Healthcare Resilience Evaluation Using Novel Multi-Criteria Method

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Abstract. The application of computational science methods and tools in healthcare is growing rapidly. These methods support decision-making and policy development. They are commonly used in decision support systems (DSSs) used in many fields. This paper presents a decision support system based on the newly developed SSP-SPOTIS (Strong Sustainable Paradigm based Stable Preference Ordering Towards Ideal Solution) method. The application of the proposed DSS is demonstrated in the example of assessing healthcare systems of selected countries concerning resilience to pandemic-type crisis phenomena. The developed method considers the strong sustainability paradigm by reducing linear compensation criteria with the possibility of its modeling. The research demonstrated the usefulness, reliability, and broad analytical opportunities of DSS based on SSP-SPOTIS in evaluation procedures focused on sustainability aspects considering a strong sustainability paradigm.

Keywords: Healthcare assessment · Sustainability · Decision support system · Strong sustainability paradigm.

1 Introduction

The application of computational science methods and tools such as numerical methods, computational models in healthcare, and smart technologies is growing rapidly. These methods support decision-making, facilitate policy development, and provide computational support in healthcare. One aspect that determines the sustainability of healthcare systems is their resilience to pandemic-type emergencies. As the COVID-19 pandemic highlighted, the vulnerability of healthcare systems contributes to increasing global economic, social, and public health failures caused by health crises [11].

This paper presents a decision support system based on the newly developed SSP-SPOTIS (Strong Sustainable Paradigm based Stable Preference Ordering

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Towards Ideal Solution) method. The application of the proposed DSS is presented in the example of evaluating healthcare systems of selected countries concerning resilience to pandemic-type crisis phenomena [8]. The developed method considers the strong sustainability paradigm by reducing linear compensation criteria with the possibility of its modeling. SSP-SPOTIS is based on the classic multi-criteria decision analysis (MCDA) method, which is SPOTIS (Stable Preference Ordering Towards Ideal Solution) [3]. SPOTIS method provides a stable ordering of alternatives toward an ideal solution. It is noteworthy that, unlike MCDA methods such as AHP (Analytic Hierarchy Process) [12], ELECTRE (ELimination and Choice Expressing the Reality) [5], and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [9], it is resistant to the phenomenon of reversal of rankings. In contrast to methods such as PROMETHEE and ELECTRE [10], SPOTIS has low computational complexity and requires simple information about the decision problem, such as a decision matrix with data performances of alternatives against criteria and specification of bounds values for each criterion. SPOTIS provides a flexible approach that considers decision makers' preferences to determine reference solutions, as opposed to methods such as TOPSIS, VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje), and CODAS (COmbinative Distance-based ASsessment) [4].

The rest of the paper is organized as follows. Section 2 demonstrates the methodology of the research. Section 3 presents research results and discusses them. Finally, in section 4, conclusions are outlined, and future work directions are drawn.

2 Methodology

The following steps of the SSP-SPOTIS method are given below. They were developed based on the fundaments of the SPOTIS method, which rules are provided in [3]. The development of the SSP-SPOTIS method is designed to enable the modeling of linear compensation reduction at the Ideal Solution Point (ISP) with respect to which distances of alternatives are computed for the aim of the evaluation. In the classic SPOTIS method ISP is determined considering minimum and maximum bounds of the decision matrix or it is determined individually by decision maker. In the SSP-SPOTIS ISP can be determined automatically by setting s coefficient modeling reducing criteria compensation. Software in Python 3 with the developed method and datasets are available in the GitHub repository at link `https://github.com/energyinpython/SSP-SPOTIS`.
Step 1. Construct the decision matrix $X = [x_{ij}]_{m\times n}$ as Equation (1) presents. The decision matrix includes performance values x_{ij} gathered for m alternatives, where $i = 1, 2, \ldots, m$ with respect to n assessment criteria, where $j = 1, 2, \ldots, n$.

$$X = [x_{ij}]_{m\times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

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Step 2. Compute the Mean Deviation MD for each value x_{ij} from matrix X by subtracting the mean value of each alternative's performance $\overline{x}_j$ for each criterion C_j. Multiply the outcome value by the sustainability coefficient s_j specified for each criterion as a real number from 0 to 1. The s coefficient is determined for each criterion according to the preferences of experts and decision-makers. Equation (2) demonstrates the whole procedure performed in this step.

$$MD_{ij} = (x_{ij} - \overline{x}_j)s_j \tag{2}$$

Step 3. Assign 0 value to these MD values that for profit criteria C_j are lower than 0 (when x_{ij} is less than $\overline{x}_j$) and to these MD values that for cost criteria C_j are higher than 0 (when x_{ij} is higher than $\overline{x}_j$), as Equation (3) shows,

$$MD_{ij} = 0 \; \forall \; MD_{+ij} < 0 \; \vee \; MD_{-ij} > 0 \tag{3}$$

where MD_{+ij} define MD values for profit criteria and MD_{-ij} represent MD values for cost criteria. This stage protects against unintended improvement of performance values that are outliers from the average toward the worst.

Step 4. Construct the matrix T with reduced compensation to determine minimum and maximum bounds with reduced compensation required for building Ideal Solution Point (ISP) considering reduced compensation. In this aim, subtract MD_{ij} values from performance values x_{ij} contained in decision matrix X as Equation (4) presents. A compensated decision matrix T is the result of this procedure.

$$t_{ij} = x_{ij} - MD_{ij} \tag{4}$$

Step 5. Define the MCDA problem by specifying minimum and maximum bounds of score values for each criterion included in compensated decision matrix $T = [t_{ij}]_{m \times n}$, as Equation (5) shows. For each criterion $C_j (j = 1, 2, \ldots, n)$ the minimum and maximum bounds of this criterion are determined respectively by T_j^{min} and T_j^{max}. Size of array with T_{bounds} is $2 \times n$.

$$T_{bounds} = \begin{bmatrix} T_1^{min} & T_j^{min} & \cdots & T_n^{min} \\ T_1^{max} & T_j^{max} & \cdots & T_n^{max} \end{bmatrix} \tag{5}$$

Step 6. Determine the Ideal Solution Point (ISP) defined by $T^\star$ based on T_{bounds}. If for the criterion C_j higher score value is preferred, then the ISP for criterion C_j is $T_j^\star = T_j^{max}$. On the other hand if for the criterion C_j lower score value is preferred, then the ISP for criterion C_j is $T_j^\star = T_j^{min}$. The ideal multi-criteria best solution $T^\star$ is denoted as the point of coordinates $(T_1^\star, T_j^\star, \ldots, T_n^\star)$.

Step 7. Determine the normalized distances d_{ij} from ISP for each alternative A_i using Equation (6).

$$d_{ij}(A_i, t_j^\star) = \frac{|X_{ij} - T_j^\star|}{|T_j^{max} - T_j^{min}|} \tag{6}$$

Step 8. Calculate the weighted normalized average distance as Equation (7) presents,

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$$d(A_i, t^\star) = \sum_{j=1}^{n} w_j d_{ij}(A_i, t_j^\star) \tag{7}$$

where w_j denotes the weight of jth criterion. Criteria weights were calculated in this research by applying an objective weighting method called CRITIC (Criteria Importance Through Inter-criteria Correlation) [1]. CRITIC determines criteria weights based on a decision matrix with the performances of alternatives.
Step 9. Create alternatives' ranking by sorting $d(A_i, t^\star)$ values in ascending order. The most preferred alternative has the lowest $d(A_i, t^\star)$ value.

The structure model of healthcare systems assessment toward crisis resilience refers to some extension to the conceptual approach introduced by World Health Organization, exposing the significance of how a health system is organized (workforce, physical resources) and financed [2, 13]. The framework was developed with some specific dimensions, including service delivery during the outbreak, absorption of new technologies, and system efficiency and robustness [7]. The proposed model includes 13 criteria (C_1-C_{13}) belonging to seven main groups (G_1-G_7) displayed in Table 1. Profit criteria with the maximization aim are defined by $\uparrow$, and cost criteria with the aim of minimization are denoted by $\downarrow$.

Table 1: Multi-criteria model for healthcare evaluation.

Criteria group	Proposed indicators
G_1 - System's financial resources [8]	C_1 - Public expenditure on health - share of GDP ($\uparrow$), C_2 - Public expenditure on health per capita ($\uparrow$)
G_2 - System's human resources [7]	C_3 - Practicing physicians - density per 1 000 population ($\uparrow$), C_4 - Practicing nurses - density per 1 000 population ($\uparrow$)
G_3 - System's infrastructure [2]	C_5 - hospital beds per 1 000 population ($\uparrow$), C_6 - curative (acute) care beds per 1 000 population ($\uparrow$)
G_4 - Service delivery [7]	C_7 - Hospitalized patients per million ($\downarrow$), C_8 - Intensive Care Unit patients per million ($\downarrow$)
G_5 - Absorption of new medical products and technologies [6]	C_9 - Total tests per thousand population ($\uparrow$), C_{10} - Vaccination rate (% of population vaccinated) ($\uparrow$)
G_6 - System's efficiency [7]	C_{11} - Observed case-fatality ratio due to COVID-19 ($\downarrow$), C_{12} - Deaths per 1.000,000 population due to COVID-19 ($\downarrow$)
G_7 - System's robustness [6]	C_{13} - Excess deaths (% change from average) ($\downarrow$)

Data for this research was collected from the following sources: Our World in Data: `https://ourworldindata.org/`, OECD Health Statistics 2022: `https://www.oecd.org/els/health-systems/health-data.htm`, The World Bank Data and World Health Organization European Healthcare Information Gateway (Accessed on 4 February 2024). The survey refers to the United States of America (USA) and 25 European countries. The most recent and simultaneously complete data for the countries under consideration against the criteria included in the model was obtained for 2021. Performances of the assessed countries are provided in the GitHub repository.

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3 Results

This section provides assessment results of selected countries in relation to criteria of healthcare's resilience to crises using DSS based on the SSP-SPOTIS multi-criteria method. The research was carried out taking into account the modeling of the reduction of the criteria's linear compensation by incrementally increasing the value of the sustainability coefficient. Low values of the s coefficient represent a slight reduction in compensation, while large values of the s coefficient mean that the reduction in compensation is significant. A value of s equal to 0 represents the use of the classic SPOTIS method with full linear compensation of criteria. On the other hand, a value of the s coefficient equal to 1 denotes full compensation reduction. Low values of the s coefficient cause a low reduction in the compensation of weaker values of some criteria by better performances of other criteria. In contrast, the higher the value of the s coefficient, the stronger the prevention of compensating weak values of several criteria by exceptionally favorable performances of other criteria considered in the evaluation. The present work investigates the behavior of rankings under the influence of increasing the value of the s coefficient from 0.0 to 0.5 with a step of 0.05. In the first stage of the research, compensation reduction was modeled by modifying the value of the s coefficient for all model criteria simultaneously.

Table 2 displays a fragment of the matrix, including weighted normalized average distance values of evaluated alternatives obtained by applying increasing s coefficient values in the SSP-SPOTIS method. The complete matrix is provided in the Supplementary material on GitHub.

Table 2: Countries' SSP-SPOTIS scores for all criteria compensation reduction.

Country	0 (SPOTIS)	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
United States	0.518	0.517	0.515	0.513	0.512	0.511	0.510	0.509	0.509	0.509	0.509
Austria	0.324	0.313	0.302	0.290	0.277	0.269	0.263	0.260	0.259	0.263	0.269
Belgium	0.377	0.369	0.360	0.350	0.340	0.330	0.319	0.308	0.301	0.294	0.291
Bulgaria	0.661	0.656	0.652	0.647	0.645	0.645	0.648	0.652	0.656	0.660	0.665
...	...	...	...	...	...	...	...	...	...	...	...

Value 0.0 of s coefficient represents using the classic SPOTIS method with no reduced compensation of ISP. Rankings derived from these values sorted in ascending order are visualized in Figure 1. It can be noticed that Austria is the stable leader of the rankings for the s coefficient in the range from 0 to 0.4. This country dropped to the second place of the ranking only with a reduction in the compensation of the criteria caused by increasing of s coefficient to 0.45 and 0.5. This means that Austria has balanced performance values for all criteria, and a reduction in compensation does not result in a worse healthcare rating for the country's system. An interesting case is Switzerland, which ranks third in the ranking of the classic SPOTIS method without compensation reduction. However, as compensation reduction increases, it gradually moves up, and finally,

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with compensation reduction caused by s coefficient set to 0.45, it jumps to the top of the ranking. This proves that the country's healthcare performances are balanced across all the model's criteria. In a similar situation, an increase in compensation reduction not only does not cause a drop from good-ranking positions but actually contributes to advancement, which can be observed in countries such as Belgium, Denmark, France, Ireland, Sweden, the United Kingdom, and Czechia. On the other hand, a drop in ranking with an increase in compensation reduction can be seen for countries such as Norway, Finland, Greece, and the United States. This means that for these countries, good performances for certain criteria are able to compensate for poor values for other criteria. Therefore, when the compensation reduction is increased, the score of these countries decreases.

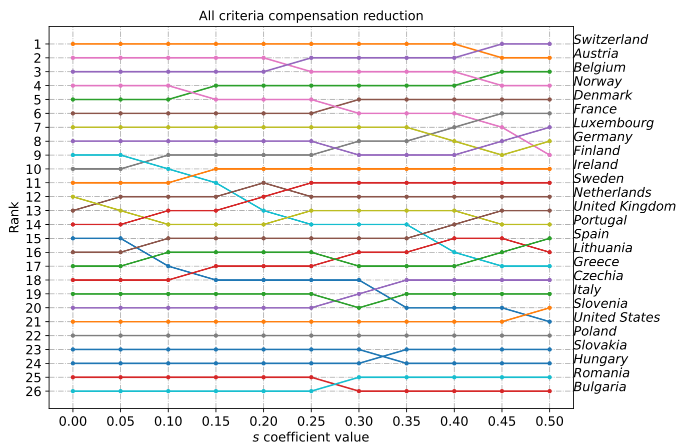

Fig. 1: Rank shifts caused by increasing compensation reduction of all criteria.

In the next step, the impact of an increase in compensation reduction in individual criterion groups was examined. Charts for simulating the compensation reduction of the other G_1-G_7 criteria are provided in the GitHub repository in the Supplementary material. Shifts in rankings caused by an increase in the s coefficient in the G_2 criterion group show the advancement of Denmark, Germany, Ireland, and Sweden. This means that even if the performances within this group were slightly worse for these countries, as simulated in this analysis, the performances within the rest of the healthcare criteria are stable and balanced enough that these countries not only do not fall in the rankings but still move up relative to the compared countries. In contrast, decreases in ranking with increases in reductions in G_2 criteria compensation were recorded for Belgium, Greece, and the United Kingdom. This suggests that reductions in the performances of the G_2 criteria in these countries are causing the dropping, as the performances for the other criterion groups are not strong and stable enough to prevent this.

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Noteworthy shifts in the case of G_1 criteria compensation reductions include the decrease of the United States, in the case of G_3 criteria compensation reductions, the advancement of Lithuania and the drop of Germany, in the case of G_4 criteria compensation reductions the promotion of Sweden, and the fall of Greece, in the case of G_5 criteria compensation reductions the decrease of Austria, in the case of G_6 criteria compensation reduction the advance of Belgium, in the case of G_7 criteria compensation reduction the drop of Luxembourg. The analysis demonstrated that Austria, Switzerland, Norway, Belgium, Finland, and Denmark are leaders of the rankings, regardless of the criteria compensation reduction. It confirms the excellent performances and high resilience of these countries' healthcare systems to emergencies according to the adopted model criteria.

4 Conclusions

This paper presented a newly developed methodological framework for DSS for multi-criteria evaluation, considering the modeling of criteria compensation based on the innovative SSP-SPOTIS multi-criteria method. The presented method is compliant with a strong sustainability paradigm, which is essential in sustainability assessment. The possibility to model the reduction of criteria compensation by setting the value of the coefficient s automatizes and facilitates the procedure. The practical application of the developed DSS was demonstrated for a practical example of assessing the resilience of healthcare systems in selected countries in relation to adopted model criteria. The performed research demonstrated the usefulness and reliability of DSS based on SSP-SPOTIS in evaluation procedures focused on sustainability aspects considering a strong sustainability paradigm. The proposed DSS allows the modeling of criterion compensation reduction and conducting simulations, which gives broad analytical opportunities. Future work directions cover developing strong sustainability paradigm based multi-criteria methods based on other MCDA compensation methods and comparative analysis of their results. The proposed approach is planned to be tested further in a benchmarking analysis covering a more comprehensive range of the s coefficient values and including different dimensions of datasets.

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