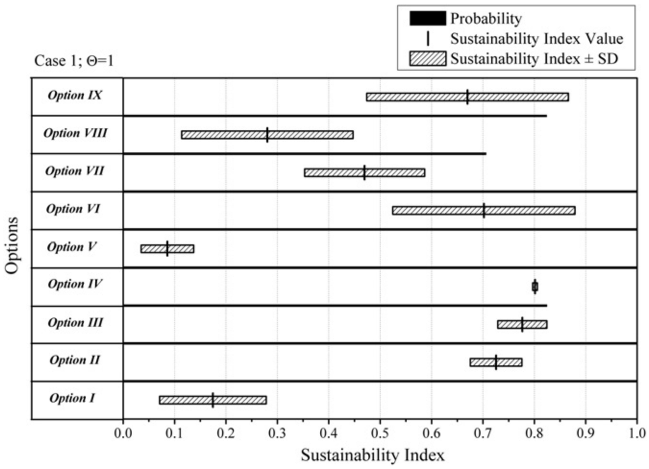

Fig. 2. Sustainability index and its standard deviation for each option for the Case 1 and $\theta = 1$.

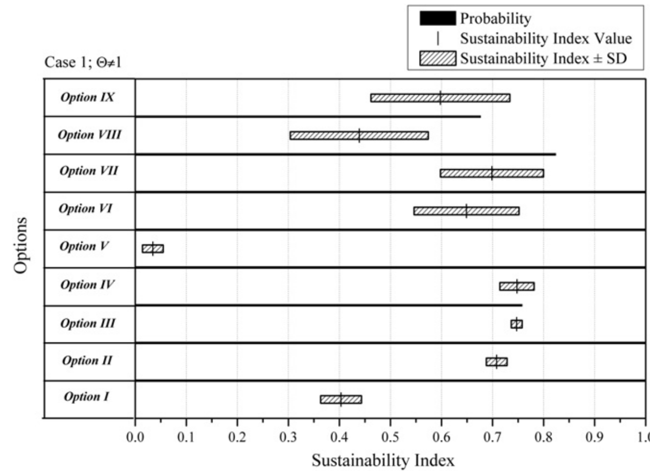

Fig. 3. Sustainability index and its standard deviation for each option for the Case 1 and $\theta \neq 1$.

options with different degree of nonlinearity. In Figs. 2–3 sustainability index and its standard deviation for each option for the Case 1 is shown, respectively for $\theta = 1$ and $\theta \neq 1$. It is of particular interest to show that the application of nonlinearity in different cases leads to the verification of sustainability index as the parameter of validation for the selected options under consideration.

Application of this procedure in validation of the selected options under nonlinearity constrains opens possibility to the

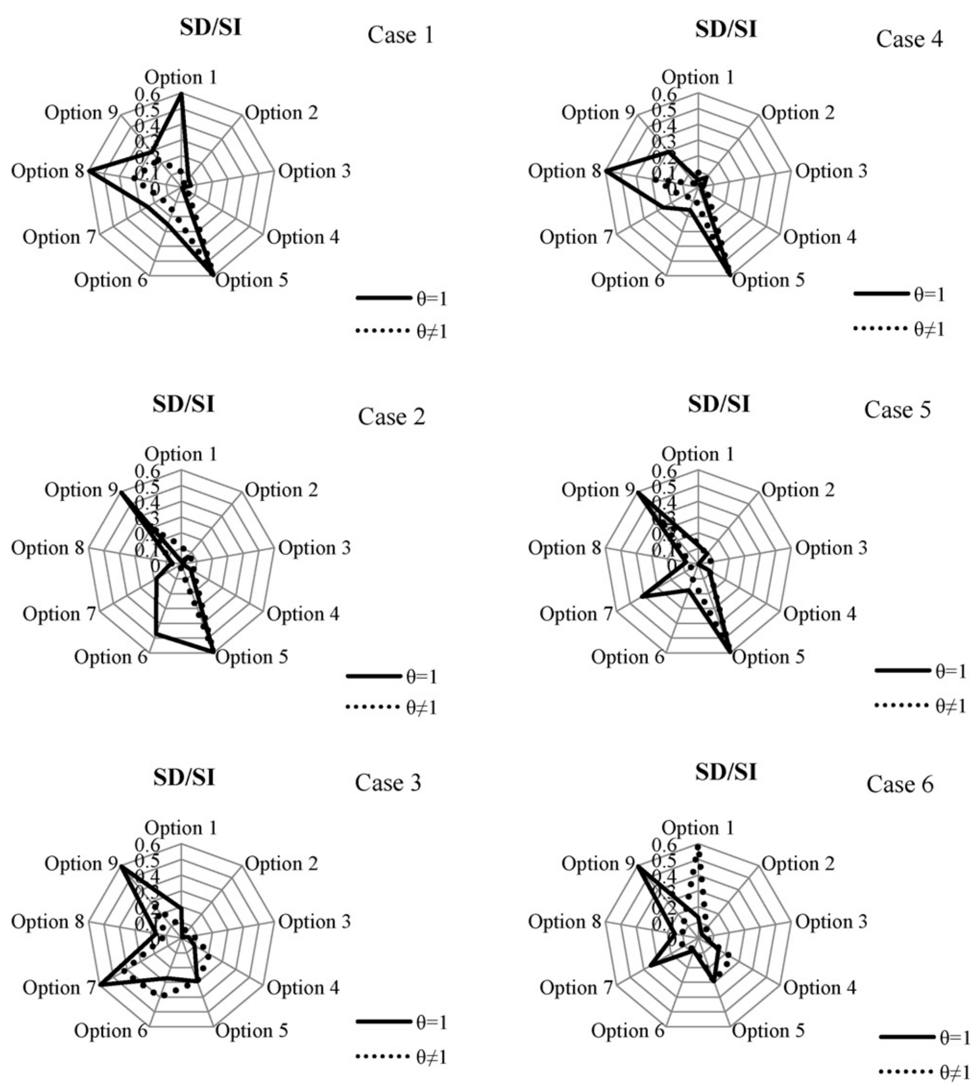

Fig. 4. SD/SI quotient (Cases 1–6).

decision makers to quantify quality of the selected option under consideration.

Calculated sustainability index mainly depends on selected criteria and pre-defined constrains.

As a measure of sustainability index (SI) calculation accuracy, the quotient of standard deviation (SD) and sustainability index (SI) was chosen. The ratio SD/SI is smaller for more accurately calculated sustainability index. In Fig. 4, using radar type of graph, calculated quotient of SD/SI is shown for each of nine different options for each of six different cases representing functional dependence between SD/SI ratio and type of normalization. The choice of normalization type (linear in comparison with non-linear normalization) will not always lead to smaller SD/SI quotient as a measure of precision of mathematically calculated sustainability index. But, looking up in radar graphs for all presented cases and options, it is obvious that surface area with dot contour (presenting non-linear type of normalization) is closer to the center of graph then surface area with solid line contour (presenting linear type of normalization). For some options in all six cases, non-linear normalization gave more precisely calculated sustainability index as a result, but in general, using non-linear normalization we can get less inaccurate calculated sustainability index values.

5. Conclusion

Construction and buildings' operation are, from the perspective of sustainable development, unsustainable energy processes. It begins with free land occupation and continuous with implementation of materials obtained in production processes with energy consumption. At the end, final obtained structure consumes significant amounts of energy for building maintaining, providing comfort for occupants, and also generating large amount of waste. The economic aspect of building stock sustainability is, at first place, in the price of consumed energy. If, beside economic, consideration includes ecological and social aspects, which are related to the possibility of resources depletion, environmental pollution, as well as the lifestyle of the modern society, it is obvious that the building stock in the analysis of sustainability must be treated as a complex power system.

Series of continuous measurements accomplished in the Belgrade's flats and houses in order to carry out the project "Development and application of complementary methods for assessing energy efficiency indicators and quality of residential buildings' interior in Belgrade". Measurements were performed on representative sample of households in different residential objects at different locations in the city and suburbs. The sample is divided into nine sub-groups (options) based on the qualitative characterization in accordance with construction period, type of heating system and type of object.

In this paper eleven economic, environmental and social criteria were formed to describe sustainability of nine chosen options. Numerical values of criteria (sub-indicators) are calculated on the basis of parameters obtained by performed measurements and questionnaire filled by household members. Those values present the input values to the model used for calculating the general index of sustainability needed to assess the quality of chosen options.

Six different cases are formed based on pre-defined constraints as a non-numerical information in a form of priorities. Priorities are given to the criteria (sub-indicators) at first agglomeration level and to the indicators (economic, environmental and social) at second agglomeration level by weighting coefficients. Mathematical procedure for the overall sustainability index determination over the process of economic, environmental and social indicators agglomeration of selected options and cases is presented in details. For the calculation purpose, FORTRAN programme was developed.

Sustainability index and its standard deviation were calculated for each of nine options and each of six different cases with linear ($\theta = 1$) and non-linear ($\theta \neq 1$) way of sub-indicators' normalization. The quotient of standard deviation (SD) and associated sustainability index (SI) as a function of θ parameter was obtained for all options and all cases characterizing the way of normalization.

Analysis of the sustainability index calculation accuracy was performed using radar type of graphs. Less inaccuracy in sustainability index calculation was obtained for majority of nine selected options and six different cases under investigation by non-linear type of normalization in comparison with liner type.

Computer programs can be easily used to implement mathematical way for the calculation of sustainability index of different options in the observed system giving us capability to choose the most sustainable option based on pre-defined constrains. Keeping this in mind, accuracy of the sustainability index calculation becomes very important. The future work will be based on finding all factors that affect accuracy of the calculated value of the sustainability index.

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