Journal of Innovation & Knowledge 10 (2025) 100651

Contents lists available at ScienceDirect

Journal of Innovation & Knowledge

journal homepage: www.elsevier.com/locate/jik

Innovative approaches to green digital twin technologies of sustainable smart cities using a novel hybrid decision-making system

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A R T I C L E I N F O

JEL Codes:
O33
Q01
R11
Q55

Keywords:
Knowledge-based systems
Sustainability
Digital twin
Sustainable smart cities
Innovation

A B S T R A C T

Digital twin technologies play a very important role in the provision of smart cities. However, it is not clear which innovative strategies should be implemented first on how to optimize digital twin technologies for sustainable smart cities. The main performance indicators should be identified to use the limited resources more efficiently and to generate more effective investment strategies. Accordingly, the purpose of this study is to generate innovative approaches to green digital twin technologies of sustainable smart cities. To achieve this issue, first, important criteria of digital twin technologies for assessing sustainable smart cities are weighted via spherical fuzzy simple weight calculation (SIWEC). The second part includes ranking innovative alternatives for green digital twin technologies by considering spherical fuzzy simple additive weighting (SAW). The main contribution of this manuscript is to identify the most effective investment strategies for the improvements of digital twin technologies to reach smart cities by establishing a novel model. The preference of the SIWEC method in the criteria weighting process provides some advantages to the model. The most important feature of this method is that the direct importance of the criterion is taken into consideration in the questions asked to the experts. In this way, it is possible for the experts to give more sensitive answers. The findings indicate that smart grid integration (weight: 0.231) is determined as the most important criterion in the development of digital twin technologies for the provision of smart cities. Circular economy (weight: 0.230) is another variable that plays an important role in the provision of smart cities. On the other hand, decentralized energy system with microgrids is found as the most important alternative for this situation. Some critical actions should be taken to improve the smart grid effectiveness. In this scope, providing renewable energy incentives has a strong influence on the improvements of these projects.

Introduction

Smart cities are cities that aim to use resources more efficiently and support environmental sustainability. To achieve this goal, advanced information and communication technologies are used. Therefore, the integration of technological infrastructure and effective data management are very critical to achieve smart city goals. In this context, digital twin technologies play a very important role in the provision of smart cities. In green digital twin technologies, digital copies of physical assets are created (Huda et al., 2024). In this way, the performance and environmental impacts of these assets are analyzed. Therefore, it is aimed to optimize projects with digital twin technologies. Today, it is possible to talk about very different green digital twin technologies. With the integration of the Internet of Things, real-time data collection can be made to keep the digital twin up to date. By analyzing this data correctly, it is possible to effectively track critical data such as energy production and consumption. Artificial intelligence technology can also be taken into consideration in green digital twin applications. With this technology, data from digital twins can be analyzed and predictions can be made for the future (Sharifi et al., 2024). This situation supports the

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https://doi.org/10.1016/j.jik.2025.100651
Received 15 October 2024; Accepted 1 January 2025
Available online 9 January 2025

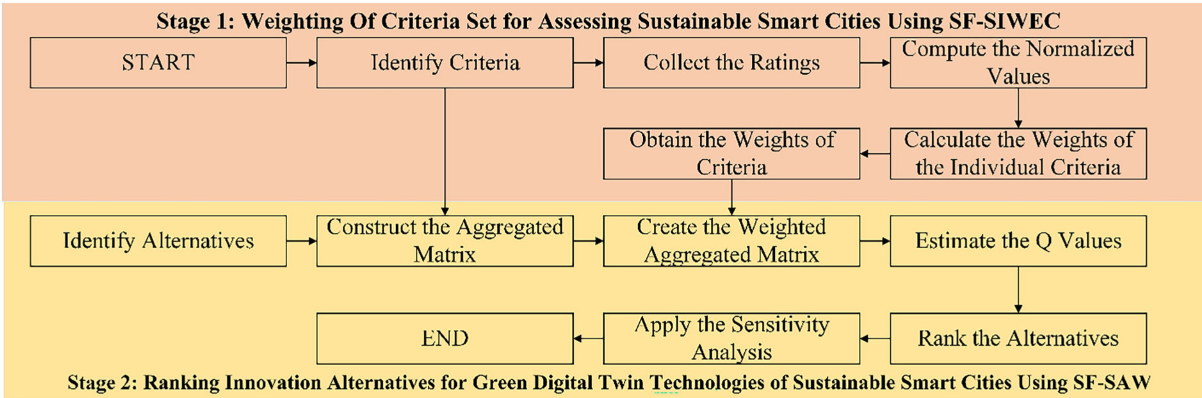

Fig. 1. Recommended Methodology.

Table 1
The Determined Criteria for Assessing Sustainable Smart Cities.

Definitions	Codes
Circular economy	CIRECNMY
Energy Optimization	EGYOPT
Environmental infrastructure	ENTINF
Water management	WYRMNG
Carbon-neutral systems	CRBNTRSYS
Smart grid integration	SMRGRDINT
Climate-Adapted Design	CLMADP

acquisition of insights for improving the process. Moreover, building information modeling is another important example of green digital twin technology. In this process, the energy performance of buildings is analyzed. With this modeling, it is possible to present strategy suggestions that can achieve energy savings (Tang & Li, 2024).

Green digital twin technologies are important for smart cities in many ways. With the application of these technologies, it is possible to achieve energy efficiency. With these analyzes, energy consumption can be reduced, and this contributes to the cost efficiency of businesses. Another advantage of green digital twin technology is that it supports the reduction of carbon emissions (Fadhel et al., 2024). In the evaluations made with these technologies, it is possible to determine the main factors of carbon emissions (Su et al., 2023). As a result, it allows the right strategies to be determined for more effective management of this problem. On the other hand, these technologies also allow real-time monitoring of data. Due to this condition, potential problems can be detected at an early stage. This helps to take the necessary actions in a timely manner. Furthermore, renewable energy integration is another advantage of digital twin technology (Bibri et al., 2024). With this technology, the use of different renewable energy alternatives together can be optimized. Owing to this issue, it is possible to provide uninterrupted electricity production (Prakash et al., 2024).

The factors that have the greatest impact on the performance of green digital twin technologies need to be determined. This is primarily important in terms of effective use of resources. Both financial and human resources of businesses are quite limited. In this context, these resources need to be evaluated effectively to increase the performance of businesses (Cui & Cao, 2024). Otherwise, the actions taken to improve these projects cause costs to increase very radically. This situation causes businesses to experience financial problems. Determining the most effective variables is also necessary for making the right strategic investment decisions. If the most important factors are not determined, businesses may determine less efficient strategies. This situation may cause the operational efficiency of businesses to decrease (Nassereddine & Khang, 2024). Consequently, a priority analysis should be carried out for the factors that have the greatest impact on the performance of these projects. On the other hand, there are very few studies for this concept. This issue creates a very important research gap on this issue. This issue also increases the need for studies in which the most important factors are determined.

Accordingly, the purpose of this study is to develop innovative approaches to green digital twin technologies of sustainable smart cities. A new model has been proposed to reach this objective. In the first section, important criteria of digital twin technologies for assessing sustainable smart cities are weighted via spherical fuzzy SIWEC method. In this process, the criteria are identified and normalized values are computed. The second part includes ranking innovative alternatives for green digital twin technologies by considering spherical fuzzy SAW methodology. Within this context, weighted aggregated matrix and q values are identified. After that, a comprehensive sensitivity analysis is applied to measure the reliability of the ranking results. By considering these issues, the research questions of this manuscript are demonstrated as follows.

Table 2
The Ratings of Criteria.

	CIRECNMY	EGYOPT	ENTINF	WYRMNG	CRBNTRSYS	SMRGRDINT	CLMADP
Expert1	8	2	3	8	4	9	6
Expert2	8	5	2	4	3	8	2
Expert3	9	4	2	1	3	9	8

Table 3
The Initial Decision-making Matrix.

	CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
Expert1	.80	.20	.20	.20	.80	.20	.30	.70	.30	.80	.20	.20	.40	.60	.40	.90	.10	.10	.60	.40	.40
Expert2	.80	.20	.20	.50	.50	.50	.20	.80	.20	.40	.60	.40	.30	.70	.30	.80	.20	.20	.20	.80	.20
Expert3	.90	.10	.10	.40	.60	.40	.20	.80	.20	.10	.90	.10	.30	.70	.30	.90	.10	.10	.80	.20	.20

Table 4
The Normalized Values.

	CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
Expert1	.893	.081	.185	.249	.706	.246	.370	.573	.360	.893	.081	.185	.488	.450	.463	.962	.027	.078	.709	.239	.425
Expert2	.893	.081	.185	.602	.339	.547	.249	.706	.246	.488	.450	.463	.370	.573	.360	.893	.081	.185	.249	.706	.246
Expert3	.962	.027	.078	.488	.450	.463	.249	.706	.246	.125	.848	.124	.370	.573	.360	.962	.027	.078	.893	.081	.185

(1) Which indicators for assessing sustainable smart cities have the greatest significance weights?
(2) Which innovative alternatives for green digital twin technologies of sustainable smart cities should be priorly implemented?

The main motivation of this study is the need to determine the priority digital twin technologies for the development of sustainable smart cities. Due to problems such as the increase in energy consumption and the criticality of environmental problems, the development of sustainable smart cities is of vital importance. However, there is no consensus in the literature on which digital twin technologies are most suitable for sustainable smart cities. Hence, there is a strong need that these prior strategies should be identified. Another motivation of this study is the need for innovative approaches to the development of digital twin technologies. Due to the limited resources of businesses, the most important variables need to be determined. Otherwise, reaching the wrong strategies leads to financial problems for businesses. On the other hand, there are very few studies in the literature that calculate the importance weight of these factors. Multi-criteria decision-making models can be established to achieve these goals. With these models, the criteria with the highest importance weight and the best investment alternatives can be determined. The important issue in this process is the need to minimize the uncertainty in the process.

The main contribution of this study is to identify the most effective investment strategies for the improvements of digital twin technologies to reach smart cities by establishing a new fuzzy decision-making model. The most important theoretical contribution of the study to the literature is the prioritization of digital twin technologies for sustainable smart cities. There is a lack of a clear roadmap in the literature regarding digital twin technologies that can be used in sustainable smart cities. This study determines the most important factors of these investments. Therefore, this study has a guiding role for the investors in making strategic decisions. Moreover, this study identifies innovative alternatives for the development of existing digital twin technologies. This situation helps businesses determine the right strategies to use their limited resources in the most efficient way. Furthermore, the study provides strategic guidance on which digital twin technologies are more effective for the development of sustainable smart cities. In this way, countries can achieve their sustainable development goals much more easily. On the other side, the main superiorities of the proposed model are denoted as follows.

(1) The preference of the SIWEC method in the criteria weighting process provides some advantages to the model. The most important feature of this method is that it does not compare the criteria with each other. Instead, the direct importance of the criterion is taken into consideration in the questions asked to the experts. In this way, it is possible for the experts to give more sensitive answers. There is no serious causality relationship between the factors affecting the performance of digital twin technology investments to be developed for smart cities. In this context, the preference of the SIWEC method is more suitable for this study compared to techniques such as DEMATEL and M-SWARA. These techniques consider causal directions between the criteria. However, this calculation method is not appropriate for the evaluations of performance indicators of sustainable smart cities. The AHP technique is also a weighting model that does not take into consideration the causality relationship between the criteria. In this method, experts are asked to evaluate the criteria through pairwise comparisons. However, inconsistency problems may occur in some expert evaluations. On the other hand, in the SIWEC method, experts are asked to directly indicate the importance levels of the criteria. This approach allows experts to reflect their evaluations more precisely.
(2) The use of spherical fuzzy numbers also increases the quality of the analysis process. The greatest advantage of these numbers

Table 5
The Score Values of Normalized Values and Standard Deviations.

	CIRECNMY	EGYOPT	ENTINF	WYRMNG	CRBNTRSYS	SMRGRDINT	CLMADP	Std Dev
Expert1	2.564	−0.276	−0.010	2.564	.216	3.408	.984	1.477
Expert2	2.564	.426	−0.276	.216	−0.010	2.564	−0.276	1.269
Expert3	3.408	.216	−0.276	−0.602	−0.010	3.408	2.564	1.801

compared to others is that they use a more comprehensive data set. In this way, it is possible to perform more effective analyses. In addition to this condition, hesitancy is also taken into consideration in the analysis process. This contributes to the more effective minimization of uncertainty. As a result, it is much easier to increase the consistency of the analysis results. In this context, spherical fuzzy sets have some advantages over other types of fuzzy numbers. For example, classical fuzzy numbers only take into consideration a membership degree. In spherical fuzzy numbers, membership, non-membership and hesitancy degrees are considered. This supports a more accurate management of uncertainty. On the other hand, the greatest advantage of spherical fuzzy numbers over Pythagoras and q-ROF sets is that they perform analysis with a wider data set. This allows for more comprehensive analyses.

(3) The use of the SAW technique in the ranking of alternatives also provides some advantages to the model. Methods such as TOPSIS, VIKOR and CODAS rank the alternatives based on the distance to the ideal value. On the other hand, using Euclidean distances in this process is often criticized. The SAW method ranks the alternatives by looking at the ratio of the total score of the alternatives to the highest total score. This situation also offers the opportunity to obtain a more realistic result.

This study consists of 6 different sections. Section 2 includes summaries of previous studies in the literature that affect digital twin technology performance. By analyzing these studies, the missing part in the literature is determined. The model developed to eliminate this deficiency is explained in Section 3. Section 4 shares the analysis results of this model. The last two sections consist of basic results, comparison of these results with other studies, and future work recommendations.

Literature review

Circular economy is extremely important for the performance of green digital twin technologies. Circular economy supports more efficient use of resources. In this context, reducing waste is one of the biggest benefits of circular economy (Zhang et al., 2024). Therefore, circular economy and green digital twin technologies interact with each other. In this process, circular economy is supported by digital transformation and innovation (Ma et al., 2024). On the other hand, digital twins perform analyses to continuously improve circular economy applications. In other words, both factors positively affect each other (Shehadeh et al., 2024). In this context, it is possible to reach circular economy targets more easily with analyses to be performed on digital twins. Similarly, Kumar et al. (2024) identified that energy optimization can be achieved much easier with circular economy applications. Patil et al. (2024) denoted that this allows digital twins to minimize energy consumption. The sustainability performance of digital twin applications can be increased with energy savings. This issue allows more investments to be made in green digital twin technology projects.

Smart grid integration can also have an impact on green digital twin investment performance. The most up-to-date technology is used in smart grids. In this way, comprehensive analysis can be performed for energy production and consumption. This is very critical for ensuring energy supply security (Yan & Kunhui, 2024). Providing uninterrupted energy supports increasing customer satisfaction. Therefore, the use of advanced technology contributes to more successful digital twin performance (Qin and Niu, 2024). More effective digital twin analysis can be performed with advanced methods. Smart grids also provide real-time data on energy distribution (Kanimozhi et al., 2024). Green digital twins can predict possible faults in the grid using this data. This offers the opportunity to intervene correctly in these problems. On the other hand, Kulkarni et al. (2024) defined that smart grid integration ensures the successful implementation of energy management strategies. Similarly, Subhadarshini and Prusty (2024) denoted that digital twins can also optimize energy demand according to consumer habits. In summary, thanks to smart grids, digital twins enable the development of comprehensive strategies that can reduce energy costs.

Environmental infrastructure is of critical importance for the performance of green digital twin technologies. Environmental infrastructure is particularly essential for the development of smart buildings and smart cities. Digital twin technology also plays a very important role in achieving this goal. For digital twin technology to be successfully implemented, environmental infrastructure must be successfully determined (Jin et al., 2024). Moreover, environmental infrastructure has the capacity to collect real-time data via sensors. Green digital twin can also perform very comprehensive analyses with this data (Zhen & Yao, 2024). In this way, correct strategies can be developed to ensure energy efficiency. Otherwise, if incorrect data is obtained, correct simulations cannot be performed with digital twin Matei and Cocoșatu (2024). This situation causes the optimization of energy investments to fail. On the other hand, Bamakan and Far (2024) demonstrated that environmental infrastructure is also necessary for the sustainability of transportation processes. Tao et al. (2024) identified that data obtained from environmental elements are examined in detail thanks to digital twin. As a result, it is possible to reduce the carbon footprint.

Energy optimization can also affect performance of green digital twin technologies. Digital twins analyze data on many different variables in detail and try to produce strategies for the development of projects. In this process, one of the data most used by digital twin technology is energy optimization simulations (Wang et al., 2024). In these analyzes, the actions required to ensure the efficiency of energy management processes can be determined (Piras et al., 2024). The validity of these actions can also be tested with digital twin technologies. One of the most important goals of energy optimization is to reduce costs. In this context, the most appropriate energy consumption models are tried to be determined (Sung et al., 2024). In digital twin technologies, these models are analyzed, and it is aimed to reduce unnecessary energy expenditures. Moreover, Hu and Assaad (2024) determined that this situation is also necessary for the effectiveness of energy storage processes. Energy optimization contributes to the determination of the energy supply-demand balance of projects. Arowoiya et al. (2024) indicated that temporal fluctuations in energy demand can be understood more clearly. This situation allows the analyzes made by digital twins regarding energy storage processes to be more accurate.

As a result of the literature review on green digital twin technologies, some important results can be obtained. As can be understood from the studies, the main factors affecting the performance of these projects are compliance with circular economy targets, smart grid integration, environmental infrastructure and energy optimization. On the other hand, these components are generally examined separately in existing studies. Therefore, it is seen that there is a lack of studies showing how these variables interact with each other. In this context, studies are needed to determine the variables that affect the performance of green digital twin technologies the most. By determining these variables,

Table 6
The Weights of Individual Criteria.

	CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
Expert1	.952	.024	.150	.300	.597	.292	.442	.439	.415	.952	.024	.150	.576	.308	.508	.989	.005	.050	.802	.121	.416
Expert2	.932	.041	.166	.659	.253	.559	.279	.643	.273	.541	.363	.492	.413	.493	.393	.932	.041	.166	.279	.643	.273
Expert3	.995	.002	.036	.623	.238	.524	.329	.534	.317	.167	.743	.165	.483	.367	.441	.995	.002	.036	.971	.011	.126

Table 7
The Total Values.

	Spherical Fuzzy			Score
CIRECNMY	1.000	.000	.007	3.970
EGYOPT	.828	.036	.494	1.303
ENTINF	.582	.151	.487	.449
WYRMNG	.967	.007	.183	3.059
CRBNTRSYS	.758	.056	.517	.958
SMRGRDINT	1.000	.000	.003	3.987
CLMADP	.991	.001	.111	3.496

Table 8
The Weights and Priorities of the Criteria.

	Weights	Priorities
CIRECNMY	.230	2
EGYOPT	.076	5
ENTINF	.026	7
WYRMNG	.178	4
CRBNTRSYS	.056	6
SMRGRDINT	.231	1
CLMADP	.203	3

Table 9
The Selected Innovation Alternatives.

Alternatives	Codes
AI-based optimization of sustainability	AIOPT
Smart infrastructure using IoT	SMRINFLOT
Decentralized energy systems with microgrids	DECENGSYS
Energy data monitoring with edge computing	DATAMONT
Land use planning with geospatial analytics	LANDPLN

businesses will be able to both develop effective investment strategies and use their limited human and financial resources efficiently.

Recommended methodology

Within the scope of the purpose of the article to rank innovative approaches to green digital twin technologies of sustainable smart cities, a hybrid decision-making methodology is recommended. In the first stage of the recommended methodology, important criteria for assessing sustainable smart cities are weighted with the help of SIWEC method. In the second stage, using the SAW method, innovation alternatives for green digital twin technologies of sustainable smart cities are ranked with the calculated criterion weights. The reason for preferring the SIWEC and SAW methods is to include them in the analysis in non-numerical cases. In addition, Spherical fuzzy numbers, one of the fuzzy sets, are used to manage uncertainty for linguistic scales. The detailed schematic representation of the recommended methodology is exhibited in Fig. 1.

Spherical fuzzy SIWEC

The SIWEC method is a multi-criteria decision-making technique in which criteria are weighted considering the range of experts' ratings. This allows experts to provide more accurate and realistic information. The SIWEC method developed with spherical fuzzy numbers is summarized below (Puška et al., 2024).

In the first step, experts are asked to rate the criteria, and the ratings are transformed into Spherical fuzzy numbers. The initial decision-making matrix is constructed, with $\widetilde{x} = (\alpha, \beta, \gamma)$ being a spherical fuzzy number. The initial decision-making matrix with n criteria and m experts is formed by Eq. (1).

Table 10
The Assessments About Innovation Alternatives.

Expert1	CIRECNMY	EGYOPT	ENTINF	WYRMNG	CRBNTRSYS	SMRGRDINT	CLMADP
AIOPT	4	2	7	7	7	6	6
SMRINFLOT	8	8	3	2	1	1	4
DECENGSYS	9	8	9	7	8	9	9
DATAMONT	2	2	4	7	5	8	6
LANDPLN	4	4	1	4	3	7	7
Expert2	**CIRECNMY**	**EGYOPT**	**ENTINF**	**WYRMNG**	**CRBNTRSYS**	**SMRGRDINT**	**CLMADP**
AIOPT	7	9	1	2	7	3	4
SMRINFLOT	9	8	2	7	4	4	2
DECENGSYS	8	8	8	7	8	9	9
DATAMONT	6	2	3	9	7	5	8
LANDPLN	6	5	5	6	5	5	1
Expert3	**CIRECNMY**	**EGYOPT**	**ENTINF**	**WYRMNG**	**CRBNTRSYS**	**SMRGRDINT**	**CLMADP**
AIOPT	1	2	7	8	4	9	5
SMRINFLOT	4	2	3	1	3	1	1
DECENGSYS	8	8	9	7	8	9	8
DATAMONT	3	7	9	6	9	4	3
LANDPLN	9	7	2	3	1	8	5

$$\widetilde{A} = \begin{bmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{x}_{m1} & \cdots & \widetilde{x}_{mn} \end{bmatrix} \tag{1}$$

Afterwards, the elements of the initial decision-making matrix are normalized by dividing by the highest score value of matrix $\widetilde{A}$. Eq. (2) shows the calculation of normalized values. This operator is the multiplication of a positive number and a Spherical fuzzy number.

$$\widetilde{nor}_{ij} = \frac{1}{\max SCR(\widetilde{x}_{ij})}\widetilde{x}_{ij} \tag{2}$$

$$Agg(\widetilde{E}_1, \widetilde{E}_2, \ldots, \widetilde{E}_k) = \left\{ \left[1 - \prod_{i=1}^{k}\left(1 - \alpha_{\widetilde{E}_i}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}}, \prod_{i=1}^{k}\beta_{\widetilde{E}_i}^{\frac{1}{k}}, \left[\prod_{i=1}^{k}\left(1 - \alpha_{\widetilde{E}_i}^2\right)^{\frac{1}{k}} - \prod_{i=1}^{k}\left(1 - \alpha_{\widetilde{E}_i}^2 - \gamma_{\widetilde{E}_i}^2\right)^{\frac{1}{k}}\right]^{\frac{1}{2}} \right\} \tag{8}$$

Where, $SCR(\widetilde{x}_{ij})$ is score value of $\widetilde{x}_{ij}$ and, formulated by Eq. (3).

$$SCR(\widetilde{x}_{ij}) = \left(2^*\alpha_{ij} - \gamma_{ij}\right)^2 - \left(\beta_{ij} - \frac{\gamma_{ij}}{2}\right)^2 \tag{3}$$

After computing the standard deviations of the score values of the normalized values, the weights of the individual criteria are estimated with Eq. (4).

$$\widetilde{h}_{ij} = \widetilde{nor}_{ij} \times sd_j \tag{4}$$

Next, the $\widetilde{h}_{ij}$ values are summed using Eq. (5).

$$\widetilde{t}_i = \sum_{j=1}^{m}\widetilde{h}_{ij} \tag{5}$$

Finally, the score values of the totals are normalized with Eq. (6) and the weights of criteria are obtained.

$$weight_i = \frac{SCR(\widetilde{t}_i)}{\sum_{i=1}^{n} SCR(\widetilde{t}_i)} \tag{6}$$

Spherical fuzzy SAW

The SAW method, which considers the sum of weighted values, is a ranking method. In the SAW method, the optimal alternative is determined according to the weighted sums of the alternatives. The SAW method developed with spherical fuzzy numbers is shared below (Tafazzoli et al., 2024).

Each alternative is evaluated by the experts respect to the criteria and experts' assessments are transformed to Spherical fuzzy numbers. The evaluation matrix of the kth expert is given in Eq. (7).

$$\widetilde{E}_k = \begin{bmatrix} \widetilde{e}_{11} & \cdots & \widetilde{e}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{e}_{m1} & \cdots & \widetilde{e}_{mn} \end{bmatrix} \tag{7}$$

The aggregated matrix is created by computing the average of all experts' spherical fuzzy evaluations with Equation (8).

Next, Eq. (9) presents the calculation of the weighted aggregated matrix.

$$\widetilde{WA} = weight \times \widetilde{AGG} \tag{9}$$

The values of the weighted aggregated matrix for each alternative are summed using the spherical fuzzy sum operator. Eq. (10) gives information about calculating of total values.

$$\widetilde{sum}_j = \sum_{i=1}^{n}\widetilde{WA}_i \tag{10}$$

Finally, the score values of the total values are divided by the highest score value with the help of Eq. (11) and the alternatives are ranked.

$$Q_j = \frac{SCR(\widetilde{sum}_j)}{\max SCR(\widetilde{sum}_j)} \tag{11}$$

Analysis results

The analysis findings on innovative approaches to green digital twin technologies of sustainable smart cities are presented in this section.

Table 11
The Aggregated Matrix.

	CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
AIOPT	.499	.545	.312	.664	.400	.159	.603	.433	.281	.663	.363	.250	.631	.378	.330	.721	.304	.258	.511	.493	.439
SMRINFLOT	.784	.229	.215	.708	.317	.210	.271	.732	.273	.463	.600	.249	.298	.723	.306	.251	.786	.264	.269	.756	.280
DECENGSYS	.842	.159	.164	.800	.200	.200	.875	.126	.131	.700	.300	.300	.800	.200	.200	.900	.100	.100	.875	.126	.131
DATAMONT	.420	.607	.333	.472	.577	.263	.689	.348	.247	.777	.229	.254	.763	.247	.286	.625	.391	.364	.637	.383	.305
LANDPLN	.730	.288	.281	.561	.448	.403	.327	.711	.356	.460	.552	.379	.350	.680	.374	.695	.311	.331	.526	.513	.365

Table 12
The Weighted Aggregated Matrix.

	CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
AIOPT	.253	.869	.172	.207	.933	.058	.108	.978	.058	.313	.835	.137	.167	.947	.104	.395	.759	.169	.244	.866	.236
SMRINFLOT	.444	.712	.153	.226	.917	.081	.045	.992	.047	.205	.913	.118	.072	.982	.077	.122	.946	.132	.123	.945	.132
DECENGSYS	.498	.654	.129	.273	.885	.091	.193	.947	.043	.336	.807	.173	.235	.914	.079	.565	.587	.092	.505	.657	.106
DATAMONT	.209	.891	.177	.137	.959	.083	.129	.973	.056	.390	.770	.163	.218	.925	.107	.329	.805	.222	.317	.823	.175
LANDPLN	.401	.751	.187	.168	.941	.140	.054	.991	.063	.204	.900	.183	.085	.979	.098	.377	.763	.215	.252	.873	.195

Table 13
The Sums.

CIRECNMY			EGYOPT			ENTINF			WYRMNG			CRBNTRSYS			SMRGRDINT			CLMADP		
.619	.413	.308	.545	.519	.252	.845	.156	.166	.634	.392	.313	.615	.411	.342	.619	.413	.308	.545	.519	.252

Table 14
The Q Values.

Innovative Alternatives	Q
AIOPT	.187
SMRINFLOT	.032
DECENGSYS	1.000
DATAMONT	.210
LANDPLN	.151

Weighting of criteria set for assessing sustainable smart cities using SF-SIWEC

Literature is used in the selection of criteria for assessing sustainable smart cities. As a result of the research, the criteria determined for assessing sustainable smart cities are reported in Table 1.

Having a circular economy is an effective factor especially in the sustainability of cities. In smart cities, optimization processes, systems, smart grids are the main determining elements. Similarly, for green cities, climate-adapted designs, water management, carbon emissions and environmental issues are processes that must be addressed. Since the SF-SIWEC method is preferred to determine the importance priorities of the criteria in the assessments of sustainable smart cities, ratings about the criteria are collected from three different experts who have studies on smart cities. The ratings given by the three experts are shown in Table 2.

Afterwards, the criterion ratings are transformed into Spherical fuzzy numbers. The initial decision-making matrix formed by Eq. (1) is shared in Table 3.

In the next step, the values are normalized with the help of Eqs. (2) and (3). The normalized values are summarized in Table 4.

The standard deviations of the score values of the normalized values are calculated. The score values and the standard deviation values of the experts are displayed in Table 5.

Normalized values and standard deviation values are multiplied using Eq. (4) and the weights of individual criteria are obtained. The results are illustrated in Table 6.

Afterwards, the spherical fuzzy sums of the values are computed by Eq. (5). The spherical fuzzy total values and score values of the values are exhibited in Table 7.

Finally, the weights of the criteria are estimated as a result of Eq. (6), which is calculated using the score values in Table 9. The weights and priorities of the criteria are summarized in Table 8.

According to the results of Table 8, the primary criteria for assessing sustainable smart cities are smart grid integration and circular economy. As can be seen when these results are examined, economy is important in terms of sustainability and smart grid integration in terms of technology in sustainable smart cities.

Ranking innovation alternatives for green digital twin technologies of sustainable smart cities using SF-SAW

The SF-SAW method is used to rank innovative alternatives applied in practice for green digital twin technologies of sustainable smart cities. The selected innovation alternatives are determined in Table 9.

Within the scope of this method, assessments are first collected from three different experts. These assessments formed in Eq. (7) are given in Table 10.

In the next step, after the assessments are transformed into Spherical fuzzy numbers, the aggregated matrix is constructed with the help of Equation (8). The aggregated matrix is shown in Table 11.

Next, Eq. (9) presents the weighted aggregated matrix. The matrix is tabulated in Table 12.

Using Eq. (10), the total values of the alternatives are obtained and shared in Table 13.

Finally, the score values of the totals are calculated and the Q value

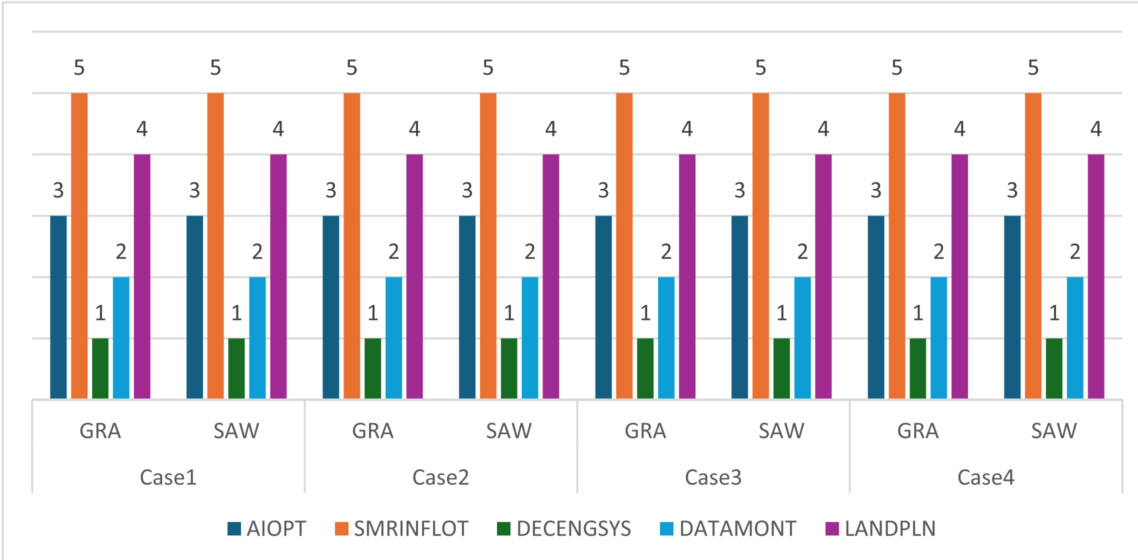

Fig. 2. The Comparison of Ranking Results.

required to rank the alternatives is obtained by Eq. (11). The ranking of innovative alternatives for green digital twin technologies of sustainable smart cities is given in Table 14.

As can be seen from Table 14, the best innovative alternative for green digital twin technologies of sustainable smart cities is decentralized energy systems with microgrids.

Comparison of ranking results using gra method and sensitivity analysis

Comparing the results with a second method shows the validity of the ranking results, while obtaining the results again with different weighting situations proves the consistency of the results. For this purpose, the GRA method is preferred as a second method and sensitivity analysis is performed. Fig. 2 visually presents the reliability and validity of the ranking results.

According to Fig. 2, it can be seen that the ranking results of different weights and methods are the same. This increases confidence in the ranking results. In all conditions and situations, decentralized energy systems with microgrids are identified as the best innovative alternative.

Discussion

Smart grid integration is determined as the most important criterion in the development of digital twin technologies for the provision of smart cities. Smart grids contribute to the optimization of energy production, consumption and distribution processes. This situation contributes significantly to the increase of energy efficiency. It is possible to mention many different advantages of this situation. In this way, rapid responses can be given to sudden changes in energy demand. In this way, it is possible to minimize energy interruptions. Due to this situation, customer expectations can be met more successfully. In addition to this condition, Lnenicka et al. (2024) defined that smart grids also support the integration of renewable energy. This situation contributes to the reduction of the negative impact of projects on the environment. Cugurullo et al. (2024) identified that the carbon footprint is reduced and vital problems such as global warming can be combated more successfully. According to Chen et al. (2024), another advantage of smart grids is that they collect and analyze real-time data on energy use. In this way, energy consumption models can be optimized, and smart cities can achieve their goals more successfully.

Circular economy is another variable that plays an important role in the provision of smart cities. Circular economy is an economic model that aims to use resources more efficiently and reduce waste. This model is very critical for smart cities to be sustainable. Yu et al. (2024) denoted that increasing resource efficiency allows projects to use less energy in their operational processes. As a result, natural resources are consumed much less. This is also very important for achieving environmental sustainability goals. Abdulla et al. (2024) underlined that reducing waste also allows projects to harm the environment less. This situation both threatens people’s health less and supports the positive development of the image of businesses. Similarly, reusing waste in the recycling process helps businesses reduce their raw material costs. Nikolaeva (2024) determined that circular economy encourages increasing energy efficiency and using renewable energy sources. This situation helps countries reduce their dependence on fossil fuels. Because of this issue, it is possible to significantly reduce the carbon emission problem.

Conclusion

Conclusion remarks

This study aims to identify innovative approaches to green digital twin technologies of sustainable smart cities. In the first part, important criteria of digital twin technologies for assessing sustainable smart cities are weighted with spherical fuzzy SIWEC method. The second part consists of ranking innovative alternatives for green digital twin technologies by using spherical fuzzy SAW methodology. The findings indicate that smart grid integration is determined as the most important criterion in the development of digital twin technologies for the provision of smart cities. Circular economy is another variable that plays an important role in the provision of smart cities. On the other hand, decentralized energy system with microgrids is found as the most important alternative for this situation.

Policy implications

Some policy practices can be determined to ensure a more successful smart grid integration. Providing renewable energy incentives helps achieve this goal. Financial incentives should be provided to increase the integration of renewable energy sources into smart grid systems. In this context, providing tax deductions allows the operational costs of projects to be reduced. This increases the interest of investors in these projects as it increases the profit margin. Providing low-interest financial loans is another application that can be considered in this context.

This allows the projects to access the funds they need more easily. Since the costs are very high in energy investment projects, financial institutions may not be very willing to provide loans. Low-interest loans provided by governments also help solve this problem. Furthermore, various policy applications can be presented to ensure a circular economy. In this context, recycling systems should be developed as a priority. An important policy suggestion is for local governments to invest in waste collection and recycling systems. Funding for such investments by the state enables the development of these projects. Recycling standards can be established to encourage the reuse of products. This helps these processes to be carried out more successfully. In addition to them, national security standards should be established to increase the resilience of smart grids against cyber-attacks. Energy infrastructures include very critical processes for a country. In this context, security gaps in the system reduce user confidence. Cybersecurity protocols and regular testing processes can be made mandatory and inspections on energy providers can be increased.

Limitation and future research suggestions

The main contribution is to identify the most effective investment strategies for the improvements of digital twin technologies to reach smart cities. The preference of the SIWEC method in the criteria weighting process provides some advantages to the model. The most important feature of this method is that the direct importance of the criterion is taken into consideration in the questions asked to the experts. In this way, it is possible for the experts to give more sensitive answers. However, the main limitation of this study is that the assessments of the experts are considered with equal weights. The average value of all expert assessments is used to construct decision matrix. This situation can have the negative impacts of the effectiveness of the findings. The main reason is that these experts may have different qualifications. To handle this situation, in the following studies, the weights of the experts can be computed based on their demographical issues. In this process, machine learning and artificial intelligence techniques can be considered to identify the expert weights. Another limitation of the study is that a theoretical model is proposed in the study, but its applicability in the real world is not tested. Future studies can also examine the applicability of the proposed strategies in local, regional or international contexts. Theoretical models are usually based on assumptions. However, real-world applications may confirm these assumptions or indicate the need for improvement.

CRediT authorship contribution statement

Jifeng Cao: Resources, Investigation, Conceptualization. **Cristi Spulbar:** Project administration, Data curation, Conceptualization. **Serkan Eti:** Writing – review & editing, Writing – original draft, Supervision. **Alexandra Horobet:** Validation, Software, Methodology. **Serhat Yüksel:** Writing – original draft, Resources, Conceptualization. **Hasan Dinçer:** Writing – original draft, Visualization, Conceptualization.

Acknowledgments

This research was funded by the National Social Science Fund of China (24SGC112).

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