Evaluation of Digital Solutions for Sustainable Cities with Fuzzy AHP-EDAS Methods

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Abstract

Cities, the main living space of people, are one of the focal points of the concept of sustainability. Sustainable cities, which are of great importance in Sustainable Development Goals (SDGs), aim to create the nests of our future and to support this approach with digital solutions. The sustainable city concept aims to define many different needs of a city from a macro perspective and to make that city more environmentally friendly and more livable with the planning and investments to be made based on this definition. At this point, digital solutions are needed to meet all the needs of the residents of the city and to ensure their welfare in a sustainable way. In this context, the evaluation of digital solutions for sustainable cities is considered a Multi-Criteria Decision Making (MCDM) problem due to its mixed structure and many different criteria. However, it becomes difficult for experts to evaluate and make decisions about the system when the information is insufficient and uncertain. Therefore, in this study, the fuzzy approach is used to evaluate the MCDM problem more realistically and flexibly. The aim of the study is to propose an evaluation model and integrated analytic methods for the evaluation of digital solutions for sustainable cities. The fuzzy Analytic Hierarchy Process (AHP) method is used to calculate the weights of the criteria and fuzzy Evaluation Based on Distance from Average Solution (EDAS) is used to prioritize the digital solutions. Finally, an application is provided to demonstrate the potential of the proposed methodology.

Keywords

Digital solutions, Fuzzy ANP, Fuzzy EDAS and Sustainable Cities.

1. Introduction

Today, 3.5 billion people live in cities and this number is increasing day by day. Cities cover 3% of the world's surface area. 60-80% of energy consumption and 75% of carbon emissions occur in cities. Cities will be the future of many people. Huge problems faced by humanity, such as poverty, climate change, health services, and education, need to be solved in cities. Cities need to be planned and built stronger. Choosing a sustainable path means building cities where every citizen has a quality life, benefits from the productive dynamics of the city, produces common welfare, and ensures social stability without harming the environment (United Nations 2015; Bai et al. 2016; Litman 2021). At this point, it is necessary to correctly structure the concept of "Sustainable City"with the Sustainable Development Goals (SDGs) and to support this approach with digital solutions. Goal 11 of SDGs aims to provide access to housing, basic services, transportation services, and green spaces. It also calls for inclusive and sustainable urbanization and reducing the environmental impact of cities. Moreover, it promotes constructive economic, social, and environmental links between the city, its periphery, and the countryside (United Nations 2015).

The sustainable city concept aims to define many different needs of a city from a macro perspective and to make that city more environmentally friendly and more livable with the planning and investments to be made based on this definition (Satterthwait 1997; Haughton and Hunter 2004). For this purpose, while environmentally friendly investments such as wind energy and solar energy are made for the city's energy needs, the infrastructure systems that will be used for the most efficient transmission and distribution of the produced energy are renewed (Hecht et al. 2012; Sodiq et al. 2019; Golubchikov 2020).

At this point, digital solutions are needed to meet all the needs of the residents of the city and to ensure their welfare in a sustainable way. These digital solutions are supported by smart technologies such as artificial intelligence, the Internet of things, big data, and cloud computing. In this context, the evaluation of digital solutions for sustainable cities is considered a Multi-Criteria Decision Making (MCDM) problem due to its mixed structure and many different criteria (Hwang and Yoon 1981). However, it becomes difficult for experts to evaluate and make decisions about the system when the information is insufficient and uncertain. Therefore, in this study, the fuzzy approach (Zadeh 1965) is used to evaluate the MCDM problem more realistically and flexibly. This approach facilitates the decision-making processes of decision-makers (DMs) in complex and uncertain situations.

The aim of the study is to propose an evaluation model and integrated analytic methods for the evaluation of digital solutions for sustainable cities. The fuzzy Analytic Hierarchy Process (AHP) method is used to calculate the weights of the criteria and fuzzy Evaluation Based on Distance from Average Solution (EDAS) is used to prioritize the digital solutions. Finally, an application is provided to demonstrate the potential use of the proposed methodology. The contributions of this paper are offering a new evaluation model for sustainable cities, presenting integrated fuzzy AHP-EDAS methods in this area, and providing an application for the prioritization of digital solutions.

The organization of this paper is as the following. In the next section, the sustainable city concept and fuzzy MCDM approach are presented briefly. Then, the third section shows the proposed research methodology, and the application is provided in the fourth section. Finally, the last section concludes the paper.

2. Sustainable City Concept and Fuzzy MCDM Approach

Sustainable cities are settlements where human communities can live economically, socially, and environmentally in a healthy and high-quality manner and transfer this to future generations, consume the resources in their immediate and distant surroundings as little as possible, and show the ability to renew them (Haughton and Hunter 2004; Cooper et al. 2009; United Nations 2015).

The main objectives of sustainable cities are as follows (United Nations 2015):

- To turn the current and future expectations and problems of the city into a triggering force in all spaces and systems of the city,
- To be able to deal with physical, social, and digital planning together,
- Anticipate, identify and meet emerging challenges in a systematic, agile and sustainable manner,
- To reveal the potential of integrated service delivery and innovation by providing interaction between organizational structures in the city.

Sustainable cities aim to reduce their ecological footprint as much as possible by turning to renewable energy sources that cause the least pollution. It plans the use of land in the most effective way and prioritizes transportation options that take into account the needs and environmental priorities of the city residents. They minimize the negative impact of waste on climate change by reusing their waste as raw materials or energy using composting, recycling, and/or other recovery methods (Bibri and Krogstie 2017; Sodiq et al. 2019; Golubchikov 2020).

One of the most important goals of sustainable cities is to control the migration from rural areas to cities and to ensure expansion without disturbing the silhouette of the city. Cities must be able to provide jobs, housing, and other social services for people at all times. In this context, infrastructure and energy networks are the main veins of cities (McLaren and Agyeman 2015; Yigitcanlar and Cugurullo 2020). Sustainable energy sources are used within sustainable cities. Energy needs should be met with wind turbines, geothermal energy, and solar panels located at suitable points in these cities. In sustainable cities, infrastructure and general architecture should be planned in harmony with each other. Sustainable cities are designed to maximize the living standards of their inhabitants (Belli et al. 2020).

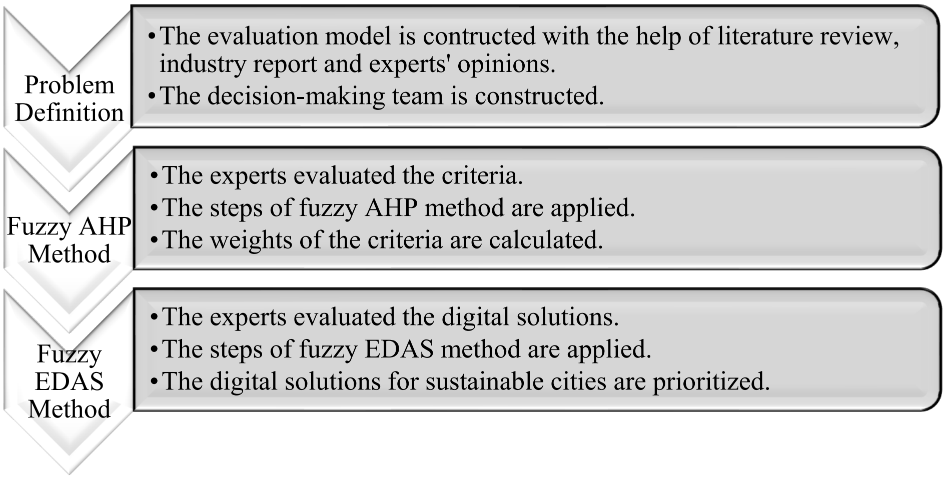
In cities where the sustainable city concept is implemented, important modernizations are made regarding the transportation system. While the rail systems and signaling systems are renewed according to today's latest technologies, additional studies are carried out to ensure that the city population has a more livable place. Within the scope of the concept, in addition to the city's need for clean water and waste management, solutions such as energyefficiency in buildings, city safety and security systems, airports, sports facilities, and health systems are implemented (Woetzel and Kuznetsova 2018; Microsoft and EY 2021; Litman 2021).

Fuzzy AHP is a method that will allow decision-makers to make decisions in an MCDM process and facilitate decision-making in uncertain situations (Ayağ 2005). When the literature is examined, it is seen that different authors present many different fuzzy AHP methods. Ghorabaee et al. (2016) offer the EDAS technique with fuzzy logic for supplier selection in the literature. In addition, the EDAS approach was integrated with advanced methodologies from the literature.

In the literature, the number of studies on sustainable cities and fuzzy approach is quite low. Awasthi and Chauhan (2012) propose a hybrid approach integrating Affinity Diagram, AHP, and fuzzy TOPSIS for sustainable city logistics planning. Parlina et al. (2021) present emerging trends in smart sustainable city research with deep autoencoders-based fuzzy C-means. In this study, the digital solutions for sustainable cities are evaluated with integrated fuzzy ANP-EDAS methods, for the first time.

3. Proposed Research Methodology

The proposed research methodology consists of three basic steps as in Figure 1.



- The evaluation model is contructed with the help of literature review, industry report and experts' opinions.
- The decision-making team is constructed.

- The experts evaluated the criteria.
- The steps of fuzzy AHP method are applied.
- The weights of the criteria are calculated.

- The experts evaluated the digital solutions.
- The steps of fuzzy EDAS method are applied.
- The digital solutions for sustainable cities are prioritized.

Figure 1. The stages of the proposed research methodology

3.1 Proposed Evaluation Model and Digital Solutions for Sustainable Cities

This study proposes the evaluation model by conducting a literature review, investigating industrial reports, and taking the experts' opinions. The proposed evaluation model is as in Table 1 (Hecht et al. 2012; Woetzel and Kuznetsova 2018;Golubchikov 2020; Microsoft and EY 2021**;** Litman 2021).

Table 1. The proposed evaluation model

Main Criteria	Sub-Criteria
Sustainable Environment (C1)	Resource management (C11)
	Water & air efficiency (C12)
	Energy distribution optimization (C13)
Sustainable Transport (C2)	Multi-mode transportation (C21)
	Road planning (C22)
	Land use accessibility (C23)
Sustainable People & Living (C3)	Digital skills for green life (C31)
	Digital health (C32)
	Digital education (C33)
Sustainable Economy (C4)	Economic growth and stability (C41)
	Sustainable agriculture (C42)
	Job growth and poverty alleviation (C43)
Sustainable Governance (C5)	Integrated, comprehensive, and inclusive planning (C51)
	Safety, security, and privacy (C52)

	Technology and utilization efficiency (C53)

Digital solutions for sustainable cities are as follows (Woetzel and Kuznetsova 2018; Litman 2021):

- ***Digital transportation management and e-hailing (DS1):*** E-hailing services provide computer or mobile device users a handy method to be picked up and delivered by a car. E-hailing and ride-sharing were studied independently. E-hailing services first arrived in most major cities three to six years ago, dramatically changing the face of the sector in such a short time. E-hailing is a remarkable example of the rapid transformation brought about by smart-city technology in both traditional sectors and citizen life.
- ***Digital government services and civic-engagement tools (DS2):*** From tax returns to construction permissions, government services are being digitized and made available online. Although adoption rates vary greatly, the majority of the world's governments are expected to digitize their services in recent years. Citizens can utilize civic-engagement tools to participate in crowdsourcing, voting, and decision making; report non-critical concerns; and seek services.
- ***Digital healthcare services and health wearable devices (DS3):*** Wearable health devices, which are linked to various platforms and applications, enable users to enhance their physical well-being. User-friendly interfaces aid in data analysis and decision-making about modifying behavior or selecting a treatment program.
- ***Digital reskilling and learning programs (DS4):*** Smart technology may also be used in education, from digitizing course materials and tests to creating a personalized educational trajectory. While the survey results only include one practical sort of online education—reskilling courses—these platforms are also utilized in elementary and secondary school education to study programming or languages, among other things.
- ***Digital meters for real-time tracking apps in water and electricity consumption (DS5):*** Smart meters include an app that allows real-time monitoring of resource use. This feature enables customers to better understand their usage habits and optimize their payments by using resources during off-peak hours. Because citizens are driven by off-peak taxes or fees, reallocating electric electricity to off-peak hours improves the economy.

3.2 Fuzzy AHP-EDAS Methods

AHP is developed by Saaty (1980) probably the best-known and most widely used model in decision-making. It is a robust decision-making methodology to determine the priorities among different criteria. Fuzzy AHP used in this study includes the following steps (Büyüközkan and Çifçi 2012):

Step 1: Construct the fuzzy comparison matrices by using triangular fuzzy numbers in Table 2.

Table 2.The fuzzy scale

Linguistic expression	**Fuzzy Scale**
Extremely more importance (EMI)	(8, 9, 10)
Very strong importance (VSI)	(6, 7, 8)
Strong importance (SI)	(4, 5, 6)
Moderate importance (MI)	(2, 3, 4)
Equal importance (EI)	(1, 1, 2)

Step 2: α-cut matrices are constructed. The α-cut is known to incorporate DMs' confidence over his/her preferences. The index of optimism μ estimates the degree of satisfaction for the judgment matrix. A larger value of the index μindicates a higher degree of optimism. The index of optimism is a linear convex combination defined as

$$\tilde{a}_{ij}^{\alpha} = \mu\tilde{a}_{ijl}^{\alpha} + (1-\mu)\tilde{a}_{ijl}^{\alpha}\forall\alpha \in [0,1] \tag{1}$$

Step 3: Matrices are normalized using (2) and the consistency ratio (CR) for each matrix is calculated.

$$\tilde{r}_{ij} = \frac{\tilde{a}_{ij}^{\alpha}}{\sum_{i}^{k}\tilde{a}_{ij}^{\alpha}} \tag{2}$$

$$\boldsymbol{CI} = \frac{\boldsymbol{\lambda_{max}} - \boldsymbol{n}}{\boldsymbol{n} - \boldsymbol{1}} \tag{3}$$

$$\boldsymbol{CR} = \frac{\boldsymbol{CI}}{\boldsymbol{RI}} \tag{4}$$

where $\boldsymbol{CI}$ refers to consistency index, $\boldsymbol{\lambda_{max}}$ is the largest eigenvector of the matrix, n is the number of criteria, and $\boldsymbol{RI}$ is the random index.

Step 4: The weights of the main criteria ($\tilde{\boldsymbol{w}}_i{}^{CR}$ *)* are obtained using the arithmetic mean. And, these steps are applied for each sub-criteria, and global weights ($\tilde{\boldsymbol{w}}_{ij}{}^{G}$) are calculated by multiplying the weight of the main criteria.

$$\tilde{\boldsymbol{w}}_{ij}{}^{G} = \tilde{\boldsymbol{w}}_i{}^{CR} \times \tilde{\boldsymbol{w}}_j{}^{CR} \tag{5}$$

Ghorabaee et al. (2015) introduced the EDAS technique and proved its validity. For the evaluation of alternatives, this technique examines the average answer. It is also an approach based on distance. The following are the steps of the fuzzy EDAS technique (Ghorabaee et al. 2016):

Step 1: A fuzzy scale in Table 2 is used to generate the matrix between components and strategic goals.

Step 2: Positive and negative distances from average (PDA-NDA) matrices are computed. The set of beneficial criteria is denoted by *B*, whereas the set of non-beneficial criteria is denoted by *N*.

$$\widetilde{pda}_{ij} = \begin{cases} \frac{\psi(\tilde{x}_{ij} \ominus \widetilde{av}_j)}{\kappa(\widetilde{av}_j)} & if\ j \in B \\ \frac{\psi(\widetilde{av}_j \ominus \tilde{x}_{ij})}{\kappa(\widetilde{av}_j)} & if\ j \in N \end{cases} \tag{6}$$

$$\widetilde{nda}_{ij} = \begin{cases} \frac{\psi(\widetilde{av}_j \ominus \tilde{x}_{ij})}{\kappa(\widetilde{av}_j)} & if\ j \in B \\ \frac{\psi(\tilde{x}_{ij} \ominus \widetilde{av}_j)}{\kappa(\widetilde{av}_j)} & if\ j \in N \end{cases} \tag{7}$$

where $\widetilde{av}_j$ denotes the average solutions matrix and $\kappa(\widetilde{av}_j)$ is the defuzzified number.

Step 3: The weighted sum of positive and negative distances is computed.

$$\widetilde{sp}_i = \oplus_{j=1}^{m}(\tilde{w}_j \otimes \widetilde{pda}_{ij}) \tag{8}$$

$$\widetilde{sn}_i = \oplus_{j=1}^{m}(\tilde{w}_j \otimes \widetilde{nda}_{ij}) \tag{9}$$

Step 4: The values for all alternatives are normalized.

$$\widetilde{nsp}_i = \frac{\widetilde{sp}_i}{max_i(\kappa(\widetilde{sp}_i))} \tag{10}$$

$$\widetilde{nsn}_i = 1 - \frac{\widetilde{sn}_i}{max_i(\kappa(\widetilde{sn}_i))} \tag{11}$$

Step 5: The assessment score ($\widetilde{as}_i$) for all alternatives is computed.

$$\widetilde{as}_i = \frac{1}{2}(\widetilde{nsp}_i \oplus \widetilde{nsn}_i) \tag{12}$$

Step 6: The strategic goals are ranked based on their assessment values.

4. Application of the Proposed Research Methodology

"Sustainable Cities and Communities", goal 11 of the SDGs, aims to make cities and settlements inclusive, safe, resilient, and sustainable. In this context, digital solutions for sustainable cities are prioritized with the evaluation model created in this study. The weights of the criteria are calculated with the fuzzy AHP method and the digital solutions are prioritized with the fuzzy EDAS method.

Evaluations in this study are made by three DMs. All three DMs are sufficiently knowledgeable and experienced in the field of sustainable and smart cities. The weights of the DMs are considered equal. DM1 has private sector experience in sustainable project management. DM2 conducts academic and industrial research on sustainability and SDGs. DM3 has public sector experience in smart and sustainable cities.

4.1 Calculation of Criteria Weights with Fuzzy AHP Method

As a starting point, the evaluation model is constructed as in Table 1 with a literature review and expert opinions. Then, the fuzzy comparison matrix between these criteria is structured by using triangular fuzzy numbers in Table 2. The comparison matrix for the main criteria is shown in Table 3.

Table 3.The comparison matrix for the main criteria

	C1			**C2**			**C3**			**C4**			**C5**		
C1	1.000	1.000	1.000	0.250	0.333	0.500	1.000	1.000	2.000	0.500	1.000	1.000	0.167	0.200	0.250
C2	2.000	3.000	4.000	1.000	1.000	1.000	4.000	5.000	6.000	6.000	7.000	8.000	1.000	1.000	2.000
C3	0.500	1.000	1.000	0.167	0.200	0.250	1.000	1.000	1.000	2.000	3.000	4.000	2.000	3.000	4.000
C4	1.000	1.000	2.000	0.125	0.143	0.167	0.250	0.333	0.500	1.000	1.000	1.000	0.250	0.333	0.500
C5	4.000	5.000	6.000	0.500	1.000	1.000	0.250	0.333	0.500	2.000	3.000	4.000	1.000	1.000	1.000

α-cut matrices (α=0.5; μ=0.5) are constructed by using (1) and these matrices are normalized as in Table 4.CR is checked by using (3) and (4).

Table 4. The normalized matrix for the main criteria

	C1	**C2**	**C3**	**C4**	**C5**
C1	0.089	0.151	0.182	0.051	0.034
C2	0.267	0.403	0.606	0.475	0.247
C3	0.067	0.084	0.121	0.203	0.493
C4	0.133	0.059	0.045	0.068	0.062
C5	0.444	0.303	0.045	0.203	0.164

These steps are applied for all sub-criteria, and final global weights for all criteria are calculated. The final criteria weights are shown in Table 5.

Table 5. The final criteria weights

Main Criteria	Weights	Sub-Criteria	Weights	Global Weights
C1	0.101	**C11**	0.720	0.073
		C12	0.086	0.009
		C13	0.194	0.020
C2	0.399	**C21**	0.212	0.085
		C22	0.106	0.042
		C23	0.682	0.272
C3	0.194	**C31**	0.057	0.011
		C32	0.302	0.058
		C33	0.642	0.124
C4	0.073	**C41**	0.165	0.012
		C42	0.704	0.052
		C43	0.131	0.010
C5	0.232	**C51**	0.056	0.013

		C52	0.700	0.162
		C53	0.244	0.057

According to the final weights, the most appropriate criteria are "Land use accessibility (C23)", "Safety, security and privacy (C52)" and "Digital education (C33)". These three criteria stand out from the other criteria with the values they receive.

4.2 Prioritization of Digital Solutions with Fuzzy EDAS Method

Firstly, the matrix between evaluation criteria and digital solutions is constructed with the help of the fuzzy scalein Table 2. Table 6 shows the DMs' evaluations of the digital solutions.

Table 6. The evaluation matrix for the digital solutions

	C11	**C12**	**C13**	**C21**	**C22**	**C23**	**C31**	**C32**	**C33**	**C41**	**C42**	**C43**	**C51**	**C52**	**C53**
DS1	EMI	EMI	VSI	EI	EI	MI	EMI	EMI	VSI	VSI	EMI	EMI	SI	MI	SI
DS2	SI	VSI	VSI	MI	SI	SI	VSI	SI	SI	MI	VSI	EI	MI	EI	MI
DS3	VSI	SI	EMI	EMI	EMI	EMI	SI	EI	VSI	SI	EMI	EMI	VSI	EI	SI
DS4	EMI	VSI	EMI	EMI	EMI	EMI	EI	VSI	EI	VSI	EMI	SI	VSI	SI	MI
DS5	MI	EI	MI	VSI	VSI	EMI	SI	VSI	EMI	SI	SI	EMI	SI	VSI	SI

The PDA and NDA matrices are built with (6) and (7) and $\widetilde{sp}_i$ and $\widetilde{sn}_i$ values are calculated using (8) and (9). $\widetilde{nsp}_i$, $\widetilde{nsn}_i$ and $\widetilde{as}_i$ parameters are computed by using (10)-(12). The final valuesareillustrated in Table 7.

Table 7. The final ranking

	NSP			**NSN**			**AS**			**Defuzz. Value**	**Ranking**
DS1	0.828	1.079	1.094	0.468	0.525	0.628	0.648	0.802	0.861	0.7703	2
DS2	0.702	0.895	0.914	0.941	0.985	0.987	0.822	0.940	0.951	0.9041	1
DS3	0.221	0.264	0.308	0.001	0.064	0.281	0.111	0.164	0.294	0.1898	3
DS4	0.279	0.344	0.403	-0.079	-0.072	0.169	0.100	0.136	0.286	0.1740	5
DS5	0.276	0.372	0.427	-0.111	-0.052	0.163	0.083	0.160	0.295	0.1792	4

At the conclusion of the fuzzy EDAS method, the most appropriate digital solution is "Digital government services and civic-engagement tools (DS2)", while digital transportation management and e-hailing (DS1), digital healthcare services and health wearable devices (DS3), digital meters for real-time tracking apps in water and electricity consumption (DS5), and digital reskilling and learning programs (DS4) have positioned at the second, third, fourth, and fifth ranks as the final performance values, respectively.

5. Conclusion

This paper aimed to propose an evaluation model for sustainable cities and prioritize digital solutions using an integrated fuzzy MCDM approach. The weights of the criteria were obtained with the fuzzyAHP method, and the fuzzy EDAS method was used to prioritize digital solutions.

An application was shown to demonstrate the methodology's efficacy, and the outcomes of this examination were presented. The most appropriate criteriawere found as "Land use accessibility (C23)", "Safety, security and privacy (C52)" and "Digital education (C33)", and the first ranked digital solution was determined as "Digital government services and civic-engagement tools (DS2)". In the digital state process, information and communication technologies can be used to make public organizations more effective and efficient and strengthen democracy, as well as to enable citizens to access certain information over the internet, and facilitate certain transactions. Thus, it makes the political system and public administration more transparent, democratic, sensitive, and effective.

For future investigation, aggregation operators can be used to aggregate DMs' evaluations in group decision-making. On the other hand, other extensions (e.g. elicit information, pythagorean fuzzy sets, spherical fuzzy sets) of fuzzy sets may be implemented into the framework.

Acknowledgements

The authors would like to express their gratitude towards industry specialists. Galatasaray University's Scientific Research Projects Commission provided support for this work (FOA-2021-1059).

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