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A Different Approach to the Evaluation of Smart Cities' Indicators

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Abstract: The article aims to propose a different approach to assessing smart cities which combines some commonly used indicators with several new ones in line with the concept of sustainability. The aspect of sustainable development as an essential driver for the smart city and the combination of indicators for sustainable and smart city concepts have been analysed fragmentarily so far. There are many different approaches to

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evaluate the indicators of city smartness; however, very little attention is paid to the analysis of the reciprocal importance of the indicators. Ten indicators representing a smart city were selected that would be keep in line all the three pillars of sustainability—environmental, social, and economic. An expert survey was conducted to assign the weights of indicators using the pairwise comparison approach. The results were processed by utilising the fuzzy analytic hierarchy process (AHP), which reduces the subjectivity in the experts' answers. The presented approach differs from the ones commonly used and while it does not cover a wide range of usual indicators, it proposes some new ideas for further research. Some represent cities to attract young and intelligent citizens, others relate to comfortable and safe living conditions and the environmental situation. The results revealed that the most vital smartness indicators are foreign direct investments, pollutant emission, and the share of people registered as unemployed among the working-age population. These indicators cannot be easily identified as ones representing a smart city, but rather as indicators representing investment and environmental, sustainable aspects. Hence, finding a balance between the indicators related to sustainable and smart city is what highlights the need for further research.

Keywords: *fuzzy AHP, fuzzy numbers, indicators of smartness, smart cities, sustainability*

1. Introduction

Smart cities (SC) have been investigated by a wide range of scholars from various scientific fields, which shows their importance in modern-day science. SC could be considered as a driver towards sustainable development (AlKhatib *et al.*, 2020; De Guimarães *et al.*, 2020; Kourtit, Elmlund & Nijkamp, 2020), which has made it one of the essential research topics today.

Some scholars examine SC in terms of efficient energy management and consumption (Dang, Pham & Nguyen, 2020; Said & Tolba, 2020; Silva, Khan & Han, 2020). Others link the concept of SC to the existence of intelligent information and communication technologies (Uwe & Gerber, 2019; Kumar *et al.*, 2020). Estévez-Ortiz *et al.* (2016) analyse social media, such as social networking, microblogging, multimedia platforms, crowdsourcing platforms, collaborative tools using sentiment analysis, and focus on the interaction between the sentiments of society, internet opinions, and local governance. Jelonek *et al.* (2020) present a model for planning directions in city development and involve the following main groups of subjects that determine the image of a city: residents, public administration entities, companies, separating utility companies, educational institutions and universities, hospitals and healthcare facilities, and the local media: the press, radio and television. Abdel-Basset *et al.* (2020) investigate SC from the perspective of disaster response systems and argue that SC could be used to easily manage natural disasters.

Caird and Hallett (2019) determine the value of smart urban developments and indicate the following essential characteristics: integration of information and communication technology (ICT) infrastructure and technologies; the development of human capital; a concept of big data, which describes information/data assets; the development phases of SC; and, finally, a diverse range of smart city projects, etc. ITC infrastructure, according to Uwe and Gerber (2019), is directly related to various possible risks (cyber-attacks, natural disasters) that need to be managed.

Ahvenniemi *et al.* (2017) discuss the concept of SC as a sustainable city, focusing more on indicators measuring environmental sustainability and less on social and economic aspects. Supporting the opinion by Sancino and Hudson (2020) that SC could be considered a driver for economic growth, more indicators representing economic aspects were chosen for the research, although these are still in line with all the three basic areas of sustainability—environmental, social, and economic.

Many different approaches analyse the indicators of city smartness. However, it is not apparent which indicators are the most important and vital for cities to become smart. The article discusses a different approach, combining commonly used indicators with several new ones, covering the concept of sustainable and smart city.

The article aims at addressing the research question of identifying indicators, including those related to sustainable and smart city concept, by ranking the indicators for a city's ability to receive a smart city label.

The article is structured into three main parts. First, the theoretical literature review exposes the interrelation between smart city and sustainability and outlines the selection of indicators. Second, the methodological part is dedicated to describing the analysed methods for the research. Furthermore, the third part covers the research results leading to the conclusions and discussion.

2. Literature review

2.1 The concept of smart city

According to Dameri and Cocchia (2013), the SC was initially mentioned in 1994; hence, the SC concept is relatively new, but it has also captured the attention of scientists from different fields and pushed to the background other collocations such as sustainable cities, green cities, creative cities, and others (Pevcin, 2019). The origin of the concept likely derives from the phenomenon of intangible goods becoming budget assets in the period between the 1980s and the new millennium for the first time in the history of economy (De Falco, 2019).

Many scholars define SC as efficient energy users. For instance, Neirotti *et al*. (2014) propose a concept of SC through natural resources and energy, transport and mobility, buildings, living, government, and economy and people. The authors state that economic development and urban structural variables will most likely be affected by the city's digital path, its geographical location, and population density, with related congestion problems. According to Caird and Hallett (2019), a SC incorporates "digital, human and physical systems into the built environment". Chourabi *et al.* (2012) focus on a broader range of key characteristics: management and organisation, technology, governance, the political context, people and communities, the economy, infrastructure, and the environment.

SC is often associated with innovative technologies. Strielkowski *et al*. (2020) claim that the SC concept covers the technology-based intelligent city with social capital that could create interconnections between different fields: education, culture, arts, and business. Carvalho (2017) agrees and argues that the cities that are able to develop collaborative networks for creating an appropriate living environment are called SC.

There are scientists who associate SC with proper planning (Dutta *et al.*, 2020; Jelonek *et al.*, 2020) and relate to their social, economic and political planning (De Falco, 2019). Despite the fact that others consider SC as sustainable (Caird & Hallett, 2019; Estévez-Ortiz *et al.*, 2016), there are authors who support the idea that only when ICT is applied to all sustainable development decisions, the SC could carry the concept of a smart, sustainable city (Ahad *et al.*, 2020; Elgazzar & El-Gazzar, 2017; Macke *et al.*, 2019; Yigitcanlar *et al.*, 2019), whereas others also confront the concept of SC as "smart, sustainable cities" stating that keeping in mind only the rise of technological efficiency cannot ensure real sustainability in a city (Ibrahim, El-Zaart & Adams, 2017; 2018).

Therefore, the research question addresses the indicators for the city's ability to receive a smart city label ranking, including the concept of sustainable and smart city.

2.2 Indicators of smart cities

There are many criteria, opinions and approaches as to what kind of indicators could help receive an SC label. Before analysing the indicators, it is worth going through the entities of SCs. Although many studies name the scope of technology and technological solutions as the key entity of SC (Ahad *et al.*, 2020; Jararweh *et al.*, 2020; Singh *et al.*, 2020; Yigitcanlar *et al.*, 2019), the same authors also support many other entities, and that makes up the whole picture of an SC. For example, Ahad *et al.* (2020) name demographical and environmental aspects in line with economics. Yigitcanlar *et al.* (2019) name community and policy which, together with technology, can build the SC as they are related to entities of government, environment, economy and society. Guelzim *et al.* (2016) are more precise in detailing the entities of SCs and in addition to the most frequently mentioned economy, environment, governance and policies, they name also smart infrastructure, smart policies, smart transportation, smart healthcare, smart agriculture, smart education, smart industry, smart energy, and smart feedback mechanisms.

In sum, it could be stated that the concept of SC covers many entities such as liveable, inclusive, creative, innovative, digital, intelligent, sustainable, green cities, etc. and finally, such cities are in general global (De Falco, 2019).

Nowadays, foreign direct investments (FDI) are one of the most significant economic indicators. De Falco (2019) claims that one of the indicators that makes a city smart is the ability to attract foreign direct investments (FDI). In fact, FDI could make the city's economy more sound (Wall *et al.*, 2015), which, in turn, leads to city smartness (Wall & Stavropoulos, 2016). Also, Chourabi *et al.* (2012) highlight globalism as a significant feature of SC. Globalisation relates not only to FDI but also to the mobility of people—for example, immigrants. Population migration has several reasons, but the economic situation in the immigrants' home countries is a very common one. The host countries welcome highly qualified immigrants despite their reason for migration; however, very often, such people face unemployment, at least during the first months of residence in the foreign country. The rate of unemployment covers both economic and social aspects, but in this research, this indicator is more related to the economic aspect. The number of international immigrants is linked to the globalisation of the economy and the social situation in the cities due to an increase in population density. International immigrants are especially crucial in those cities which attempt to be/become smart. According to Peňaška and Veľas (2019), it is important to follow the trends in mass migration as these can bring new challenges that will require unique solutions. Monzon (2015) states that for the transformation of a city into a smart one, it is necessary to solve the unemployment problem. Unemployment rate is used in a wide range of studies investigating SC as an indicator of smartness (Wall & Stavropoulos, 2016; Peňaška & Veľas, 2019) and it is one of the elements of a smart economy. Based on this, the FDI, the number of international immigrants (units), the ratio of people registered as unemployed in the working-age population (%), and the number of IT companies (units) were selected as indicators covering the economic aspect.

According to Hajduk (2016), SC refers to those cities that have a developed infrastructure. In other words, smart are these cities today that employ new technologies in order to solve infrastructure problems (Berglund *et al.*, 2020), which is mainly the case in big cities due to the increasing number of residents. Infrastructure could be understood in both a traditional and comprehensive way. Traditionally, infrastructure could be defined as a set of buildings, roads and other facilities needed for supporting life in the city. Pollution measured via emission of pollutants and forest cover are representative of environmental issues. The number of universities are often mentione alongside public transport routes as indicators of infrastructure. On the other hand, the number of public transport routes directly affect the environmental situation due to the possibility to optimise the number of cars in the city, avoiding one or two passengers per personal vehicle. Taking into account the characteristics of the environmental aspect, the number of public transport routes (units), forest cover (%), and the emission of pollutant (tons) were selected as environmental indicators.

Scientists investigating the impact of infrastructure on the smartness of cities reveal that universities could be considered as a driver of smartness

(Grimaldi & Fernandez, 2017). Universities attract motivated young people who are capable of introducing new ideas, developing innovations, and this, in turn, makes a city smarter. Not only the number of universities itself but the number of graduates is essential for the development of national economies as they will be taxpayers and business owners (Zunda, Zeps & Strode, 2020). It is crucial on the micro-level as well, including the municipalities, i.e. cities, to become smart. The number of universities, as mentioned above, is treated as an infrastructure measure, but this indicator also influences the level of innovation in a particular city. However, merely the number of universities is probably not sufficient. Therefore, adding another indicator—university graduates—was considered. Innovation in our study is expressed by the number of IT companies in this digital, Industry 4.0 era. IT companies can help reduce traffic accidents by participating directly in the regulation of traffic flows. But most importantly, the number of road traffic accidents is related to the social aspect. In relation to these opinions, the number of university graduates (units), the number of universities (units), and the number of road traffic accidents (units) were selected as social indicators for the research.

Concerning the research problem, the indicators partly representing the entities of smart city and in line with the concept of sustainability were selected on the three basic areas of sustainability—environmental, social, and economic. In conclusion, it should be noted that despite various entities covering the indicators selected for the research, the main focus was to establish a proper proportion between sustainability and SC, as well as to combine commonly used indicators with several new ones.

3. Methodology

In order to identify the most important indicator that would make a city smart, the analytic hierarchy process (AHP) with a fuzzy approach was used. AHP is based on pairwise comparison, which is considered one of the most reliable methods of expert evaluation. The limitation of AHP is that experts' answers could be affected by uncertainty, and in an effort to avoid this, fuzzy logic was employed. The number of experts was chosen based on Libby and Blashfield (1978), who proved that if the number of experts equals six or higher, their assessment's reliability exceeds 80%. Moreover, Rudzkienė (2009) states that in order to receive the most reliable results, the number of experts should vary from five to nine. Hence, a total of seven experts were chosen for the research, three of whom were scholars working in the field of SC and four were architects working with and researching SC. The experts were provided with a questionnaire developed on the basis of a pairwise comparison procedure. The judges were asked to compare prominent factors using a 1–9 scale proposed by Saaty (1984). After the pairwise comparison matrices were completed, they were tested for consistency by calculating the consistency ratio (CR) (Saaty, 1993). The matrices were assumed to be consistent if CR < 0.2. Only the consistent ones were used for further research. Then the values of the individual pairwise comparison matrices were transformed to fuzzy triangular numbers using the information presented in Table 1.

Table 1. Fuzzy AHP scale

The intensity of importance of one criterion over another	1–9 scale number	Fuzzy number, $\tilde{m}_{ij}$	Triangular fuzzy numbers
Equal importance	1	$\tilde{1}$	(1, 1, 2)
Moderate importance	3	$\tilde{3}$	(2, 3, 4)
Strong importance	5	$\tilde{5}$	(4, 5, 6)
Very strong importance	7	$\tilde{7}$	(6, 7, 8)
Extreme importance	9	$\tilde{9}$	(8, 9, 9)
Intermediate values	2, 4, 6, 8	$\tilde{x}(x$=2,4,6,8)	(x–1,x,x+1)

Source: Cobo et al., 2014

Fuzzy numbers were chosen because they reduce the subjectivity of judgements and overcome this significant flow (Golabi & Radmanesh, 2020). The triangular fuzzy number could be defined in the following way: consider $m = (l,m,u)$ on R to be a triangular fuzzy number with membership function $\tilde{\mu}_A$(x): R→[0;1] is defined as follows (Tan *et al.*, 2017)

$$\mu_{\tilde{m}}(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u, \\ 0, & \text{otherwise} \end{cases} \quad \{1\}$$

where:

$\mu_{\tilde{m}}(x)$—triangle-shaped membership function, m—the best estimate, l—the lowest estimate, u—the highest estimate.

After the pairwise comparison matrices' values had been transformed into fuzzy numbers, the following matrices were developed for each expert:

$$\widetilde{M} = (\widetilde{m}_{ij})_{n\times n} = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (1,1,1) \end{bmatrix} \quad \{2\}$$

Then the aggregated matrix was computed using the geometric mean:

$$\widetilde{m}_{ij}^{A} = \sqrt[n]{\widetilde{m}_{i1} \otimes \widetilde{m}_{i2} \otimes \ldots \otimes \widetilde{m}_{in}}\,, \quad \{3\}$$

where:
$\widetilde{m}_{ij}^{A}$—assessment of aggregated element of i-th row and j-th column, n—number of pairwise comparison matrices.

After the aggregated matrix is composed, the weights of the factors were calculated (Ayhan, 2013):

$$\widetilde{w}_i = \widetilde{m}_{ij}^{A} \otimes \left(\widetilde{m}_{i1}^{A} \oplus \widetilde{m}_{i2}^{A} \oplus \ldots \oplus \widetilde{m}_{in}^{A}\right)^{-1}, \quad \{4\}$$

where:
$\widetilde{w}_i = (Lw_i, Mw_i, Uw_i)$——fuzzy weight of i-th alternative, Mw_i—the best fuzzy estimate, Lw_i—the lowest fuzzy estimate, Uw_i—the highest fuzzy estimate.

To conclude, the weighting procedure extent analysis method based on Chang (1996) was used for prioritising the factors. First, the fuzzy synthetic extent $\tilde{S}_i$ for the i-th object was defined:

$$\tilde{S}_i = \sum_{j=1}^{n} \widetilde{m}_{ij} \otimes \left[\sum_{k=1}^{n} \sum_{j=1}^{n} \tilde{a}_{kj}\right]^{-1}, \; i = 1, \ldots, n. \quad \{5\}$$

Second, the degree of possibility for $\tilde{S}_i \geq \tilde{S}_j$ was computed:

$$V(\tilde{S}_i \geq \tilde{S}_j) = \sup_{y \geq x} \left[\min\left(\tilde{S}_j(x), \tilde{S}_i(y)\right)\right]. \quad \{6\}$$

Third, the weight of alternative w_i was calculated:

$$w_i = \frac{V(\tilde{S}_i \geq \tilde{S}_j | j = 1, \ldots, n; j \neq i)}{\sum_{k=1}^{n} V(\tilde{S}_k \geq \tilde{S}_j | j = 1, \ldots, n; i+1 \neq k)}, i = 1, \ldots, n. \quad \{7\}$$

4. Results and discussion

The study analysed ten indicators of the smartness of cities. The following indicators were distinguished for the research:

- FDI (millions of euros) (C1)
- Number of international immigrants (units) (C2)
- Pollutant emission (tons) (C3)
- The ratio of people registered as unemployed among the working-age population (%) (C4)
- Number of university graduates (units) (C5)
- Number of universities (units) (C6)
- Number of IT companies (units) (C7)
- Number of public transport routes (units) (C8)
- Number of road traffic accidents (units) (C9)
- Forest cover (%) (C10)

The results of the research are presented in Table 2.

Table 2. Weights of indicators

Indicators	**Fuzzy weight, $\tilde{w}_i$**	**Normalised weight, w_i**	**Rank**
C1	(0.085; 0.135; 0.204)	0.1325	3
C2	(0.089; 0.132; 0.187)	0.1277	4
C3	(0.104; 0.161; 0.236)	0.1567	1
C4	(0.086; 0.138; 0.206)	0.1345	2
C5	(0.030; 0.053; 0.083)	0.0518	10
C6	(0.051; 0.077; 0.119)	0.0772	7
C7	(0.039; 0.059; 0.096)	0.0604	9
C8	(0.040; 0.060; 0.101)	0.0626	8
C9	(0.067; 0.099; 0.169)	0.1048	5
C10	(0.060; 0.087; 0.146)	0.0919	6

The research results revealed that the essential indicator characterising SC is pollutant emission (C3), and its weight is 0.1567. In fact, the results are not surprising, and once more prove that SC is a city with a friendly environment that is characterised by being pollution-free. Scientists agree that the concept of SC and pollution-free city go together. It justifies the fact that SC is usually identified as sustainable city, which, of course, makes sense, as one of the pillars of sustainability is the environmental aspect, which includes pollution criteria as well. Moreover, pollutant emission is a part of smart environment, which is one of the six elements of an SC. The second place is assigned to the percentage of people registered as unemployed among the working-age population (C4), and its weight reaches 0.1345. It is worth noting that the criteria assigned to the first two places are minimising, i.e. the lower the value, the higher is the level of smartness of a particular city. Foreign direct investment took third place in the ranking, and the weight of that criterion equals 0.1325. In fact, FDI speeds up economic growth, which in turn is a part of smart economy which is one of the six indicators of an SC. The fourth place is assigned to a number of international immigrants (C2). In fact, the number of immigrants could refer to the openness of the city, which is assumed as one of the most significant factors of SC, but is hardly measured; hence, the number of immigrants could be considered as an indicator of openness' and this indicator's weight is 0.1277. Moreover, the number of immigrants could be an element of the concept of smart people, which, in turn, is an element of an SC. The fifth place is assigned to the number of road traffic accidents (C9), which is a minimising criterion. Minimisation of road accidents could be considered something that contributes to smart mobility, as it can make the traffic more efficient and safer.

To sum up, the mentioned criteria are those that, according to the experts, are the most important for city smartness as their weights are more than 0.1. However, this does not make other criteria insufficient.

In terms of the lowest five criteria, it is worth mentioning that the weight of forest cover (C10) is almost 0.1 (more precisely, 0.919), which contributes to the smart environment and shows that ecological issues are vital for making a city the most comfortable for living. The criterion that was assigned to the seventh position is the number of universities (C6) in the city. It is evident that the higher the number of universities in the city, the greater is the number of incoming students (educational immigrants), which makes the city more open and, hence, its residents more broadminded, which in turn, is one of the essential elements of the smart people concept. The number of public transport routes is in the eighth place according to the ranking results and its weight is 0.0626. Actually, the weight is not low, which shows the significance of that criterion which contributes to smart mobility as the C9 criterion. Unlike the number of road accidents, the current criterion is maximising. The number of IT companies seemed one of the less significant criteria of an SC. Still, the weight is 0.0604, which shows that the criterion is necessary for a city to be smart, and it contributes to the concept of smart people. The least significant criteria were the concept of smart people and the number of university graduates (C5) with the weight of 0.0518.

The indicators could be expanded in future research, including not only FDI but also domestic investments. However, FDI is one of the most important economic indicators and usually follows not only with the additional financial flow but moreover brings new ideas and business culture to the country (a city, in this case).

One might question why two at first glance similar indicators—the number of university graduates (units) and the number of universities (units)—were selected in this study. It is evident that the existence of a university in a city represents the attractiveness for the young population who will enter the labour market in the future. The existence of a university pushes the development of innovations in various areas of life and is an integral part of city smartness. On the other hand, it is essential to increase the number of university graduates as these citizens are the first who can create and develop new technologies in a city.

Probably the most surprising result of the research is that IT companies are almost the least important for a SC. It is obvious that the majority of services (including traffic regulation) more or less relate to IT, which means that it is not the number of such companies that is essential, but the use/implementation of services created by IT companies.

To sum up, the indicators selected for this research represent yet another possible approach that could be considered assessing the smartness of a city as they cover economic, social and environmental issues. All of them are equally important for citizens in the globalised world.

5. Conclusions

The researchers were able to identify many entities as compulsory for an SC. Still, they should pay the most attention to find the right proportion between aspects of sustainability and SC, keeping in mind the decisive role of ICT. Whereas the article aimed to discuss a different approach, which combines commonly used indicators with several new ones, ten indicators, including the concept of sustainable and smart city, were chosen. More indicators were selected representing economic aspects for the research but still keeping in line with all three essential sustainability areas.

The expert evaluation method with a fuzzy approach was used to rank the indicators to reduce the subjectivity of assessments. Ranking of indicators attests to that SC cannot ignore the aspect of sustainability, and that pollutant emission (C3) is crucial. The second place goes to the share of people registered as unemployed in the working-age population (C4). This indicator covers both economic and social aspects and represents a smarter city and less sustainable concept. The same results are represented by the third and the fourth places—the FDI (C1) and the number of international immigrants (C2), supporting the SC concept. However, the last two positions are ranked for indicators that are strongly representative of the SC concept—the number of IT companies (C7) and the number of university graduates (units) (C5). This result shows the need to expand further research, including more indicators for every three essential sustainability areas, and highlights more SC concept indicators.

The presented approach differs from other analysed SC indicators. FDI, the number of international immigrants, the share of people registered as unemployed in the working-age population, and the number of IT companies are typical for SC characteristics. However, the rest of the presented indicators are relatively new approaches. Nevertheless, the authors believe that in assessing the cities' smartness it is necessary to include the number of universities and the number of university graduates as they define the ability of a city to attract young and intelligent people. The number of public transport routes and the number of road traffic accidents is essential for citizens to ensure both the convenience and safety of living in the city. And finally, pollutant emissions and the forest cover of the city represent the environmental issues. While the pollutant emission has been sometimes discussed in the studies, the cities' forest cover is a new approach for SC indicators and will be hopefully included in future research by other authors. Despite the new ideas presented above, the article does not cover the wide range of usually investigated SC indicators, which could be seen as a limitation.

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