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Research article

Evaluation of smart and sustainable cities through a hybrid MCDM approach based on ANP and TOPSIS technique☆

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ABSTRACT

Significant efforts are being performed to make cities smarter and more sustainable. Therefore, there is a need to compare these efforts using evaluation frameworks. According to the literature review, the basic dimensions of smart cities are generally evaluated with the criteria of regional competitiveness, transportation, information and communication technology, economy, natural resources, human and social capital, quality of life and participation of citizens in the management of cities. In this paper, Analytical Network Process (ANP) is used to weight smart and sustainable city criteria. According to the results, while 'smart living' is the most important characteristic with a 35,459% priority, 'smart governance' is the last with 5,738%. The study covers 44 cities around the world and comparisons were made by TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). According to the results, Tokyo, London and New York are in the top three in the overall ranking. But none of these cities is among the top five in terms of smart governance, mobility and environmental dimensions. According to the results obtained, the article provides some recommendations for the cities. These results aim to help cities understand their situation relative to other cities and to see areas where policymakers need to strengthen.

1. Introduction

1.1. The concept of sustainable and smart city

The concept of sustainable and smart city is one of the important topics in today's public policy due to its scope and dimensions [1]. In the Seventh World Urban Forum (WUF7) that was organized by UN-HABITAT, cities were described as the main elements that could provide solutions to the challenges facing the world. This organization focused on the importance of cities in terms of sustainable future, equality and quality of life. In the WUF7 declaration, a special section was added in the form of "the need to include key topics for sustainable cities and human settlements in the post-2015 Development Agenda" [2]. The popularity of the "smart and sustainable city" concept, which emerged in the 1990s, has been steadily increasing since the beginning of the 21st century. When urban development is assessed on a global scale, there are many mega-cities with over 20 million population, even in Asia, Latin America and Africa. They produce approximately 80 per cent of the global GDP. Also, they consume 80% of the world's energy and cause at least 70 per cent of carbon emissions. According to the 2008 report of the United Nations Population Fund, 70% of the world's population is expected to live in cities by 2050. It is estimated that about 828 million people still live in poor housing conditions, and this number is increasing rapidly [3, 4]. These problems cause many troubles in the planning, development and operation of cities. Therefore, city and country managers need to come up with smart approaches to optimize their city's economic activities, energy consumption, environmental conditions and quality of life when preparing their action plans. Many cities are defined as smart cities because they provide services with ICT infrastructure. In addition, building sustainable and smart cities means providing satisfactory and flexible career and business opportunities, safe and affordable housing, a more democratic society, a transparent governance approach and an efficient economy for its residents. It also includes investing in public transport, increasing the share of green spaces and conducting urban planning and governance through systems that enable all residents to participate [5, 6]. Smart city concept is related to other city concepts such as, information city, sustainable city, talented city, wired city, digital city, eco-city [7].

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1.2. The smart city indices and projects

The California Institute for Smart Communities is among the first organizations to focus on how communities can be smart and how a city can be designed to implement information technology [8]. In the field of urban planning, the term "smart and sustainable city" is generally regarded as a policy tool. Governments and public institutions prioritize smart management approaches in policies and programs for sustainable development, economic growth and a better quality of life [9]. Therefore, smart and sustainable city approaches should handle sustainable economic, social and environmental objectives in an integrated way [10].

It is also difficult to measure the performance of smart and sustainable city characteristics and dimensions [11]. Especially in recent years, many researchers have practised the methods that were based on indicators to evaluate the dimensions of urban smartness and sustainability. Also, they tried to bring these dimensions together and benchmark global cities by means of using these methods [6]. These studies are trying to compare many global cities by using different weighting methods with many characteristics of the smart and sustainable city that have the number of indicators ranging from twenty to eighty. Some of these are the CityCard index that is an aggregating index [12], the United Nation's (UN) city prosperity index [13] the sustainable cities index [14], the cities in motion index [15], the Global Power City Index [16, 17], the spatially adjusted liveability index [18], the cities of opportunity index for New York City and a tale of evaluation and reporting in UK smart cities [19], the Mercer Quality of Living [20], and the sustainable assessment by fuzzy evaluation (SAFE) index [6], creating smart cities [21], an application of integrated assessment for smart city development in India [22], an evaluation design for smart city development [23].

Lazaroiu and Roscia [24] proposed a methodology that evaluates the "smart and sustainable city index". This index was used in the distribution of European funds for the 2020 strategic plan. A more sophisticated system for measuring the smartness of a city was proposed by Lombardi and his colleagues in 2012. They reviewed literature that includes the EU project reports, Urban Audit data set, European Commission statistics, European Green City Index, Trends and Indicators for Monitoring the EU Thematic Strategy on Sustainability, Urban Environment Improvement and smart and sustainable city ranking of European medium-sized cities. After that, they proposed a framework that was created by using 60 indicators. The Global Power City Index was prepared by the Japanese Urban Strategies Institute and it is based on collecting observation data that includes information of various stakeholders. This index maps the strengths and weaknesses of cities and ranks them according to their socio-economic potential which is attracting creative people and excellent companies. In the United States, the Defense Council for Natural Resources has developed the Smart and sustainable city Ranking with an index that has a stronger emphasis on environmental criteria. In addition, with the support of Forbes scientist Joel Kotkin, they published a list of the world's smartest cities. In this list, a compact and efficient city concept that provides appropriate and economic conditions is taken into consideration. This ranking system promotes the city as an economic and international trade centre and a global city. The University of Vienna developed an evaluation metric for ranking 70 medium-sized European cities [25]. This metric uses specific indicators for each of the six defined smart and sustainable city dimensions, such as the concept of smart mobility is subdivided into local accessibility, international accessibility, availability of ICT infrastructure, and sustainable and secure transport systems. All of these rankings help to demonstrate good practices and serve as a tool to develop regional capital and define urban policies. The European Union has implemented smart and sustainable city practices in many cities, including Barcelona, Amsterdam, Berlin, Manchester, Edinburgh and Bath. Also, the European Commission has addressed smart cities on line 5 of the Seventh Framework Program for Research and Technological Development. This program provides financial support to facilitate the implementation of the Strategic Energy Technology Plan (SET-Plan) via programs related to "Smart Cities and Communities" [26].

According to China Smart Cities Forum statistics, six regions and 51 provinces are included in the Smart Cities program. Also, the program is included in Chinese government paper reports. 36 of them are in the new design phase, and they are evaluated within the scope of this concept. Chinese smart cities are mostly located in the Pearl and Yangtze River Deltas, Bohai Rim and Midwest regions. In addition, smart and sustainable city attempts have spread to the biggest cities such as Beijing, Shanghai and Shenzhen. The general approach in these smart and sustainable city applications is to take advantage of some ICT applications during the construction of infrastructure and to draw attention to environmental issues and to show limited interest in social issues [27]. Many Southeast Asian cities such as Singapore, Taiwan and Hong Kong have been carrying out a similar plan encouraging economic growth through smart and sustainable city programs. Singapore IT2000 plan was designed to build a "smart island" with information technology that brings business, life and play together. More recently, Singapore has launched an extensive effort on implementing Master Plan iN 2015, and it has achieved the goal of providing free mobile internet access with Wireless @ SG anywhere in the city. Taoyuan in Taiwan directs the economy to similar issues in order to improve the quality of life. Through a number of government projects such as E-Taoyuan and U-Taoyuan, there has been considerable progress in the field of e-governance [28]. Korea is another country that works hard to succeed in smart and sustainable city projects [29].

1.3. The most popular keywords and dimensions for smart and sustainable city concept

List of keywords and percent of each keywords in publications of smart and sustainable city are shown in Figure 1.

The evaluation dimensions used for some smart and sustainable city applications are shown in Table 1.

2. Literature review

These type of studies require the process of properly weighting the variables utilised in developing an index. Some of the city comparison studies cited in the paper prefer the Equal Weighting (EW) method, which gives equal importance to all variables. The methods in which the opinions of the experts are used in the weighting process of evaluations are called participatory methods [36, 37, 38]. Although they benefit much from subjective evaluations, these methods are able to give significant and meaningful results in difficult issues since they have a well-defined scientific background [39, 40]. Also, most of these weighting methods try to produce an integrated index without taking into consideration the interrelationship between indicators. Thus, they argue that all participatory approaches are "indicator rich but information poor" and that they confuse and mislead city policymakers [38]. It is possible to evaluate how different indicators change in their relations to each other using Principal Component Analysis (PCA) based on variance-based statistical techniques, but this time the opinions of the experts in their field cannot be taken. In other words, it is not a participant. Moreover, prioritizing the priorities (weights) of being a smart and sustainable city is a multi-criteria decision-making (MCDM) problem and requires evaluation in terms of many conflicting criteria. Decision-making is an act of choosing between alternatives to achieve the goal. ANP is the advanced version of Analytic Hierarchy Process (AHP). The interactions and feedbacks that was occurred between different indicators and also the opinion of the experts about the indicators were taken into consideration in order to weight the characteristics and factors of the smart city through (Analytic Network Process) proposed by the article. This is the main difference of this article from other studies in the literature.

In this article, different smart and sustainable city characteristics in the literature are presented together. RAND Corporation seeks to find solutions to public policy challenges for the purpose of making communities around the world safer, healthier and more prosperous with

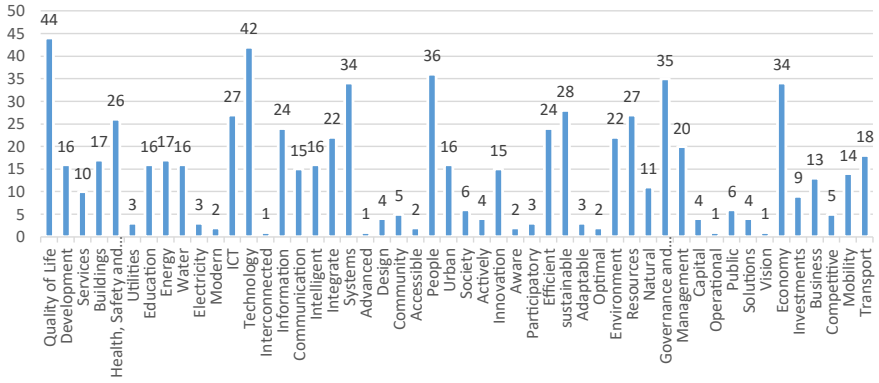

Figure 1. List of keywords and percent of each keywords in publications of smart and sustainable city.

"Mapping of Smart Cities in the EU: A RAND Europe Project" [7]. In this study, 6 dimensions and 31 factors were taken from this report "Smart cities: Ranking of European medium-sized cities" report. All criteria and indicators related to smart and sustainable city dimensions are shown in Appendix A.

AHP and ANP are the most preferred methods among the multi-criteria decision-making method (MCDM) in the literature in order to weight criteria and determine the priorities. ANP and TOPSIS have been utilised and found beneficial in many fields including modelling the smart city performance [41], creating model for smart cities [42], a methodological framework for the assessment of ubiquitous cities [43], the study of smart city evaluation based on the ANP-TOPSIS method [44], a holistic evaluation of smart city performance in the context of China with TOPSIS method [45], evaluation of sustainability indicators in smart cities for India [46], smart evaluation and integrated design in regional development [47], evaluating smart living technology strategies using the analytic network process [48], a fuzzy ANP based weighted RFM model for customer segmentation in auto insurance sector [49], a new approach for prioritization of ecosystem management [50], weighting the priorities of an airline operational and financial performance indicators with ANP [51], innovative ANP model to prioritization of PV/T systems based on cost and efficiency approaches [52], study on the quality evaluation model of diesel engine with ANP and TOPSIS method [53], the study on smart city construction assessment based on TOPSIS -" the Beijing-Tianjin-Tangshan city clusters" as the case [54].

3. The aim and scope of the study

The broad scope of the criteria and the lack of experts who have knowledge of all indicators are the major challenges of ANP studies and they are the limitations of such research. Five academicians from the Department of Humanities and Social Sciences specialized in the fields of culture and arts, science and technology, economics, sociology and psychology were interviewed and their evaluations and opinions about smart and sustainable city criteria were taken. The Department of Humanities and Social Sciences has been papering almost any kind of issues about "people" and "society" in the perspective of "social sciences", "humanities", "engineering", and "science and technology", "philosophy". The subjective evaluations of experts were collected by means of the pairwise comparison matrices after the criteria, dimensions and the network relations of criteria had been determined by them. The geometric means of these pairwise comparison matrices were used in ANP analysis. The geometric mean method was used to obtain group decision from individual scores of expert evaluations. Thus, it was tried to prevent the analysis from being affected by outliers [55]. Eventually, the priority values (weights) were obtained from the Super Decision program, and then they were interpreted.

Specifically, this article is aimed to determine the priorities of the dimensions of smart and sustainable cities and to give an idea about the areas that need to be invested and developed during smart and sustainable city planning. Also, city or country managers are expected to make comparisons with each other by using the priorities (weights) of dimensions of smart cities, and thus they will be able to see benchmark opportunities. Furthermore, the policymakers of these 44 cities are expected to see areas that need improvement by taking advantage of the comparison results of cities.

4. Methodology

4.1. Selection of cities

In this study, 44 cities in the Global Power City Index (GPCI) Yearbook [56] were compared by ANP and TOPSIS.

The list of selected cities is shown in Table 2.

Table 1. Dimensions of smart and sustainable city.

Source	Dimensions of smart and sustainable city
Mahizhnan, 1999 [30]	Information Technology Education, Information Technology Infrastructure, Information Technology Economy
Giffinger, 2007 [25]	Life Quality, Economy, Mobility, Environment, People
Eger, 2009 [31]	Governance, Technology, Economic Development, Employment Growth, Increase in Life Quality, Life Quality
Nam, 2011 [32]	Interconnection, Instrumentation, Integration, Applications, Innovation
Thuzar, 2011 [10]	Sustainable Economic Growth, Management of Natural Resources through Participatory Policies, Convergence of Economic, Social and Environmental Targets, Economic socio-political issues of the city, Economic-technical-social environment issues
Barrionuevo, 2012 [33]	Economy (GDP, sector strength, international transactions, foreign investment), Human (talent, innovation, creativity, education), Social (traditions, habits, religions, families), Environment (energy politics, waste and water management, landscape), Corporate (civilian engagement, administrative authority, elections)
Kourtit, 2012 [34]	Infrastructure capital (advanced technology communication facilities), Social capital (dense and open network connections), Human capital (skilled labor), Venture capital (creative and risk-taking business activities)

Source: Compiled by the authors based on Albino, Berardi [35].

Table 2. The cities by regions (GPCI, 2019).

Region	City
Europe	Madrid, Barcelona, London, Paris, Brussels, Amsterdam, Geneva, Frankfurt, Berlin, Zurich, Milan, Copenhagen, Vienna, Stockholm, Moscow, Istanbul
Africa	Cairo, Johannesburg
Middle East	Dubai
Asia	Mumbai, Bangkok, Kuala Lumpur, Singapore, Jakarta, Hong Kong, Beijing, Shanghai, Taipei, Seoul, Fukuoka, Osaka, Tokyo
Oceania	Sydney
North America	Vancouver, San Francisco, Los Angeles, Chicago, Toronto, Washington, D.C., New York, Boston
Latin America	Mexico City, Sao Paulo, Buenos Aires

Cities are determined according to the following criteria [57].

1. Cities located in the top ten of existing, influential city rankings, such as the Global Financial Centres Index, Global Cities Index, and Cities of Opportunity.
2. Major cities of countries which are in the top ten in terms of competition in accordance with important international competitiveness rankings, such as the Global Competitiveness Report (World Economic Forum) and Competitiveness Ranking (Institute for Management Development).

44 cities were evaluated by TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) according to 47 criteria. As a result of the analyzes, the rankings were obtained in terms of the general ranking and each dimension separately.

4.2. Defining assessment framework

The assessment framework used in the application of the study is shown in Figure 2. The priority values obtained in ANP analysis will be the weights used in calculating the weighted normalized matrix in TOPSIS analysis.

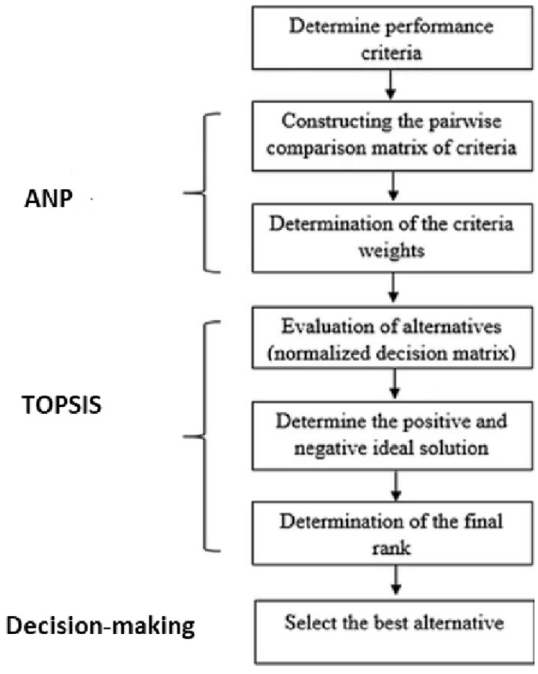

Figure 2. The ANP- TOPSIS decision-making framework (adapted by authors) [58].

4.3. Analytic network process (ANP)

ANP considers the dependencies between elements in the same set (internal dependency) and the dependencies between elements in the different sets (external dependency) [59]. Inner dependency shows that there is an interaction between the criteria within the same cluster. External dependency indicates that there is an interaction between the criteria in a different set. These dependencies are shown with arrows. A sample network structure is given in Figure 3 [60].

This network structure consists of five clusters. In the network structure, cluster A only affects cluster B. While cluster B affects clusters A and C, it also has an internal dependency. Cluster C affects D and E. D affects clusters A and E. While E affects A, C, D, it also has an inner dependency.

In ANP, a control network or control hierarchy is used to evaluate the different dimensions of criteria [61, 62]. In ANP, respectively; **(a)** Dimensions, their factor elements and clusters are defined. Thus, the factors based on expert opinions about six dimensions of smart cities are defined as smart living, smart economy, smart environment, smart people, smart mobility and smart governance. **(b)** The model was designed, **(c)** interdependencies were created. Therefore, the structure of ANP of "Smart and sustainable city" and interdependencies based on opinions of experts were drawn on the Super Decisions package program. They are shown in Figure 4. The criteria of all dimensions interact with the criteria within the dimension in which they belong. This means that all these criteria are compared in pairs. In addition to this, all of the criteria and dimensions that are paired with arrows interact with each other [63].

(d) A pairwise comparison matrix was constructed between elements and clusters; Saaty [64] proposed

A. ANP Preference Scale

Saaty [64] proposed the scale shown in Table 3 for the subjective evaluations of decision-makers about the criteria and dimensions in the pairwise comparison matrix. Therefore, this scale was used in the subjective evaluation of the decision makers for the analysis [3].

B. Group Decision Making

The geometric mean is the proposed method for ANP in order to minimize the impact of extreme values of decision-makers when a group decision is made. Thus, the paper utilized the geometric mean method while making a common group decision from the opinion of the five decision-makers. Geometric mean, n number of elements, is calculated by the formula (1). x represents the value that each decision-maker gives in the same pairwise comparison [65].

$$GM = \sqrt[n]{x_1 \,.\, x_2 \,.\, x_3 \,\ldots\, xn} \tag{1}$$

The manual data input of the pairwise comparison matrix representing the subjective views of the decision makers into the Super Decision program is shown in Figure 5.

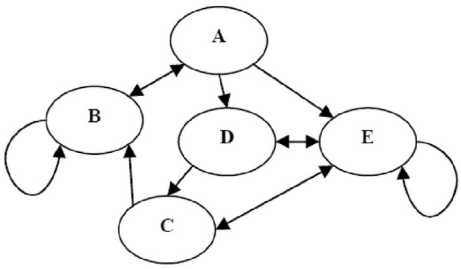

Figure 3. A sample ANP network structure.

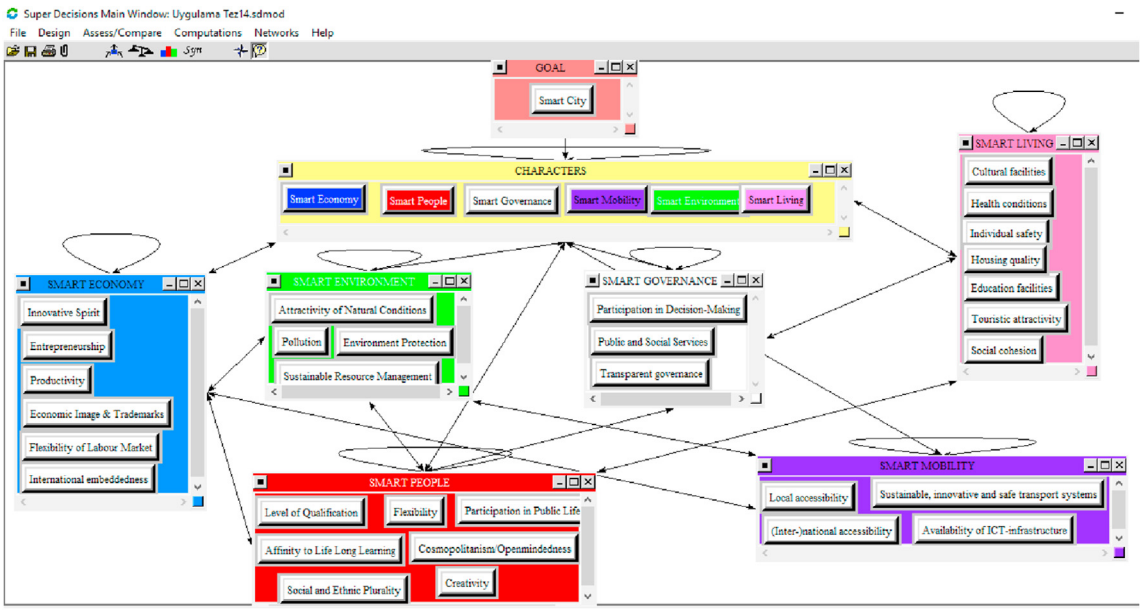

Figure 4. Smart cities ANP structure (created by authors on Super Decision Software).

Table 3. ANP preference scale for pairwise matrix.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong plus	
7	Very strong	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

The data entry screen to the Super Decision program is shown in Figure 5 as an example. The geometric mean values calculated for each pairwise comparison were entered into the program. For instance, the "smart economy" is 2.64 times more important than "smart environment". The direction of the arrow indicates which criterion is more important in a pairwise comparison. If the more important criterion is the criterion on the vertical axis, the color of the arrow is blue. Otherwise, it is red.

C. Consistency

During the decision-making process, the problem of inconsistency is encountered when different dimensions or criteria are compared in complex decision-making problems. For example, assume that A is 2 times more important than B and B is 3 times more important than C. Unfortunately, A may be 4 times more important than C, not 6 times.

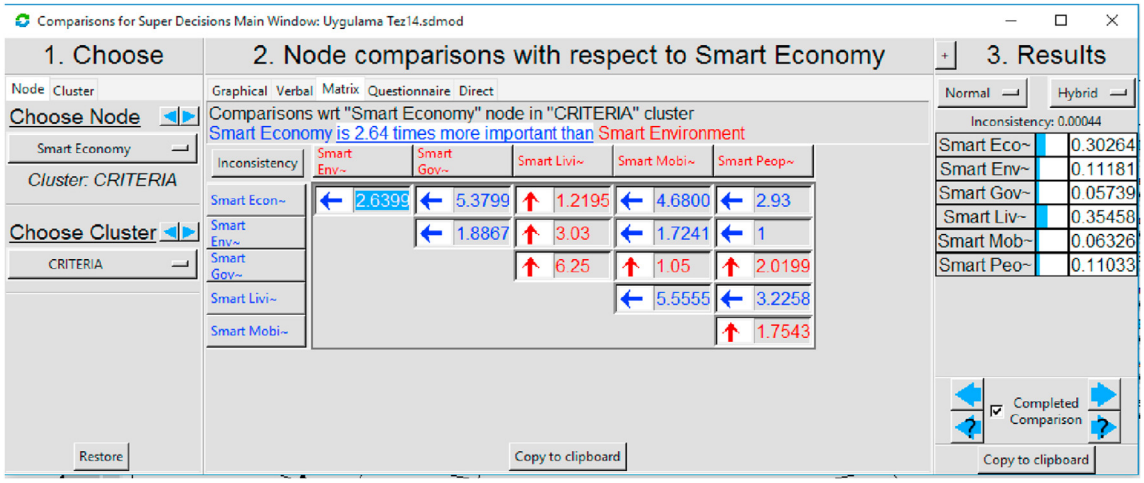

Figure 5. Pairwise comparison matrix according to the group decision.

Similarly, C may be larger than A, although A is larger than B and B is larger than C. Hence AHP and ANP allow a level of inconsistency which can be calculated by the formula (2) for pairwise comparison matrix [66]:

$$CR = CI/RI < 0.1 \quad (2)$$

(CR: consistency ratio, CI: consistency index, RI: random index)

It indicates that the inconsistency is tolerable if CR < 0.1; otherwise, inconsistent elements are determined and necessary adjustments are made for a valid decision [67]. The inconsistency of the analysis is less than 0.1.

(e) **Supermatrix:** The general structure of the supermatrix resembles the Markov chain process. A supermatrix is actually a partial matrix, and each matrix section shows the relationship between two factors in a system. Each element is represented at one row and one respective column. The computed eigenvector of the sub-elements with respect to their parent element is placed to the column representing the parent element and the rows representing the sub-elements [60].

(f) **Weighted supermatrix:** If the column sum of any column in the composed supermatrix is greater than 1 (there are more than one eigenvector), that column will be normalized. Such a supermatrix is called as a weighted supermatrix [61].

(g) **Limit matrix:** The weighted supermatrix is then raised to a significantly large power in order to have converged or stable values. The values of this limit matrix are the desired priorities of the elements with respect to the goal. Therefore, the importance weights of alternatives or comparable factors are determined by the limit supermatrix [60, 63, 68].

In the selection problem, the alternative with the greatest weight is the best alternative and in the weighting problem, the factor with the highest weight is the most important factor affecting the decision process. **(h)** Finally, the priorities obtained from the Super Decision program are interpreted. The weighted supermatrix and a sample screenshot of the priorities list are shown in Figures 6 and 7. The priority (weight) values of the smart and sustainable city dimensions are shown in Figure 8.

All priority values are listed in Figure 9.

Super Decisions Main Window: Smart City ANP Aplication.sdmod: Weighted Super Matrix

Cluster Node Labels		CHARACTERS						Goal	SMART ECONOMY
		Smart Economy	Smart Environment	Smart Governance	Smart Living	Smart Mobility	Smart People	Smart City	Economic Image & Trademarks
Smart Mobility	Sustainable, innovative and safe transport systems	0.035562	0.035562	0.035562	0.035562	0.035562	0.035562	0.000000	0.060910
SMART PEOPLE	Affinity to Life Long Learning	0.014606	0.014606	0.014606	0.014606	0.014606	0.014606	0.000000	0.024554
	cosmopolitanism openmindedness	0.012869	0.012869	0.012869	0.012869	0.012869	0.012869	0.000000	0.021634
	Creativity	0.015551	0.015551	0.015551	0.015551	0.015551	0.015551	0.000000	0.026143
	Flexibility	0.013057	0.013057	0.013057	0.013057	0.013057	0.013057	0.000000	0.021950
	Level of Qualification	0.034886	0.034886	0.034886	0.034886	0.034886	0.034886	0.000000	0.058648
	Participation in Public Life	0.010329	0.010329	0.010329	0.010329	0.010329	0.010329	0.000000	0.017364
	Social and Ethnic Plurality	0.008914	0.008914	0.008914	0.008914	0.008914	0.008914	0.000000	0.014986

Figure 6. The weighted supermatrix.

Super Decisions Main Window: Uygulama Tez14.sdmod: Pri...

Here are the priorities.

Icon	Name	Normalized by Cluster	Limiting
No Icon	Smart Economy	0.30262	0.005875
No Icon	Smart Environment	0.11183	0.002171
No Icon	Smart Governance	0.05738	0.001114
No Icon	Smart Living	0.35459	0.006884
No Icon	Smart Mobility	0.06325	0.001228
No Icon	Smart People	0.11033	0.002142
No Icon	Economic Image & Trademarks	0.21299	0.063104
No Icon	Entrepreneurship	0.07646	0.022655
No Icon	Flexibility of Labour Market	0.12746	0.037764
No Icon	Innovative Spirit	0.32456	0.096162
No Icon	International embeddedness	0.09351	0.027706
No Icon	Productivity	0.16501	0.048889

Figure 7. A sample of ANP priority list.

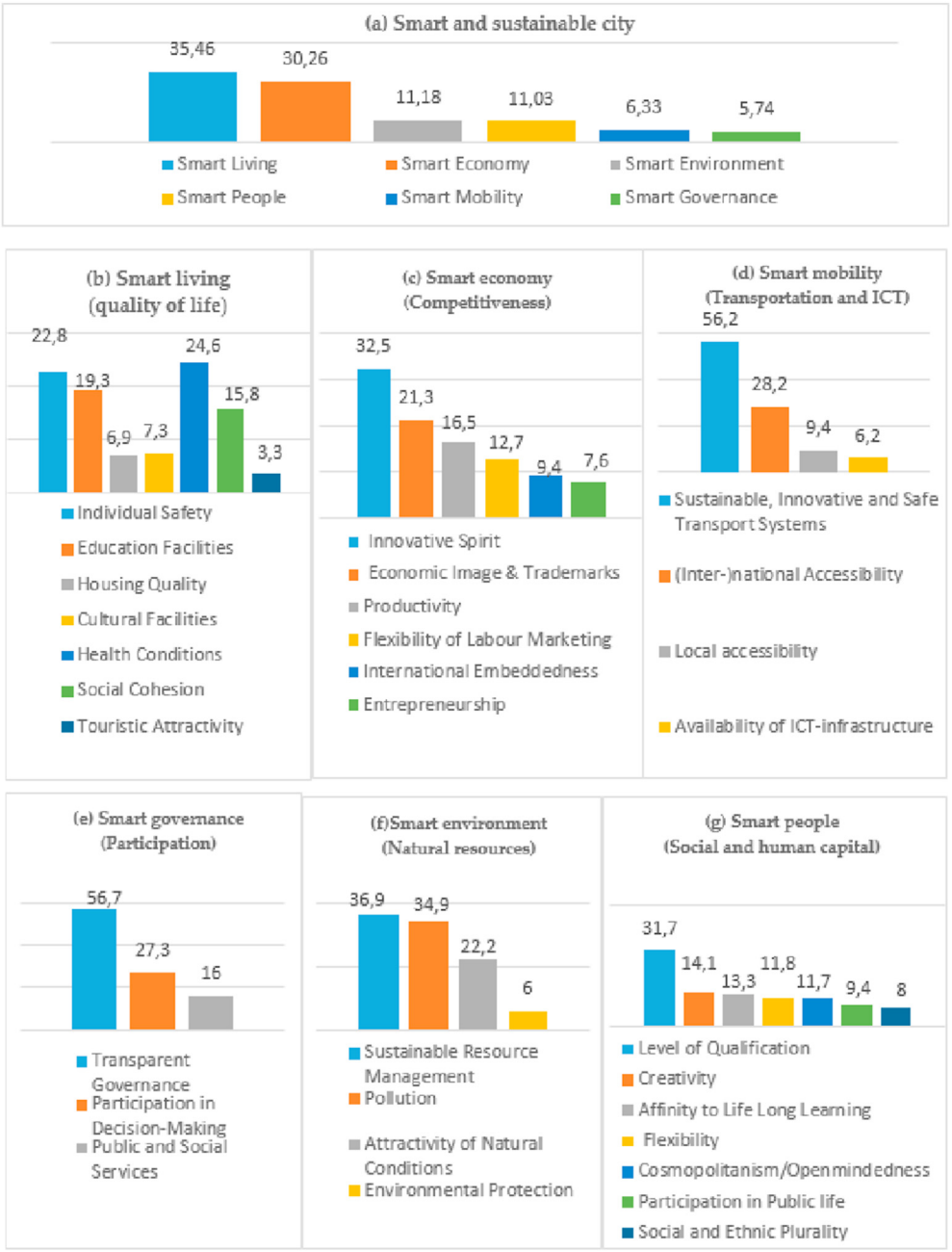

Figure 8. (a)–(g). The priority (weight) values of the smart and sustainable city dimensions –ANP.

These priority values obtained in ANP analysis will be the weights used in calculating the weighted normalized matrix in TOPSIS analysis.

4.4. TOPSIS (Technique for Order Preference by similarity to ideal solution) method steps and application

In the TOPSIS analysis, 44 cities were compared according to 47 indicators. The values obtained in ANP analysis were used as a weight in TOPSIS analysis. In ANP, the dimension or indicator with the highest priority value is considered as the indicator with the highest weight. For instance, in general evaluation, the innovative spirit indicator has the highest weight with 9.62%, while the attractivity of natural conditions has the lowest weight with 0.65%. In addition, smart living has the highest weight with 35.46%, while smart governance has the lowest weight with 5.74%. All these weights are shown in Table 5 and Figure 9.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was developed by Yoon [69]. It involves a 6-step solution process. The steps of the TOPSIS method are described as shown in Figure 10 [70, 71].

Step 1: In the rows of the decision matrix, there are decision points whose superiorities are to be listed, and in the columns, there are evaluation factors to be used in decision making. Matrix A is the initial matrix created by the decision maker. The decision matrix is shown as formula 2a:

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \quad (2a)$$

Table 4. TOPSIS decision matrix.

Cities	Smart Economy								
	Innovative spirit		Entrepreneurship	Economic image & trademarks	Productivity	Flexibility of labour market	International embeddedness		
	Innovation Index Score (Innovation Cities Index: Global 2018)	Research and Development (GPCI 2018)	The Global Entrepreneurship Index (%) (2018)	The World's Most Reputable Cities (2018 City RepTrak Scores)	GDP per employed person (2019) (constant 2011 PPP $)	Unemployment rate (2018–2019)	Companies with HQ in the city (2018–2019)	number of international airline passengers (million) (2018)	Amount of air freight (thousand tonnes - per year)
Amsterdam	50	94.2	68	75.5	99	4.40	67	1750	71
Bangkok	42	24.5	27	63.5	31	0.90	117	4100	51
Barcelona	48	53.3	45	76.5	87	10.90	64	290	37
Beijing	47	111.2	41	66	31	5.00	116	2074	83
Berlin	51	113.8	66	72	93	7.90	139	3000	3
Boston	53	163.7	84	71.7	117	3.50	40	1350	7
Brussels	43	87.8	64	72.1	105	6.10	41	543	10
Buenos Aires	43	26.7	24	52	48	11.90	32	220	7
Cairo	35	3,8	26	51.6	39	8.10	35	188	3
Chicago	53	140	84	65.7	117	3.70	105	1721	39
Copenhagen	46	71.5	74	81	98	3.70	50	635	28
Dubai	47	33.2	53	68.6	100	0.50	128	988	55
Frankfurt	44	59.3	66	75.5	93	4.80	37	2475	62
Fukuoka	41	54.6	52	71	77	3.50	19	259	7
Geneva	41	73.5	41	70	96	2.30	130	95	11
Hong Kong	48	118.4	67	69.7	114	2.90	96	5000	74
Istanbul	44	39.6	45	57.8	75	15.50	108	3300	59
Jakarta	39	4.5	21	50	25	5.10	41	900	23
Johannesburg	33	15.7	33	58	43	25.10	122	650	9
Kuala Lumpur	42	20.8	33	53	60	3.30	27	1100	44
London	56	188.3	78	76.4	82	4.50	193	1800	118
Los Angeles	55	169.6	84	69.6	117	4.40	82	2158	24
Madrid	47	50.7	45	76.1	87	10.30	55	520	42
Mexico City	43	24.6	26	52.6	40	3.50	58	1000	17
Milan	46	51.7	41	77.1	96	5.80	108	572	20
Moscow	45	79	25	51.3	54	1.40	115	380	23
Mumbai	42	22.1	28	54.7	20	7.00	370	906	14
New York	55	227.1	84	75	117	4.30	217	1400	34
Osaka	45	105.2	52	65	77	4.00	174	950	7
Paris	53	135.1	69	73.3	97	7.70	168	1500	66
San Francisco	55	129.2	84	75.9	117	2.20	496	500	14
Sao Paulo	43	27.7	20	64.7	33	12.70	91	508	15
Seoul	52	155.9	54	66.1	72	3.40	114	2952	21
Shanghai	47	95.9	41	64.7	31	3.90	147	4000	35
Singapore	54	137.8	53	73.1	154	2.30	64	1850	65
Stockholm	48	89.9	73	80.8	100	5.80	74	110	14
Sydney	53	95.4	75	81.5	93	2.50	75	900	16
Taipei	44	71.2	27	51.3	31	3.70	90	2300	15
Tokyo	56	189.1	52	81.8	77	3.20	613	3100	35
Toronto	53	88.7	79	77.6	88	6.40	444	443	32
Vancouver	49	72.9	79	76.4	88	4.60	232	280	8
Vienna	49	53.3	66	80.9	97	12.30	69	216	14
Washington, DC	49	112.1	84	69.2	117	5.60	50	566	8
Zurich	43	72.3	80	78.5	107	2.30	79	493	9

In matrix A_{ij}, m represents the number of decision points, n represents the number of evaluation factors.

Step 2: Creating the Standard Decision Matrix (R)

The Standard Decision Matrix is calculated by using the elements of matrix A and the following formula 3:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}} \quad (3)$$

The matrix R is defined by the matrix shown below:

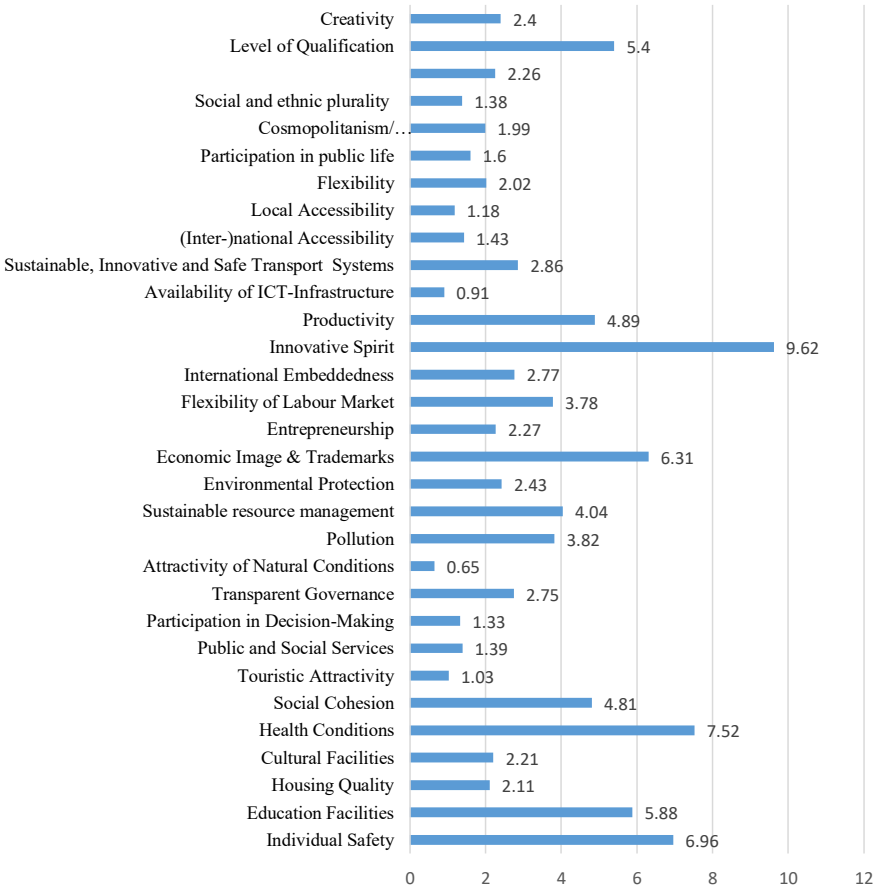

Figure 9. The priority (weight) values of smart and sustainable city criteria (%).

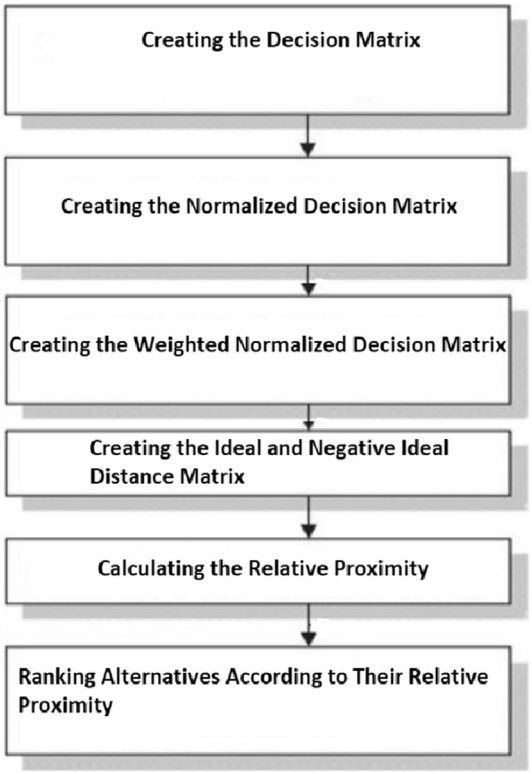

Figure 10. The steps of TOPSIS method (adapted by authors) [72].

$$R_{ij} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \quad (4)$$

Step 3: Creating the Weighted Standard Decision Matrix (V): First, the weight values (w_i) of the evaluation factors are determined ($\sum_{i=1}^{n} w_i = 1$). Then the elements in each column of the R matrix are multiplied by the corresponding w_i value to form the V matrix. The V matrix is shown below:

$$V_{ij} = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_n r_{1n} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_n r_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ w_1 r_{m1} & w_2 r_{m2} & \dots & w_n r_{mn} \end{bmatrix} \quad (5)$$

Step 4: Creating ideal (A^*) and negative ideal (A^-) solutions:
Finding the ideal solution set is shown in the following formula 6:

$$A^* = \left\{ \left(\max_i v_{ij} \middle| j \in J \right), \left(\min_i v_{ij} \middle| j \in J' \right) \right\} \quad (6)$$

The set calculated from formula (7) can be shown as $A^* = \{v_1^*, v_2^*, \dots, v_n^*\}$.

The set of negative ideal solutions is formed by selecting the smallest of the weighted evaluation factors in the V matrix. Creating the negative ideal solution set is shown in the following formula 7.

$$A^{-} = \left\{ \left(\min_{i} v_{ij} \middle| j \in J \right), \left(\max_{i} v_{ij} \middle| j \in J' \right) \right\} \quad (7)$$

The set calculated from the formula (8) can be shown as $A^{-} = \{v_1^{-}, v_2^{-}, \ldots, v_n^{-}\}$. In both formulas, J represents the benefit (maximization) and J' indicates the loss (minimization).

Step 5: In the TOPSIS method, Euclidian Distance Approach is used to find the deviations of the evaluation factor value for each decision point from the ideal and negative ideal solution set. The calculation of the ideal discrimination (S_i^{*}) measure is shown in the formula (8) and the calculation of the negative ideal discrimination (S_i^{-}) measure is shown in the formula (9):

$$S_i^{*} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{*} \right)^2} \quad (8)$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{-} \right)^2} \quad (9)$$

Step 6: The ideal and negative ideal separation measures are used to calculate the proximity (C_i^{*}) of each decision point relative to the ideal solution. The calculation of the proximity to the ideal solution is shown in the following formula 10:

Table 5. The transformed decision matrix.

	max	max	max	max	max	min	max	max	max
wj	0.04810	0.04810	0.02270	0.06310	0.04890	0.02020	0.00924	0.00923	0.00923
Cities	C1	C2	C3	C4	C5	C6	C7	C8	C9
Amsterdam	0.7391	0.4048	0.7500	0.8019	0.5896	0.0956	0.0808	0.3374	0.5913
Bangkok	0.3913	0.0927	0.1094	0.4245	0.0821	0.5465	0.1650	0.8165	0.4174
Barcelona	0.6522	0.2217	0.3906	0.8333	0.5000	0.0265	0.0758	0.0398	0.2957
Beijing	0.6087	0.4810	0.3281	0.5031	0.0821	0.0817	0.1633	0.4035	0.6957
Berlin	0.7826	0.4926	0.7188	0.6918	0.5448	0.0443	0.2020	0.5923	0.0000
Boston	0.8696	0.7161	1.0000	0.6824	0.7239	0.1254	0.0354	0.2559	0.0348
Brussels	0.4348	0.3762	0.6875	0.6950	0.6343	0.0633	0.0370	0.0913	0.0609
Buenos Aires	0.4348	0.1026	0.0625	0.0629	0.2090	0.0225	0.0219	0.0255	0.0348
Cairo	0.0870	0.0000	0.0938	0.0503	0.1418	0.0427	0.0269	0.0190	0.0000
Chicago	0.8696	0.6099	1.0000	0.4937	0.7239	0.1176	0.1448	0.3315	0.3130
Copenhagen	0.5652	0.3032	0.8438	0.9748	0.5821	0.1176	0.0522	0.1101	0.2174
Dubai	0.6087	0.1317	0.5156	0.5849	0.5970	1.0000	0.1835	0.1821	0.4522
Frankfurt	0.4783	0.2485	0.7188	0.8019	0.5448	0.0860	0.0303	0.4852	0.5130
Fukuoka	0.3478	0.2275	0.5000	0.6604	0.4254	0.1254	0.0000	0.0334	0.0348
Geneva	0.3478	0.3121	0.3281	0.6289	0.5672	0.2015	0.1869	0.0000	0.0696
Hong Kong	0.6522	0.5132	0.7344	0.6195	0.7015	0.1556	0.1296	1.0000	0.6174
Istanbul	0.4783	0.1603	0.3906	0.2453	0.4104	0.0126	0.1498	0.6534	0.4870
Jakarta	0.2609	0.0031	0.0156	0.0000	0.0373	0.0797	0.0370	0.1641	0.1739
Johannesburg	0.0000	0.0533	0.2031	0.2516	0.1716	0.0001	0.1734	0.1131	0.0522
Kuala Lumpur	0.3913	0.0761	0.2031	0.0943	0.2985	0.1343	0.0135	0.2049	0.3565
London	1.0000	0.8262	0.9063	0.8302	0.4627	0.0930	0.2929	0.3476	1.0000
Los Angeles	0.9565	0.7425	1.0000	0.6164	0.7239	0.0956	0.1061	0.4206	0.1826
Madrid	0.6087	0.2100	0.3906	0.8208	0.5000	0.0292	0.0606	0.0866	0.3391
Mexico City	0.4348	0.0931	0.0938	0.0818	0.1493	0.1254	0.0657	0.1845	0.1217
Milan	0.5652	0.2145	0.3281	0.8522	0.5672	0.0676	0.1498	0.0972	0.1478
Moscow	0.5217	0.3368	0.0781	0.0409	0.2537	0.3441	0.1616	0.0581	0.1739
Mumbai	0.3913	0.0820	0.1250	0.1478	0.0000	0.0526	0.5909	0.1653	0.0957
New York	0.9565	1.0000	1.0000	0.7862	0.7239	0.0983	0.3333	0.2661	0.2696
Osaka	0.5217	0.4541	0.5000	0.4717	0.4254	0.1072	0.2609	0.1743	0.0348
Paris	0.8696	0.5880	0.7656	0.7327	0.5746	0.0459	0.2508	0.2864	0.5478
San Francisco	0.9565	0.5616	1.0000	0.8145	0.7239	0.2116	0.8030	0.0826	0.0957
Sao Paulo	0.4348	0.1070	0.0000	0.4623	0.0970	0.0198	0.1212	0.0842	0.1043
Seoul	0.8261	0.6811	0.5313	0.5063	0.3881	0.1297	0.1599	0.5825	0.1565
Shanghai	0.6087	0.4124	0.3281	0.4623	0.0821	0.1105	0.2155	0.7961	0.2783
Singapore	0.9130	0.6001	0.5156	0.7264	1.0000	0.2015	0.0758	0.3578	0.5391
Stockholm	0.6522	0.3856	0.8281	0.9686	0.5970	0.0676	0.0926	0.0031	0.0957
Sydney	0.8696	0.4102	0.8594	0.9906	0.5448	0.1837	0.0943	0.1641	0.1130
Taipei	0.4783	0.3018	0.1094	0.0409	0.0821	0.1176	0.1195	0.4495	0.1043
Tokyo	1.0000	0.8298	0.5000	1.0000	0.4254	0.1391	1.0000	0.6126	0.2783
Toronto	0.8696	0.3802	0.9219	0.8679	0.5075	0.0594	0.7155	0.0709	0.2522
Vancouver	0.6957	0.3094	0.9219	0.8302	0.5075	0.0906	0.3586	0.0377	0.0435
Vienna	0.6957	0.2217	0.7188	0.9717	0.5746	0.0212	0.0842	0.0247	0.0957
Washington, DC	0.6957	0.4850	1.0000	0.6038	0.7239	0.0708	0.0522	0.0960	0.0435
Zurich	0.4348	0.3068	0.9375	0.8962	0.6493	0.2015	0.1010	0.0811	0.0522

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \quad (10)$$

The value C_i^* is in the range $0 \leq C_i^* \leq 1$ and $C_i^* = 1$ indicates the absolute proximity of the corresponding decision point to the ideal solution, and $C_i^* = 0$ indicates the absolute proximity of the corresponding decision point to the negative ideal solution.

The initial matrix created is shown in Table 4. However, we cannot directly use the original data in the analysis without normalization.

Before TOPSIS analysis, normalization process was applied in order to evaluate indicators with different units together. Thus, the values of each indicator are converted to be between 0 and 1 [73,74]. This also prevents the analysis from being influenced by outliers. The process of normalization is shown in formula 11:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (11)$$

In the assessment, cities are required to have minimum values in the indicators C6, C31, C34, C41, C42 and C46, while they are expected to have maximum values for the other indicators. While making analysis with multi-criteria decision making methods, the necessary transformations are made for the criteria that have negative (cost) effects, and calculations are made like the criteria that have positive effects. In the literature, the method proposed for this transformation is to divide the values of the relevant indicator into one. This process is formulated as shown below:

$$x_{ij}^I = 1/x_{ij} \quad (12)$$

Table 6. The normalized decision matrix.

Cities	C1	C2	C3	C4	C5	C6	C7	C8	C9
Amsterdam	0.1696	0.1398	0.1775	0.1842	0.1742	0.0692	0.0435	0.1429	0.2728
Bangkok	0.0898	0.0320	0.0259	0.0975	0.0243	0.3958	0.0888	0.3458	0.1925
Barcelona	0.1496	0.0765	0.0925	0.1914	0.1478	0.0192	0.0408	0.0168	0.1364
Beijing	0.1396	0.1660	0.0777	0.1156	0.0243	0.0592	0.0879	0.1709	0.3209
Berlin	0.1795	0.1701	0.1701	0.1589	0.1610	0.0321	0.1088	0.2508	0.0000
Boston	0.1995	0.2472	0.2367	0.1567	0.2139	0.0908	0.0190	0.1084	0.0160
Brussels	0.0997	0.1299	0.1627	0.1596	0.1875	0.0458	0.0199	0.0387	0.0281
Buenos Aires	0.0997	0.0354	0.0148	0.0144	0.0617	0.0163	0.0118	0.0108	0.0160
Cairo	0.0199	0.0000	0.0222	0.0116	0.0419	0.0309	0.0145	0.0080	0.0000
Chicago	0.1995	0.2106	0.2367	0.1134	0.2139	0.0852	0.0780	0.1404	0.1444
Copenhagen	0.1297	0.1047	0.1997	0.2239	0.1720	0.0852	0.0281	0.0466	0.1003
Dubai	0.1396	0.0454	0.1220	0.1343	0.1764	0.7242	0.0988	0.0771	0.2086
Frankfurt	0.1097	0.0858	0.1701	0.1842	0.1610	0.0623	0.0163	0.2055	0.2367
Fukuoka	0.0798	0.0785	0.1183	0.1517	0.1257	0.0908	0.0000	0.0142	0.0160
Geneva	0.0798	0.1078	0.0777	0.1444	0.1676	0.1459	0.1006	0.0000	0.0321
Hong Kong	0.1496	0.1772	0.1738	0.1423	0.2073	0.1127	0.0698	0.4235	0.2848
Istanbul	0.1097	0.0553	0.0925	0.0563	0.1213	0.0091	0.0807	0.2767	0.2246
Jakarta	0.0598	0.0011	0.0037	0.0000	0.0110	0.0577	0.0199	0.0695	0.0802
Johannesburg	0.0000	0.0184	0.0481	0.0578	0.0507	0.0001	0.0934	0.0479	0.0241
Kuala Lumpur	0.0898	0.0263	0.0481	0.0217	0.0882	0.0973	0.0073	0.0868	0.1645
London	0.2294	0.2852	0.2145	0.1907	0.1367	0.0673	0.1577	0.1472	0.4613
Los Angeles	0.2194	0.2563	0.2367	0.1416	0.2139	0.0692	0.0571	0.1781	0.0842
Madrid	0.1396	0.0725	0.0925	0.1885	0.1478	0.0211	0.0326	0.0367	0.1564
Mexico City	0.0997	0.0322	0.0222	0.0188	0.0441	0.0908	0.0354	0.0781	0.0562
Milan	0.1297	0.0740	0.0777	0.1957	0.1676	0.0490	0.0807	0.0412	0.0682
Moscow	0.1197	0.1163	0.0185	0.0094	0.0750	0.2492	0.0870	0.0246	0.0802
Mumbai	0.0898	0.0283	0.0296	0.0339	0.0000	0.0381	0.3182	0.0700	0.0441
New York	0.2194	0.3452	0.2367	0.1806	0.2139	0.0712	0.1795	0.1127	0.1244
Osaka	0.1197	0.1568	0.1183	0.1083	0.1257	0.0776	0.1405	0.0738	0.0160
Paris	0.1995	0.2030	0.1812	0.1683	0.1698	0.0332	0.1351	0.1213	0.2527
San Francisco	0.2194	0.1939	0.2367	0.1871	0.2139	0.1532	0.4324	0.0350	0.0441
Sao Paulo	0.0997	0.0369	0.0000	0.1062	0.0287	0.0143	0.0653	0.0357	0.0481
Seoul	0.1895	0.2351	0.1257	0.1163	0.1147	0.0939	0.0861	0.2467	0.0722
Shanghai	0.1396	0.1424	0.0777	0.1062	0.0243	0.0800	0.1160	0.3372	0.1284
Singapore	0.2095	0.2072	0.1220	0.1668	0.2955	0.1459	0.0408	0.1515	0.2487
Stockholm	0.1496	0.1331	0.1960	0.2224	0.1764	0.0490	0.0499	0.0013	0.0441
Sydney	0.1995	0.1416	0.2034	0.2275	0.1610	0.1330	0.0508	0.0695	0.0521
Taipei	0.1097	0.1042	0.0259	0.0094	0.0243	0.0852	0.0644	0.1904	0.0481
Tokyo	0.2294	0.2865	0.1183	0.2297	0.1257	0.1007	0.5384	0.2594	0.1284
Toronto	0.1995	0.1312	0.2182	0.1993	0.1500	0.0430	0.3852	0.0300	0.1163
Vancouver	0.1596	0.1068	0.2182	0.1907	0.1500	0.0656	0.1931	0.0160	0.0201
Vienna	0.1596	0.0765	0.1701	0.2232	0.1698	0.0154	0.0453	0.0104	0.0441
Washington, DC	0.1596	0.1674	0.2367	0.1387	0.2139	0.0513	0.0281	0.0407	0.0201
Zurich	0.0997	0.1059	0.2219	0.2058	0.1919	0.1459	0.0544	0.0344	0.0241

In this study, the values of the indicators shown in the decision matrix that have a negative effect on performance were transformed using the formula mentioned above and TOPSIS analysis was applied with this new transformed matrix. While some part of the transformed matrix is shown in Table 5.

In the second step, the square of each element of the converted decision matrix is divided by the square root of the sum of each column of the values formed from these squares as shown in formula 3. Thus, a normalized decision matrix is obtained with these calculated values. While some part of the matrix is shown in Table 6.

In the third step, the values calculated in the previous step are multiplied by the related weights obtained in the ANP in order to obtain the weighted normalized matrix. While some part of the matrix is shown in Table 7.

In the fourth step, ideal and negative ideal distance values are calculated by making the calculations specified in formulas 7 and 8.

Some part of the matrix of ideal distance values is shown in Table 8 and some part of the matrix of negative ideal distance values is shown in Table 9.

In the last two steps, ideal and negative ideal values are calculated by using formula 8 and formula 9. Then the relative proximity value for each alternative is obtained with formula 10. Finally, a ranking table from the best alternative to the worst alternative is obtained by ordering these

Table 7. TOPSIS weighted normalized matrix.

	max	max	max	max	max	min	max	max	max
wj	0.04810	0.04810	0.02270	0.06310	0.04890	0.02020	0.00924	0.00923	0.00923
Cities	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
Amsterdam	0.0082	0.0067	0.0040	0.0116	0.0085	0.0014	0.0004	0.0013	0.0025
Bangkok	0.0043	0.0015	0.0006	0.0062	0.0012	0.0080	0.0008	0.0032	0.0018
Barcelona	0.0072	0.0037	0.0021	0.0121	0.0072	0.0004	0.0004	0.0002	0.0013
Beijing	0.0067	0.0080	0.0018	0.0073	0.0012	0.0012	0.0008	0.0016	0.0030
Berlin	0.0086	0.0082	0.0039	0.0100	0.0079	0.0006	0.0010	0.0023	0.0000
Boston	0.0096	0.0119	0.0054	0.0099	0.0105	0.0018	0.0002	0.0010	0.0001
Brussels	0.0048	0.0062	0.0037	0.0101	0.0092	0.0009	0.0002	0.0004	0.0003
Buenos Aires	0.0048	0.0017	0.0003	0.0009	0.0030	0.0003	0.0001	0.0001	0.0001
Cairo	0.0010	0.0000	0.0005	0.0007	0.0020	0.0006	0.0001	0.0001	0.0000
Chicago	0.0096	0.0101	0.0054	0.0072	0.0105	0.0017	0.0007	0.0013	0.0013
Copenhagen	0.0062	0.0050	0.0045	0.0141	0.0084	0.0017	0.0003	0.0004	0.0009
Dubai	0.0067	0.0022	0.0028	0.0085	0.0086	0.0146	0.0009	0.0007	0.0019
Frankfurt	0.0053	0.0041	0.0039	0.0116	0.0079	0.0013	0.0002	0.0019	0.0022
Fukuoka	0.0038	0.0038	0.0027	0.0096	0.0061	0.0018	0.0000	0.0001	0.0001
Geneva	0.0038	0.0052	0.0018	0.0091	0.0082	0.0029	0.0009	0.0000	0.0003
Hong Kong	0.0072	0.0085	0.0039	0.0090	0.0101	0.0023	0.0006	0.0039	0.0026
Istanbul	0.0053	0.0027	0.0021	0.0036	0.0059	0.0002	0.0007	0.0026	0.0021
Jakarta	0.0029	0.0001	0.0001	0.0000	0.0005	0.0012	0.0002	0.0006	0.0007
Johannesburg	0.0000	0.0009	0.0011	0.0036	0.0025	0.0000	0.0009	0.0004	0.0002
Kuala Lumpur	0.0043	0.0013	0.0011	0.0014	0.0043	0.0020	0.0001	0.0008	0.0015
London	0.0110	0.0137	0.0049	0.0120	0.0067	0.0014	0.0015	0.0014	0.0043
Los Angeles	0.0106	0.0123	0.0054	0.0089	0.0105	0.0014	0.0005	0.0016	0.0008
Madrid	0.0067	0.0035	0.0021	0.0119	0.0072	0.0004	0.0003	0.0003	0.0014
Mexico City	0.0048	0.0015	0.0005	0.0012	0.0022	0.0018	0.0003	0.0007	0.0005
Milan	0.0062	0.0036	0.0018	0.0124	0.0082	0.0010	0.0007	0.0004	0.0006
Moscow	0.0058	0.0056	0.0004	0.0006	0.0037	0.0050	0.0008	0.0002	0.0007
Mumbai	0.0043	0.0014	0.0007	0.0021	0.0000	0.0008	0.0029	0.0006	0.0004
New York	0.0106	0.0166	0.0054	0.0114	0.0105	0.0014	0.0017	0.0010	0.0011
Osaka	0.0058	0.0075	0.0027	0.0068	0.0061	0.0016	0.0013	0.0007	0.0001
Paris	0.0096	0.0098	0.0041	0.0106	0.0083	0.0007	0.0012	0.0011	0.0023
San Francisco	0.0106	0.0093	0.0054	0.0118	0.0105	0.0031	0.0040	0.0003	0.0004
Sao Paulo	0.0048	0.0018	0.0000	0.0067	0.0014	0.0003	0.0006	0.0003	0.0004
Seoul	0.0091	0.0113	0.0029	0.0073	0.0056	0.0019	0.0008	0.0023	0.0007
Shanghai	0.0067	0.0068	0.0018	0.0067	0.0012	0.0016	0.0011	0.0031	0.0012
Singapore	0.0101	0.0100	0.0028	0.0105	0.0145	0.0029	0.0004	0.0014	0.0023
Stockholm	0.0072	0.0064	0.0044	0.0140	0.0086	0.0010	0.0005	0.0000	0.0004
Sydney	0.0096	0.0068	0.0046	0.0144	0.0079	0.0027	0.0005	0.0006	0.0005
Taipei	0.0053	0.0050	0.0006	0.0006	0.0012	0.0017	0.0006	0.0018	0.0004
Tokyo	0.0110	0.0138	0.0027	0.0145	0.0061	0.0020	0.0050	0.0024	0.0012
Toronto	0.0096	0.0063	0.0050	0.0126	0.0073	0.0009	0.0036	0.0003	0.0011
Vancouver	0.0077	0.0051	0.0050	0.0120	0.0073	0.0013	0.0018	0.0001	0.0002
Vienna	0.0077	0.0037	0.0039	0.0141	0.0083	0.0003	0.0004	0.0001	0.0004
Washington, DC	0.0077	0.0081	0.0054	0.0087	0.0105	0.0010	0.0003	0.0004	0.0002
Zurich	0.0048	0.0051	0.0050	0.0130	0.0094	0.0029	0.0005	0.0003	0.0002

values from largest to smallest. These values and ranking are shown in Table 10.

Then, the same procedures are made separately for each dimension, and rankings are obtained in terms of the relevant dimensions. These rankings are shown in Table 11.

5. Results

Table 11 shows the smart city scores for each city at the general and each dimension level. When cities are evaluated separately for each dimension, they are analyzed in terms of few and the same indicators. Therefore, in these rankings, more emphasis has been placed on the cities that attract the most attention with their good and bad performances.

In this section, the paper also presents a comparative examination of the ANP/TOPSIS analysis and other indexes. Table 12 shows the top 10 cities in this ranking and those in seven other indexes that have been considered.

5.1. Evaluation in terms of all criteria

The smart and sustainable city concept consists of six characteristics. While 'Smart Living' is the most important characteristic with a 35,459% priority, 'Smart Governance' is the last with 5,738%. Although the smart economy character ranks second among six characteristics, the innovative spirit factor in this character is ranked first with 9.62% ANP priority value in the overall priority order. It is seen how innovative spirit, economic image & trademarks, productivity are at the forefront of the new city and community design. Individual safety, access to health services and the educational infrastructure are more important than other factors according to the results. The health conditions factor in the smart living

Table 8. TOPSIS ideal distance matrix.

Cities	C1	C2	C3	C4	C5	C6	C7
Amsterdam	8.28591E-06	9.76592E-05	1.80435E-06	8.24299E-06	3.51792E-05	0.000175032	2.09132E-05
Bangkok	4.51122E-05	0.000226956	2.28997E-05	6.95514E-05	0.000175943	4.40099E-05	1.72583E-05
Barcelona	1.47305E-05	0.000167018	1.07204E-05	5.83385E-06	5.22048E-05	0.0002028	2.11436E-05
Beijing	1.86433E-05	7.42728E-05	1.30322E-05	5.18463E-05	0.000175943	0.000180453	1.7328E-05
Berlin	5.7541E-06	7.09779E-05	2.28363E-06	1.9946E-05	4.32733E-05	0.000195451	1.57613E-05
Boston	2.07148E-06	2.2225E-05	0	2.11859E-05	1.59208E-05	0.000163687	2.30327E-05
Brussels	3.88977E-05	0.000107292	2.8193E-06	1.9541E-05	2.79224E-05	0.000187757	2.29523E-05
Buenos Aires	3.88977E-05	0.000222054	2.53737E-05	0.000184432	0.000130669	0.00020447	2.36803E-05
Cairo	0.000101502	0.000275702	2.37103E-05	0.000189416	0.0001538	0.000196106	2.34364E-05
Chicago	2.07148E-06	4.19469E-05	0	5.38338E-05	1.59208E-05	0.00016662	1.81035E-05
Copenhagen	2.30164E-05	0.00013387	7.04824E-07	1.32918E-07	3.64701E-05	0.00016662	2.22357E-05
Dubai	1.86433E-05	0.000207883	6.77336E-06	3.61869E-05	3.39116E-05	0	1.65013E-05
Frankfurt	3.31436E-05	0.000155685	2.28363E-06	8.24299E-06	4.32733E-05	0.000178767	2.32745E-05
Fukuoka	5.17869E-05	0.000164529	7.2174E-06	2.42243E-05	6.89513E-05	0.000163687	2.47519E-05
Geneva	5.17869E-05	0.00013045	1.30322E-05	2.8918E-05	3.91216E-05	0.000136441	1.63655E-05
Hong Kong	1.47305E-05	6.53314E-05	2.03694E-06	3.0407E-05	1.86072E-05	0.000152578	1.87506E-05
Istanbul	3.31436E-05	0.000194386	1.07204E-05	0.000119626	7.25797E-05	0.000208632	1.78903E-05
Jakarta	6.65174E-05	0.000273977	2.79745E-05	0.000210019	0.000193526	0.00018124	2.29523E-05
Johannesburg	0.000121757	0.0002471	1.83325E-05	0.000117641	0.000143287	0.000213948	1.69121E-05
Kuala Lumpur	4.51122E-05	0.000235321	1.83325E-05	0.000172262	0.000102758	0.000160373	2.40896E-05
London	0	8.32389E-06	2.53737E-07	6.05607E-06	6.02873E-05	0.000176039	1.23747E-05
Los Angeles	2.30164E-07	1.8281E-05	0	3.09117E-05	1.59208E-05	0.000175032	1.97799E-05
Madrid	1.86433E-05	0.000172052	1.07204E-05	6.74766E-06	5.22048E-05	0.000201676	2.18425E-05
Mexico City	3.88977E-05	0.000226732	2.37103E-05	0.00017708	0.000151137	0.000163687	2.16083E-05
Milan	2.30164E-05	0.000170107	1.30322E-05	4.58774E-06	3.91216E-05	0.000186037	1.78903E-05
Moscow	2.78499E-05	0.000121276	2.45349E-05	0.000193198	0.000116295	9.20599E-05	1.73978E-05
Mumbai	4.51122E-05	0.000232365	2.21033E-05	0.000152525	0.000208819	0.000192071	4.14236E-06
New York	2.30164E-07	0	0	9.60332E-06	1.59208E-05	0.000173988	1.10008E-05
Osaka	2.78499E-05	8.21619E-05	7.2174E-06	5.86168E-05	6.89513E-05	0.00017057	1.35196E-05
Paris	2.07148E-06	4.67992E-05	1.58585E-06	1.50052E-05	3.77842E-05	0.000194797	1.38917E-05
San Francisco	2.30164E-07	5.29942E-05	0	7.22949E-06	1.59208E-05	0.000133011	9.60299E-07
Sao Paulo	3.88977E-05	0.000219843	2.88696E-05	6.07289E-05	0.000170267	0.000205601	1.91151E-05
Seoul	3.68263E-06	2.803E-05	6.34342E-06	5.11921E-05	7.81967E-05	0.000162081	1.74677E-05
Shanghai	1.86433E-05	9.51767E-05	1.30322E-05	6.07289E-05	0.000175943	0.000169312	1.52337E-05
Singapore	9.20657E-07	4.40926E-05	6.77336E-06	1.57196E-05	0	0.000136441	2.11436E-05
Stockholm	1.47305E-05	0.000104081	8.52837E-07	2.07684E-07	3.39116E-05	0.000186037	2.03804E-05
Sydney	2.07148E-06	9.59035E-05	5.70908E-07	1.86916E-08	4.32733E-05	0.000142592	2.03048E-05
Taipei	3.31436E-05	0.000134386	2.28997E-05	0.000193198	0.000175943	0.00016662	1.91884E-05
Tokyo	0	7.98418E-06	7.2174E-06	0	6.89513E-05	0.000158599	0
Toronto	2.07148E-06	0.00010591	1.76206E-07	3.66355E-06	5.06581E-05	0.000189324	2.00359E-06
Vancouver	1.1278E-05	0.000131472	1.76206E-07	6.05607E-06	5.06581E-05	0.000176972	1.01832E-05
Vienna	1.1278E-05	0.000167018	2.28363E-06	1.68224E-07	3.77842E-05	0.000205014	2.07603E-05
Washington, DC	1.1278E-05	7.31238E-05	0	3.29719E-05	1.59208E-05	0.000184762	2.22357E-05
Zurich	3.88977E-05	0.000132497	1.12772E-07	2.26168E-06	2.56896E-05	0.000136441	2.0004E-05

Table 9. TOPSIS negative ideal distance matrix.

Cities	C1	C2	C3	C4	C5	C6	C7
Amsterdam	6.65174E-05	4.51856E-05	1.62392E-05	0.000135047	7.25797E-05	1.95165E-06	1.61628E-07
Bangkok	1.86433E-05	2.36921E-06	3.45364E-07	3.78505E-05	1.40717E-06	6.38876E-05	6.73732E-07
Barcelona	5.17869E-05	1.35479E-05	4.40515E-06	0.000145846	5.22048E-05	1.49143E-07	1.42056E-07
Beijing	4.51122E-05	6.37781E-05	3.10828E-06	5.31672E-05	1.40717E-06	1.42487E-06	6.60052E-07
Berlin	7.45732E-05	6.69034E-05	1.49141E-05	0.000100519	6.19736E-05	4.18061E-07	1.01018E-06
Boston	9.20657E-05	0.000141371	2.88696E-05	9.77964E-05	0.000109422	3.35968E-06	3.09367E-08
Brussels	2.30164E-05	3.90141E-05	1.36454E-05	0.000101435	8.40231E-05	8.54731E-07	3.39532E-08
Buenos Aires	2.30164E-05	2.89957E-06	1.12772E-07	8.30737E-07	9.11752E-06	1.07372E-07	1.18555E-08
Cairo	9.20657E-07	0	2.53737E-07	5.31672E-07	4.19825E-06	3.88342E-07	1.79587E-08
Chicago	9.20657E-05	0.000102569	2.88696E-05	5.11921E-05	0.000109422	2.95441E-06	5.18838E-07
Copenhagen	3.88977E-05	2.5342E-05	2.05527E-05	0.000199585	7.07538E-05	2.95441E-06	6.74153E-08
Dubai	4.51122E-05	4.77923E-06	7.67554E-06	7.18504E-05	7.44288E-05	0.000213948	8.33466E-07
Frankfurt	2.78499E-05	1.70313E-05	1.49141E-05	0.000135047	6.19736E-05	1.579E-06	2.2729E-08
Fukuoka	1.47305E-05	1.42689E-05	7.2174E-06	9.15887E-05	3.77842E-05	3.35968E-06	0
Geneva	1.47305E-05	2.68614E-05	3.10828E-06	8.30737E-05	6.7172E-05	8.67989E-06	8.64332E-07
Hong Kong	5.17869E-05	7.2616E-05	1.55696E-05	8.06002E-05	0.000102758	5.17435E-06	4.15926E-07
Istanbul	2.78499E-05	7.08646E-06	4.40515E-06	1.26355E-05	3.51792E-05	3.34361E-08	5.55667E-07
Jakarta	8.28591E-06	2.70931E-09	7.04824E-09	0	2.90737E-07	1.35588E-06	3.39532E-08
Johannesburg	0	7.82991E-07	1.19115E-06	1.32918E-05	6.152E-06	0	7.44234E-07
Kuala Lumpur	1.86433E-05	1.59794E-06	1.19115E-06	1.86916E-06	1.86072E-05	3.8539E-06	4.48967E-09
London	0.000121757	0.000188216	2.37103E-05	0.000144748	4.47038E-05	1.84683E-06	2.1239E-06
Los Angeles	0.000111399	0.000151996	2.88696E-05	7.9784E-05	0.000109422	1.95165E-06	2.7843E-07
Madrid	4.51122E-05	1.21621E-05	4.40515E-06	0.000141477	5.22048E-05	1.8121E-07	9.09159E-08
Mexico City	2.30164E-05	2.39216E-06	2.53737E-07	1.40395E-06	4.6518E-06	3.35968E-06	1.067E-07
Milan	3.88977E-05	1.26863E-05	3.10828E-06	0.000152525	6.7172E-05	9.74996E-07	5.55667E-07
Moscow	3.31436E-05	3.12679E-05	1.76206E-07	3.50986E-07	1.34437E-05	2.53228E-05	6.46513E-07
Mumbai	1.86433E-05	1.85168E-06	4.51088E-07	4.58774E-06	0	5.89813E-07	8.64269E-06
New York	0.000111399	0.000275702	2.88696E-05	0.000129803	0.000109422	2.06357E-06	2.75021E-06
Osaka	3.31436E-05	5.68511E-05	7.2174E-06	4.6729E-05	3.77842E-05	2.45456E-06	1.68538E-06
Paris	9.20657E-05	9.53219E-05	1.69228E-05	0.00011275	6.89513E-05	4.48876E-07	1.55743E-06
San Francisco	0.000111399	8.69477E-05	2.88696E-05	0.000139317	0.000109422	9.5723E-06	1.59614E-05
Sao Paulo	2.30164E-05	3.15834E-06	0	4.48785E-05	1.96538E-06	8.30477E-08	3.63664E-07
Seoul	8.30893E-05	0.000127915	8.14777E-06	5.38338E-05	3.14462E-05	3.59423E-06	6.33114E-07
Shanghai	4.51122E-05	4.6901E-05	3.10828E-06	4.48785E-05	1.40717E-06	2.60816E-06	1.14936E-06
Singapore	0.000101502	9.92825E-05	7.67554E-06	0.000110822	0.000208819	8.67989E-06	1.42056E-07
Stockholm	5.17869E-05	4.09892E-05	1.97985E-05	0.000197018	7.44288E-05	9.74996E-07	2.12207E-07
Sydney	9.20657E-05	4.63932E-05	2.13209E-05	0.000206075	6.19736E-05	7.21341E-06	2.19994E-07
Taipei	2.78499E-05	2.51179E-05	3.45364E-07	3.50986E-07	1.40717E-06	2.95441E-06	3.53632E-07
Tokyo	0.000121757	0.000189851	7.2174E-06	0.000210019	3.77842E-05	4.13452E-06	2.47519E-05
Toronto	9.20657E-05	3.98546E-05	2.45349E-05	0.000158206	5.37748E-05	7.52497E-07	1.26711E-05
Vancouver	5.8922E-05	2.64009E-05	2.45349E-05	0.000144748	5.37748E-05	1.75264E-06	3.18269E-06
Vienna	5.8922E-05	1.35479E-05	1.49141E-05	0.000198299	6.89513E-05	9.52709E-08	1.75378E-07
Washington, DC	5.8922E-05	6.48515E-05	2.88696E-05	7.65607E-05	0.000109422	1.06963E-06	6.74153E-08
Zurich	2.30164E-05	2.59444E-05	2.53737E-05	0.000168692	8.80236E-05	8.67989E-06	2.52544E-07

character is the second with 7.52% and the individual safety factor is the third with 6.96% priority value. Also, the qualification level in the smart people has 5.4% priority value in the general ranking and is the sixth in the overall ranking. Sustainable resource management is considered as the most important criterion in the smart environment dimension.

When the general ranking is examined, Tokyo, London and New York are in the top three. According to the other indexes, London and New York are in the first two in general rankings of the indexes, while Tokyo is in the first place in the general ranking of the TOPSIS analysis. Tokyo stands out with its innovative spirit, economic image and trademark, companies with headquarters in the city, transparent governance, ICT infrastructure, health and safety scores. London ranks first in the smart people and second in the general and smart living rankings and third in the smart economy ranking with its innovative spirit, international embeddedness, top universities, cultural and educational facilities scores. New York ranks first in the smart economy and third in the general ranking, with its innovation, R&D, entrepreneurship and flexibility of the labour market. But, according to the smart environment assessment, none of these cities is among the top ten. New York ranks seventh in smart living evaluation. Also, New York is not among the top ten in smart people, smart governance, smart mobility and smart environment rankings.

When the results of the all analysis are evaluated together, the cities of USA (New York, Boston, Los Angeles, San Francisco, and Chicago) and London, Paris, Stockholm, Copenhagen, Berlin, Geneva, Barcelona, Vienna, Frankfurt, Zurich, Seoul, Singapore, Tokyo, Sydney, Hong Kong, Taipei and Vancouver are among the top cities. In terms of smart governance, mobility and the environment, US cities do not have good scores compared to other dimensions. The above mentioned European

Table 10. TOPSIS ideal and negative ideal solution values and ranking.

Cities	Si*	Si⁻	Rank	Cities	Ci*
Amsterdam	0.052868	0.05929	1	Tokyo	0.6115798
Bangkok	0.067506	0.05112	2	London	0.5923252
Barcelona	0.051151	0.04946	3	New York	0.5775037
Beijing	0.064338	0.05167	4	Boston	0.5745617
Berlin	0.050696	0.05602	5	Singapore	0.5645908
Boston	0.048708	0.065781	6	Sydney	0.5573827
Brussels	0.060888	0.053181	7	Los Angeles	0.5526279
Buenos Aires	0.062448	0.041992	8	San Francisco	0.5516827
Cairo	0.066678	0.02041	9	Seoul	0.5470812
Chicago	0.053396	0.05776	10	Paris	0.5443925
Copenhagen	0.050336	0.058691	11	Zurich	0.5421279
Dubai	0.048913	0.05187	12	Copenhagen	0.5383162
Frankfurt	0.057092	0.056316	13	Vienna	0.534846
Fukuoka	0.055423	0.054516	14	Amsterdam	0.5286293
Geneva	0.061693	0.056848	15	Toronto	0.5262811
Hong Kong	0.053602	0.058334	16	Berlin	0.5249447
Istanbul	0.054377	0.036788	17	Stockholm	0.5227683
Jakarta	0.08285	0.048059	18	Hong Kong	0.5211371
Johannesburg	0.050661	0.026533	19	Washington, DC	0.5202747
Kuala Lumpur	0.080502	0.051641	20	Chicago	0.5196301
London	0.046808	0.068009	21	Vancouver	0.5176613
Los Angeles	0.04839	0.059775	22	Osaka	0.5163143
Madrid	0.049095	0.049812	23	Dubai	0.5146701
Mexico City	0.083132	0.051672	24	Madrid	0.5036246
Milan	0.059308	0.053703	25	Frankfurt	0.4965787
Moscow	0.068341	0.052338	26	Fukuoka	0.495875
Mumbai	0.075545	0.045876	27	Barcelona	0.4915963
New York	0.044638	0.061015	28	Geneva	0.479564
Osaka	0.054063	0.05771	29	Taipei	0.4782686
Paris	0.04875	0.05825	30	Milan	0.4752015
San Francisco	0.04175	0.051376	31	Brussels	0.4662178
Sao Paulo	0.068748	0.038789	32	Beijing	0.4454003
Seoul	0.050726	0.061272	33	Shanghai	0.4348132
Shanghai	0.067446	0.051888	34	Moscow	0.433696
Singapore	0.046166	0.059863	35	Bangkok	0.4309342
Stockholm	0.049215	0.053911	36	Istanbul	0.4035321
Sydney	0.047129	0.059349	37	Buenos Aires	0.4020682
Taipei	0.058916	0.054008	38	Kuala Lumpur	0.3907963
Tokyo	0.042311	0.06662	39	Mexico City	0.3833121
Toronto	0.05029	0.05587	40	Mumbai	0.3778259
Vancouver	0.05189	0.05569	41	Jakarta	0.3671176
Vienna	0.05166	0.05940	42	Sao Paulo	0.3607038
Washington, DC	0.05099	0.05530	43	Johannesburg	0.3437184
Zurich	0.05005	0.05926	44	Cairo	0.2343606

cities, Tokyo, Fukuoka and Vancouver have the best scores in these dimensions.

Mumbai, Jakarta, Cairo, Johannesburg and Sao Paulo are the last five cities in the general evaluation. Cairo is among the last five countries in all assessments. In all assessments, the cities of Africa, the Middle East and Latin America rank in the last ten. Also, it is seen that the cities which have good scores in the smart economy and smart living also get good scores in the general ranking.

5.2. Smart living (quality of life)

The concept of "Smart living (quality of life)" was assessed by seven factors. While individual safety is the most important factor with a 22.81% priority, the touristic attraction is the last with 3,378%. In terms of this dimension, Tokyo, London, and Boston are in the top three. Because these cities have very good values in the indicators related to health, safety and education. On the other hand, Mumbai, Kuala Lumpur, Sao Paulo, Johannesburg, and Cairo are the last five cities in this assessment. These last five cities in rankings have very low values in education and safety indicators.

5.3. Smart economy (competitiveness)

The concept of a smart economy (competitiveness) is evaluated with six factors. While the innovative spirit is the most important factor with a 32,456% priority and entrepreneurship factor is the last with 7,646%.

Table 11. Performance of each city in terms of general and each dimension according to TOPSIS.

General ranking (smart city)		Smart people		Smart economy		Smart governance		Smart mobility		Smart environment		Smart living	
1. Tokyo	0.6115798	1. London	0.787636	1. New York	0.78074	1. Stockholm	0.855696	1. Copenhagen	0.945788	1. Vancouver	0.739344	1. Tokyo	0.744152
2. London	0.5923252	2. San Francisco	**0.707158**	2. Tokyo	**0.716793**	2. Zurich	**0.854608**	2. Frankfurt	**0.903684**	2. Boston	**0.667913**	2. London	**0.716985**
3. New York	0.5775037	3. Tokyo	**0.700257**	3. London	**0.712524**	3. Copenhagen	**0.853598**	3. Vienna	**0.902892**	3. Stockholm	**0.652541**	3. Boston	**0.688588**
4. Boston	0.5745617	4. Seoul	**0.695891**	4. Singapore	**0.697883**	4. Vancouver	**0.845106**	4. Amsterdam	**0.902598**	4. Zurich	**0.642413**	4. Seoul	**0.687987**
5. Singapore	0.5645908	5. Boston	**0.695429**	5. San Francisco	**0.684253**	5. Geneva	**0.829114**	5. Zurich	**0.847064**	5. Sydney	**0.633557**	5. Paris	**0.680324**
6. Sydney	0.5573827	6. Sydney	**0.692893**	6. Los Angeles	**0.682212**	6. London	**0.822281**	6. Berlin	**0.845349**	6. Dubai	**0.622147**	6. Berlin	**0.663018**
7. Los Angeles	0.5526279	7. Chicago	**0.686986**	7. Boston	**0.668607**	7. Berlin	**0.81669**	7. Barcelona	**0.814434**	7. Vienna	**0.610406**	7. New York	**0.662372**
8. San Francisco	0.5516827	8. Zurich	**0.676838**	8. Paris	**0.633505**	8. Amsterdam	**0.815203**	8. Geneva	**0.810539**	8. Copenhagen	**0.595295**	8. Vienna	**0.662288**
9. Seoul	0.5470812	9. Amsterdam	**0.670425**	9. Chicago	**0.61454**	9. Singapore	**0.807007**	9. Tokyo	**0.784878**	9. San Francisco	**0.593548**	9. Taipei	**0.659652**
10. Paris	0.5443925	10. Los Angeles	**0.670286**	10. Hong Kong	**0.604416**	10. Frankfurt	**0.799164**	10. Fukuoka	**0.759244**	10. Geneva	**0.592059**	10. Sydney	**0.649888**
11. Zurich	0.5421279	11. New York	**0.66687**	11. Sydney	0.604138	11. Sydney	**0.779154**	11. Osaka	**0.754483**	11. Fukuoka	**0.583158**	11. Los Angeles	**0.647272**
12. Copenhagen	0.5383162	12. Osaka	**0.663274**	12. Toronto	0.588991	12. Toronto	**0.777885**	12. Stockholm	**0.747683**	12. Taipei	**0.580983**	12. Osaka	**0.642412**
13. Vienna	0.534846	13. Copenhagen	**0.661098**	13. Stockholm	0.579484	13. Washington, DC	**0.753239**	13. Brussels	**0.729336**	13. Toronto	**0.573229**	13. Singapore	**0.641559**
14. Amsterdam	0.5286293	14. Dubai	**0.657685**	14. Amsterdam	0.579299	14. Chicago	**0.745172**	14. Taipei	**0.701491**	14. Chicago	**0.569887**	14. Fukuoka	**0.640914**
15. Toronto	0.5262811	15. Geneva	**0.657267**	15. Washington, DC	0.574933	15. New York	**0.740595**	15. Madrid	**0.6766**	15. Washington, DC	**0.564337**	15. Hong Kong	**0.637428**
16. Berlin	0.5249447	16. Washington, DC	**0.651563**	16. Berlin	0.571319	16. Los Angeles	**0.738262**	16. Milan	**0.673938**	16. Buenos Aires	**0.562079**	16. Madrid	**0.637084**
17. Stockholm	0.5227683	17. Shanghai	**0.648202**	17. Seoul	0.555514	17. San Francisco	**0.738262**	17. Hong Kong	**0.645674**	17. Amsterdam	**0.556327**	17. Zurich	**0.629592**
18. Hong Kong	0.5211371	18. Beijing	**0.643775**	18. Copenhagen	0.548801	18. Vienna	**0.738073**	18. Singapore	**0.638606**	18. Singapore	**0.544249**	18. Copenhagen	**0.623494**
19. Washington, DC	0.5202747	19. Frankfurt	**0.643654**	19. Zurich	0.540421	19. Boston	**0.734864**	19. Seoul	**0.636487**	19. Tokyo	**0.540435**	19. Amsterdam	**0.623158**
20. Chicago	0.5196301	20. Vancouver	**0.640515**	20. Vancouver	0.533934	20. Brussels	**0.734421**	20. Paris	**0.623273**	20. Osaka	**0.536293**	20. Toronto	**0.615315**
21. Vancouver	0.5176613	21. Singapore	**0.638848**	21. Vienna	0.531053	21. Tokyo	**0.733381**	21. Vancouver	**0.621141**	21. Seoul	**0.522546**	21. Barcelona	**0.613772**
22. Osaka	0.5163143	22. Paris	**0.638521**	22. Brussels	0.502984	22. Osaka	**0.726315**	22. New York	**0.574422**	22. Berlin	**0.514178**	22. Washington, DC	**0.606286**
23. Dubai	0.5146701	23. Toronto	**0.637423**	23. Frankfurt	0.49703	23. Paris	**0.721517**	23. London	**0.548822**	23. Frankfurt	**0.513508**	23. Moscow	**0.602836**
24. Madrid	0.5036246	24. Kuala Lumpur	**0.63684**	24. Milan	0.486543	24. Fukuoka	**0.719731**	24. Chicago	**0.441194**	24. New York	**0.508517**	24. Frankfurt	**0.599208**
25. Frankfurt	0.4965787	25. Mexico City	**0.629532**	25. Barcelona	0.48495	25. Dubai	**0.637745**	25. Beijing	**0.432691**	25. Los Angeles	**0.488859**	25. Vancouver	**0.594934**
26. Fukuoka	0.495875	26. Milan	**0.626128**	26. Madrid	0.476904	26. Madrid	**0.619227**	26. Dubai	**0.426823**	26. Madrid	**0.456936**	26. Milan	**0.587572**
27. Barcelona	0.4915963	27. Stockholm	**0.62548**	27. Geneva	0.44677	27. Barcelona	**0.606727**	27. Toronto	**0.425509**	27. London	**0.438178**	27. Chicago	**0.583598**
28. Geneva	0.479564	28. Brussels	**0.624946**	28. Dubai	0.444985	28. Seoul	**0.577744**	28. Sydney	**0.417009**	28. Paris	**0.400794**	28. San Francisco	**0.578888**
29. Taipei	0.4782686	29. Moscow	**0.624167**	29. Osaka	0.443782	29. Hong Kong	**0.570275**	29. Washington, DC	**0.406835**	29. Kuala Lumpur	**0.397376**	29. Bangkok	**0.574767**
30. Milan	0.4752015	30. Hong Kong	**0.623818**	30. Beijing	0.425523	30. Taipei	**0.523019**	30. Boston	**0.390924**	30. Milan	**0.391658**	30. Dubai	**0.573855**
31. Brussels	0.4662178	31. Bangkok	**0.617687**	31. Fukuoka	0.397732	31. Milan	**0.478869**	31. Buenos Aires	**0.378431**	31. Brussels	**0.391479**	31. Geneva	**0.57092**
32. Beijing	0.4454003	32. Jakarta	**0.600095**	32. Shanghai	0.392406	32. Kuala Lumpur	**0.450696**	32. Shanghai	**0.370722**	32. Moscow	**0.387395**	32. Stockholm	**0.563384**
33. Shanghai	0.4348132	33. Taipei	**0.597**	33. Istanbul	0.318653	33. Johannesburg	**0.367187**	33. San Francisco	**0.360513**	33. Barcelona	**0.381785**	33. Brussels	**0.556917**
34. Moscow	0.433696	34. Berlin	**0.583651**	34. Moscow	0.279362	34. Buenos Aires	**0.335723**	34. Kuala Lumpur	**0.336246**	34. Johannesburg	**0.372613**	34. Beijing	**0.556732**
35. Bangkok	0.4309342	35. Fukuoka	**0.581773**	35. Bangkok	0.26846	35. Istanbul	**0.332658**	35. Johannesburg	**0.29986**	35. Bangkok	**0.360142**	35. Shanghai	**0.54976**
36. Istanbul	0.4035321	36. Mumbai	**0.575282**	36. Sao Paulo	0.262023	36. Sao Paulo	**0.332612**	36. Bangkok	**0.27668**	36. Hong Kong	**0.355455**	36. Buenos Aires	**0.53936**
37. Buenos Aires	0.4020682	37. Barcelona	**0.527511**	37. Taipei	0.245209	37. Beijing	**0.326786**	37. Moscow	**0.253741**	37. Mexico City	**0.340936**	37. Istanbul	**0.53415**
38. Kuala Lumpur	0.3907963	38. Vienna	**0.527363**	38. Kuala Lumpur	0.226246	38. Shanghai	**0.326184**	38. Los Angeles	**0.243852**	38. Sao Paulo	**0.288328**	38. Jakarta	**0.52992**
39. Mexico City	0.3833121	39. Madrid	**0.525638**	39. Buenos Aires	0.188055	39. Moscow	**0.319726**	39. Sao Paulo	**0.235805**	39. Beijing	**0.284526**	39. Mexico City	**0.517927**
40. Mumbai	0.3778259	40. Buenos Aires	**0.515816**	40. Mexico City	0.183116	40. Mexico City	**0.318902**	40. Mexico City	**0.181068**	40. Istanbul	**0.251888**	40. Mumbai	**0.50067**
41. Jakarta	0.3671176	41. Cairo	**0.473958**	41. Mumbai	0.18091	41. Bangkok	**0.286861**	41. Istanbul	**0.171568**	41. Mumbai	**0.232184**	41. Kuala Lumpur	**0.49575**
42. Sao Paulo	0.3607038	42. Sao Paulo	**0.456914**	42. Johannesburg	0.154624	42. Mumbai	**0.25656**	42. Mumbai	**0.123493**	42. Shanghai	**0.190128**	42. Sao Paulo	**0.458324**
43. Johannesburg	0.3437184	43. Istanbul	**0.356064**	43. Jakarta	0.106016	43. Jakarta	**0.186497**	43. Cairo	**0.0966421**	43. Jakarta	**0.181619**	43. Johannesburg	**0.44241**
44. Cairo	0.2343606	44. Johannesburg	**0.204538**	44. Cairo	0.0777913	44. Cairo	**0.0727457**	44. Jakarta	**0.0887073**	44. Cairo	**0.168109**	44. Cairo	**0.189114**

Table 12. Comparison with other indexes.

Ranking by city	ANP-TOPSIS General ranking	ANP-TOPSIS Smart environment	ANP-TOPSIS Smart governance	ANP-TOPSIS Smart mobility	ANP-TOPSIS Smart living	ANP-TOPSIS Smart people	ANP-TOPSIS Smart economy
1	Tokyo	Vancouver	Stockholm	Copenhagen	Tokyo	London	New York
2	London	Boston	Zurich	Frankfurt	London	San Francisco	Tokyo
3	New York	Stockholm	Copenhagen	Vienna	Boston	Tokyo	London
4	Boston	Zurich	Vancouver	Amsterdam	Seoul	Seoul	Singapore
5	Singapore	Sydney	Geneva	Zurich	Paris	Boston	San Francisco
6	Sydney	Dubai	London	Berlin	Berlin	Sydney	Los Angeles
7	San Francisco	Vienna	Berlin	Barcelona	New York	Chicago	Boston
8	Los Angeles	Copenhagen	Amsterdam	Geneva	Vienna	Zurich	Paris
9	Seoul	San Francisco	Singapore	Tokyo	Taipei	Amsterdam	Chicago
10	Paris	Geneva	Frankfurt	Fukuoka	Sydney	Los Angeles	Hong Kong
Ranking by city	CIMI 2018 (IESE)	Global Cities Index 2018 (A.T. Kearney)	Global Power City Index 2018 (MMF)	Quality of Living City Ranking 2018 (Mercer)	Global Liveability Index 2018 (Economist Intelligence Unit)	Sustainable Cities Index 2018 (Arcadis)	Global Financial Centres Index (GFCI) 2018 (Z/Yen)
1	London	New York	London	Vienna	Vienna	London	London
2	New York	London	New York	Zurich	Melbourne	Stockholm	New York
3	Amsterdam	Paris	Tokyo	Munich	Osaka	Edimburgh	Hong Kong
4	Paris	Tokyo	Paris	Auckland	Calgary	Singapore	Singapore
5	Reykjavík	Hong Kong	Singapore	Vancouver	Sydney	Vienna	Tokyo
6	Tokyo	Los Angeles	Amsterdam	Düsseldorf	Vancouver	Zurich	Shangai
7	Singapore	Singapore	Seoul	Frankfurt	Toronto	Munich	Toronto
8	Copenhagen	Chicago	Berlin	Geneva	Tokyo	Oslo	San Francisco
9	Berlin	Beijing	Hong Kong	Copenhagen	Copenhagen	Hong Kong	Sydney
10	Vienna	Brussels	Sydney	Basel	Adelaide	Frankfurt	Boston

New York, Tokyo and London are in the top three in the smart economy evaluation, while the five American cities are in the top ten. In the smart economy evaluation, the ranking is very similar to the overall ranking because the innovative spirit criterion has the largest criteria weight and the smart economy dimension has the second-highest dimension weight.

In the smart economy evaluation, there is not any European city among the last ten cities. Mexico City, Mumbai, Johannesburg, Jakarta and Cairo are the last five cities in this assessment. The main reason for this is the low R&D (innovative spirit), entrepreneurship, GDP per employed person (productivity) values.

5.4. Smart mobility (ICT and transport)

The concept of smart mobility (transportation and ICT) consists of four factors. While sustainable, innovative and safe transport systems are the most important factor with a 56.241% priority and availability of ICT infrastructure factor is the last with a 6.16% ANP priority value.

In smart mobility assessment, Copenhagen, Frankfurt and Vienna are at the top. All three of these cities have good scores on traffic safety, freedom and openness, availability of ICT infrastructure and sustainable public transportation network indicators. Especially Copenhagen is the city with the best score among all cities in terms of policies promoting free or low-cost internet access.

5.5. Smart governance (participation)

The concept of smart governance (participation) was evaluated by three factors. Transparent governance is the most important factor with a 56,655% priority and participation in decision making is the second with 27,343% and public and social services factor is the last with a 16,003% ANP priority value.

Stockholm, Zurich and Copenhagen are in the top three in terms of smart governance. Stockholm and Copenhagen stand out with their scores in the criteria of participation in decision making and transparent governance. Also, Zurich stands out with its scores in social and public services and electoral process and pluralism criteria.

5.6. Smart environment (natural resources)

The concept of smart environment (natural resources) was evaluated by four factors. While sustainable resource management is the most important factor with a 36,916% priority, pollution is the second priority with 34,925% and the attractivity of natural conditions factor is the third with 22,212% and environmental protection is the last with a 5,947% ANP priority value.

Vancouver stands out especially with its high score of public green space. It also ranks first in smart environment evaluation. Vancouver, Boston and Stockholm are in the top three places in the smart environmental ranking especially with their values in environmental protection, commitment to climate action, renewable energy rate, waste recycle rate, CO2 emissions, SPM density, SO2 and NO2 density indicators.

5.7. Smart people (social and human capital)

The concept of smart people (social and human capital) was assessed by seven factors. While level of qualification is the most important factor with a 31,564% priority and social and ethnic plurality factor is the last with a 8.088% ANP priority value.

London, San Fransisco and Tokyo are in the top three places in the smart people ranking. London has especially high values at the number of universities ranked by QS world university rankings, lifelong learning, foreign-born populations (%), flexibility and creativity indicators.

6. Conclusion

Governments and policymakers are seeking new investment and policy areas to make their cities more sustainable and productive, and make them more attractive in terms of quality of life. Different methods and measurement indices have been developed according to various meanings of the "smart and sustainable city" concept. Evaluation systems that consist of quantitative indicators are attracting great interest among city managers and policymakers. Thus, they can decide where to invest their time and resources.

This methodology produced an effective comparison between major cities. Each assessment provides very significant information along with the results that can be used in order to improve the performance of cities. Many important connections were explored during the analysis that suggests information on the situation of cities and evaluation dimensions. The following recommendations were made based on this research:

Lower-rated cities like Mexico City, Mumbai, Johannesburg, Jakarta and Cairo (especially the cities of Africa, the Middle East and Latin America) should invest in the improvement of their infrastructure to have a better economic development regarding entrepreneurship and productivity. Also, these cities should produce policies to improve the performance of their health, education and safety system. It is recommended that the cities that have bad scores in terms of smart environment scores should follow the policies and targets that the leading cities (Vancouver, Boston and Stockholm) have. The governments should encourage the cities to improve performance of some significant indicators such as environmental protection, commitment to climate action, renewable energy rate, waste recycle rate, CO2 emissions, SPM density, SO2 and NO2 density. Cities that need economic growth should give priority to educating their people to encourage knowledge-intensive industries, a typical strength of dense cities like Tokyo, London, New York, and Singapore.

Cities with low scores in terms of smart mobility should increase their performance of freedom and openness, policies promoting free or low-cost internet access, and availability of ICT infrastructure. In addition, they need to have a sustainable public transportation network in terms of local accessibility. Because they should reduce road network congestion.

Cities with low-scores in terms of quality of life should produce policies for housing quality, health, safety, cultural facilities and education for its people to attain a better standard of smart living like in Tokyo, London, and Boston.

Cities with low scores in the dimension of smart people should improve quality of their universities, strengten lifelong learning, encourage social and ethnic plurality, increase the number of employees in creative industries, encourage cosmopolitanism/open-mindedness, and support participation in public life.

The recommended method not only provides the results that are not surprising, which happens in most of the indices but also showes the priority areas to improve the performance of cities. Thus, the results of the analysis are aimed at helping policymakers to see the areas they can improve in order to maintain their smart and sustainability and to compare their current situation with their rivals.

This approach is also a reliable quantitative method to rank cities where data for all indicators are available. The weighting and ranking methods used in the study strives to simplify the evaluation of the concept of a smart and sustainable city and make it easy to understand. ANP considers the important interactions among evaluation criteria and dimensions. Unlike assumptions and methods that equally consider all components and factors, this approach offers an effective weighting system and priority (weight) values, using expert opinion through the ANP. Making use of the evaluation of experts from so many different fields is a novelty of this study and its superiority compared to many other studies.

ANP is dependent on pairwise matrices, which are composed of subjective evaluations of experts, thus different ANP analyzes in the same field may produce slightly different results. Moreover, the process of

obtaining and processing these matrices is quite long. These are considered as the limitations of this method.

7. Recommendation

The recommended method can be utilized to assess other cities and countries. By continuously updating the data from the sources indicated in Appendix A, these evaluations can be updated periodically. Thus, the sustainability of the analysis can be ensured. Also, ELECTRE, VIKOR and other MCDM methods may be used to make smart and sustainable city comparisons, and the results of this article can be compared with results of these methods.

Declarations

Author contribution statement

G. Ozkaya, C. Erdin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Appendix A. The description and source of indicators.

No.	Indicator	Description	Criteria/ Dimension	Source
1	Innovation	Innovation Index score	Innovative spirit (Smart economy)	Innovation Cities Index: Global 2018 Innovation Cities Program
2	Research and Development	Research and Development score	Innovative spirit (Smart economy)	Global Power City Index (GPCI), 2018
3	Entrepreneurship	Entrepreneurship Index score	Entrepreneurship (Smart economy)	The Global Entrepreneurship Index, 2018
4	Economic image & trademarks	City Reputation score	Economic image & trademarks (Smart economy)	City RepTrak Scores (The World's Most Reputable Cities, 2018)
5	Productivity	GDP per employed person (constant 2011 PPP $) per cities	Productivity (Smart economy)	World Cities Culture Forum Report, Eurostat, OECD, national statistical institutions
6	Flexibility of labour market	Market size/ market attractiveness/ economic vitality/ human capital/ business environment/ ease of doing business (GPCI 2018)	Flexibility of labour market (Smart economy)	Global Power City Index (GPCI), 2018
7	Headquarters	Companies with HQ in the city	International embeddedness (Smart economy)	Globalization and World Cities (GaWC)(2018-2019)
8	International airline passengers	Number of international airline passengers (million)	International embeddedness (Smart economy)	Eurostat, OECD, national statistical institutions, 2018 statistics, IATA World Air Transport Statistics, 2018
9	Air freight	Amount of air freight (thousand tonnes - per year)	International embeddedness (Smart economy)	Eurostat, OECD, national statistical institutions 2018, IATA World Air Transport Statistics, 2018
10	Universities	Number of universities ranked by QS World University Rankings	Level of qualification (Smart people)	QS World University Rankings 2020
11	Participate in education	Mean years of schooling	Level of qualification (Smart people)	Human Development Education Index 2015, Eurostat, OECD, national statistical institutions, 2018 statistics
12	English Proficiency	EF English Proficiency Index City Scores, * Cities with English native speakers were considered equal to the score of the city with the highest English Foreign Language score.	Level of qualification (Smart people)	EF English Proficiency Index City Scores, 2019

(*continued on next column*)

(*continued*)

No.	Indicator	Description	Criteria/ Dimension	Source
13	Lifelong learning	Quality of management schools/Prevalence of training in firms/Employee development	Lifelong learning (Smart people)	The Global Talent Competitiveness Index,2019
14	Social and ethnic plurality	Foreign born populations (%)	Social and ethnic plurality (Smart people)	Eurostat, OECD, United States Census Bureau, national statistical institutions
15	Flexibility	Unemployment rate per cities	Flexibility (Smart people)	Eurostat, OECD, national statistical institutions, 2018-2019 statistics
16	Creativity	Share of people working in creative industries	Creativity (Smart people)	World Cities Culture Forum Report, Eurostat, national statistical institutions
17	Cosmopolitanism/ Open-mindedness	Immigration-friendly environment index scores	Cosmopolitanism/ Open-mindedness (Smart People)	Inclusiveness Index 2018, The Global Talent Competitiveness Index 2019
18	Participation in public life	Voters turnout at city elections (%)	Participation in public life (Smart People)	Eurostat, OECD, national statistical institutions
19	Electoral process and pluralism	Electoral process and pluralism score	Participation in decision-making (Smart governance)	Democracy Index (2018)
20	Political participation	Political participation of inhabitants score	Participation in decision-making (Smart governance)	Democracy Index (2018)
21	Civil liberties	Civil liberties score	Participation in decision-making (Smart governance)	Democracy Index (2018), The Global Talent Competitiveness Index 2019
22	Female city representatives	Share of female city representatives (%)	Participation in decision-making (Smart governance)	Official web pages of the municipalities
23	Government effectiveness	Quality of public services, civil services and their independence from political pressures	Public and social services (Smart governance)	The Global Talent Competitiveness Index, 2019
24	Satisfaction with transparency of bureaucracy	E-Government Development Level	Transparent governance (Smart governance)	E-Government Development Index (EGDI), United Nations
25	Corruption	Satisfaction with fight against corruption	Transparent governance (Smart governance)	Transparency International Report, Corruption Perceptions Index, The Global Talent Competitiveness Index 2019
26	Local accessibility	Sustainable public transportation network scores	Local accessibility (Smart mobility)	Sustainable Cities Mobility Index, 2017
27	Freedom and openness	Freedom and openness score	(Inter-)national accessibility (Smart mobility)	Web Index 2014, World Wide Web Foundation
28	Policies	Policies promoting free or low cost internet access (Universal access) score	(Inter-)national accessibility (Smart mobility)	Web Index 2014, World Wide Web Foundation
29	Traffic safety	Consideration of the time spent in traffic, the dissatisfaction this generates, CO_2 consumption and other inefficiencies of the traffic system.	Sustainable, innovative and safe transport systems (Smart mobility)	Numbeo
30	Sunshine hours	Sunshine hours annually	Attractivity of natural conditions (Smart environment)	Eurostat, OECD, national statistical institutions, 2018-2019 statistics
31	Public green space share	Public green space share (%)	Attractivity of natural conditions (Smart environment)	Eurostat, OECD, national statistical institutions, 2018-2019 statistics
32	Pollution	Pollution index	Pollution (Smart environment)	Numbeo
33	Environmental protection	Environmental performance index	Environmental protection (Smart environment)	Numbeo
34	Efficient use of water	Usage of water (use per GDP)	Sustainable resource management (Smart environment)	National statistical institutions 2018-2019 statistics
35	Environment index	Commitment to climate action, renewable energy rate, waste recycle rate CO2 emissions, SPM density, SO2 and NO2 density	Sustainable resource management (Smart environment)	Global Power City Index (GPCI), 2018

(*continued on next column*)

(*continued*)

No.	Indicator	Description	Criteria/ Dimension	Source
36	Cultural interaction	Cultural interaction index (number of ınternational conferences, number of world-class cultural events, cultural content export value, environment of creative activities, proximity to world heritage sites, cultural ınteraction opportunities, number of theaters and concert halls, number of museum, number of stadiums, number of luxury hotel guest rooms, number of hotels, attractiveness of shopping options, attractiveness of dining options)	Cultural facilities (Smart living)	Global Power City Index (GPCI), 2019
37	Health	Health index (skill and competency of medical staff, speed in completing examination and reports, equipment for modern, diagnosis and treatment, accuracy and completeness in filling out reports, friendliness and courtesy of the staff, responsiveness (waitings) in medical institutions, convenience of location for resident)	Health conditions (Smart living)	Numbeo
38	Safety	Safety index	Individual safety (Smart living)	Numbeo
39	Poperty price	Poperty price to income ratio	Individual safety (Smart living)	Numbeo
40	Living city centre	Price to rent ratio city centre	Housing quality (Smart living)	Numbeo
41	Affordability	Affordability index	Housing quality (Smart living)	Numbeo
42	Education	Human capital scores (Higher education, Business schools, Movement of students, Universities, Schools, Expenditure on leisure and recreation, Expenditure on education)	Education facilities (Smart living)	IESE Cities in Motion Index, 2019
43	International inbound tourists	International inbound tourists (million), 2017	Touristic attractivity (Smart living)	National statistical institutions, 2018
44	Homeless rate	Homeless rate (per 100 000 residents)	Social cohesion (Smart living)	National statistical institutions, 2019
45	Volunteering	Helping a stranger, volunteering time, donating money	Social cohesion (Smart living)	World giving index, 2018

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