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Towards Urban Sustainability: Composite Index of Smart City Performance

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Abstract

The rapid urbanization of recent decades has intensified the need for sustainable and adaptive city models that balance economic growth, environmental protection, and social well-being. This study addresses the challenge of assessing the performance of European smart cities by proposing a composite index of urban sustainability based on citizens' perceptions. Using data from the Quality of Life in European Cities Survey (2023), the research applies a multi-criteria analytical framework grounded in the Benefit-of-the-Doubt (Data Envelopment Analysis) approach, which allows each city to determine optimal indicator weights and eliminates pre-assigned biases. The analysis integrates six dimensions of smart city performance—mobility, living, environment, economy, governance, and people—to evaluate cities' adaptability to the needs of their residents. Results reveal that cities such as Aalborg (Denmark), Luxembourg (Luxembourg), Cluj-Napoca (Romania), and Zurich (Switzerland) exhibit the highest performance, demonstrating balanced progress across sustainability-oriented domains. The findings suggest that integrating citizens' evaluations with data-driven weighting provides a more comprehensive and context-sensitive understanding of urban sustainability. The study concludes that the proposed composite index provides a robust methodological framework for benchmarking European smart cities, supporting policymakers in designing targeted strategies for enhancing livability, inclusiveness, and sustainable urban growth.

Keywords: smart city; urban sustainability; composite index; Data Envelopment Analysis (DEA); citizen perception

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1. Introduction

Urban population growth implies an increase in the capacity to meet growing needs, which has caused numerous problems related to the economic, social, and environmental spheres of sustainable urban development [1]. Intensive urbanization, reinforced by the consequences of certain citizen activities, has directed the interest of scientists and practitioners in sustainable urban development [2,3]. According to the United Nations data, the percentage of the population in urban areas exceeded the percentage of the population in rural areas. Specifically, in 2018, 55% of the total population lived in urban areas, and this percentage is expected to increase to 68% by 2050 [4]. In terms of the EU, now 75% of inhabitants live in cities and urban areas, but by 2050, that percentage will increase to 78% [5]. On the other hand, metropolitan areas represent a generator of economic growth. Metropolitan areas in OECD countries generate about 60% of total GDP [6], while the size

of a metropolitan area positively influences its GDP per capita [7]. According to the Urban Europe publication [8], significant disparities in the territorial distribution of populations across EU Member States strongly influence various economic indicators. In 2012/13, nine EU Member States recorded more than half of their GDP in predominantly urban regions; in countries such as Bulgaria, Denmark, and Sweden, these regions covered up to 1.5% of the land area yet generated around twenty times their land share in national GDP. By contrast, in densely populated states like the Netherlands, Belgium, and the United Kingdom, predominantly urban regions contributed only 1.7 to 2.8 times their share of the total area to national GDP. Alternatively, in 2022, rural areas have consistently contributed a relatively small and stable portion of the EU's GDP, typically falling behind national averages in economic growth. Predominantly urban regions produce about half of the EU's GDP, while intermediate areas account for 33.7% and rural regions just 16.3% [9]. Urban growth emphasizes the issue of the availability of resources to meet the growing needs of the population. In addition, rapid urbanization can reduce urban resilience and the quality of life of citizens, mostly due to environmental pollution and inadequate urban infrastructure [10]. In cities across the EU, the most pressing concern for residents is the lack of affordable housing (51%), followed by unemployment or limited job opportunities (33%), insufficient quality public services (32%), and poverty or homelessness (32%) [5]. Previous problems have led to a significant deterioration in living conditions (livability) in cities [11]. Most of today's cities represent a developed, densely populated urban area focused on the realization of socio-economic benefits while ignoring the environmental consequences [12]. However, the negative effect on the environment is manifested not only in cities but also outside urban areas, since cities are not self-sufficient and must acquire resources from their surroundings. Consequently, urban areas represent both the causes of numerous environmental problems and the centers of economic and social development. Considering the above, it can be pointed out that urban sustainability is an important link in achieving overall sustainability [13]. Contemporary development concepts increasingly present cities as drivers of sustainable development, not as generators of problems [14]. Verma and Raghubanshi [13] summarize sustainable urban development as a process that includes improving the quality of life, equality, minimizing energy consumption, sustainable transport, environmental protection, waste management, preservation of public space, cultural and natural heritage, and water resources. Cities play a key role in ensuring the well-being of their inhabitants in terms of employment opportunities and access to education [15]. They strive to attract a qualified and educated workforce and strive to become competitive in terms of the quality of life they offer to their citizens. In order to increase their urban magnetism, cities undertake comprehensive strategic changes aimed at modernizing urban infrastructure and improving accessibility and mobility, as well as applying modern technologies to redesign city services [16]. Application of modern, green technologies focused on adequate waste management, as well as smart use of urban infrastructure, can enable cities to become greener and leaner [1]. The issue of smart and sustainable growth of cities becomes particularly important. Faced with technological changes, environmental challenges, and the growing needs of citizens, cities around the world strive to find sustainable and reliable development solutions [16]. In particular, it is necessary to create solutions that enable adaptation of the city to the current, as well as future, needs of the urban population [17]. Kim [18] identifies several solutions to the problem of rapid urbanization: (i) building new cities; (ii) construction of new and improvement of existing infrastructure; and (iii) application of smart city technology. He further states that the application of smart city technology represents the most attractive solution since information and communication technologies (ICTs) use the existing hard infrastructure, and such a solution is faster and cheaper than the other two.

Recognizing the need to change conventional urban development has resulted in numerous initiatives aimed at creating smart cities. The concept of smart cities has experienced great popularity in recent years, with the idea of applying ICTs in order to improve the functioning of cities [19]. Furthermore, the principal purpose of creating smart cities is to improve urban sustainability with the help of ICTs [20]. The concept of smart cities supports environmental sustainability by focusing on the reduction of harmful gas emissions in urban areas using innovative technologies [21], contributes to economic sustainability by creating new business models, and enhances social sustainability by striving to increase the quality of life of residents. The main challenges faced by the smart city are the provision of adequate employment and education opportunities, well-developed traffic infrastructure, social inclusion, and affordable housing [22]. Considering that the development of sustainable smart cities focuses on meeting the needs of residents, citizens' perceptions of city services become of great importance. Nevertheless, in practice, it happens that the creators of urban policies and urban development strategies sometimes do not adopt the opinions of citizens. Furthermore, existing perception-based studies mostly rely on subjective weighting or simple averaging, lacking an endogenous weighting mechanism. To increase the competitiveness, attractiveness, and sustainability of cities, it is essential to monitor citizens' perceptions of various aspects of the city. Therefore, this study is motivated by the growing need to complement technology- and infrastructure-oriented smart city indices with people-centered assessments based on residents' perceptions. While several indices evaluate urban sustainability and quality of life, perception-based approaches rarely employ endogenous weighting mechanisms that reflect the multidimensional nature of urban performance. This paper contributes to the literature in three ways. First, it develops a composite perceived smart city sustainability index for European cities using indicators from the Quality of Life in European Cities survey. Second, it applies a Benefit-of-the-Doubt (BoD) DEA approach to derive endogenous, data-driven weights for perception-based dimensions, thereby avoiding arbitrary weighting schemes. Third, it provides comparative insights across European regions, highlighting patterns and disparities in residents' evaluations of smart and sustainable urban development. The paper aims to construct a European smart city sustainability performance index based on residents' perceptions and an endogenous weighting mechanism, thereby enabling unbiased cross-city comparisons. The scientific contribution of the paper lies in proposing a comprehensive index that would be used in assessing the urban performance of cities.

The rest of the paper is structured as follows. The following sections offer insights into the theoretical framework of smart cities and the methodological framework for creating composite indices of smart cities' performance, as well as research results and discussion. Final remarks will be given in the conclusion.

2. Smart Cities: Theoretical Framework

Conceptually defining smart cities is not a simple task since there is a plethora of definitions offered by different authors [23]. The development of information and communication technologies (ICTs) in the last decade of the last century paved the way for the development of the smart cities concept [24], while the concept of sustainable cities appeared in the literature in the middle of the last century [25]. Initially, practitioners and researchers considered technology as a key factor in shaping smart cities, so terms such as digital city or intelligent city can be found in the literature [26–28]. Over time, other aspects were taken into account, and a holistic view of the concept of smart cities was created [16].

What most definitions have in common is that a city is smart when it integrates ICTs and human capital to improve the quality of life of inhabitants and foster economic growth [22]. More and more authors advocate the view that urban performance depends

on both hard infrastructure and social infrastructure (which includes human and social capital) [29]. In order to solve numerous urban challenges, such as environmental protection, waste management, and traffic congestion, urban strategies focus on the implementation of smart city technology [30], which further amplifies the topicality of the concept of smart cities. Creating smart cities implies undertaking strategic efforts focused on ensuring the competitiveness and efficiency of cities in areas related to health care, quality of life and safety of residents, and quality of administration, services, and economy [31]. The process of transforming cities into smart cities implies the application of technological progress in order to alleviate or solve urban problems and provide sustainable solutions [32]. Some authors believe that the quality of life and the well-being of the inhabitants represent the fundamental goals of the development of smart cities [33], whereby the process of transformation of cities is seen as an ongoing process of reshaping social norms, cultural context, and institutions of cities [22]. Transformation is a continuous and dynamic process based on ICTs aimed at solving urban challenges and creating better conditions for living and working in the city [34]. It can be concluded that continual improvement is the main feature of smart cities [16]. Nevertheless, a comprehensive approach that includes citizens is necessary when creating a sustainable and smart living environment aimed at providing adequate living conditions with initiatives that should result in better employment opportunities, reduction in traffic congestion, reduction in commuting time, provision of accessible social services, mitigation and avoidance of environmental pollution, and more leisure for citizens [15]. Smart cities strive to empower local communities by increasing their competitiveness through innovation, while simultaneously increasing the quality of life of citizens and preserving the environment [35]. Caragliu et al. [29] define a smart city as a place where simultaneous investments in both human and social capital, as well as in traditional and modern infrastructure, encourage the realization of economic progress and improvement of the quality of life, taking into account the management of natural resources, through participatory governance. In the process of transformation of cities, city authorities have a significant role, which must have the capacity to launch initiatives related to solving environmental problems, providing better educational opportunities to citizens to increase their knowledge, encouraging entrepreneurial culture, and promoting the application of ICT solutions for solving urban problems [36]. Komninos [27] (p. 1) defines smart cities as "territories with high capacity for learning and innovation, which is built into the creativity of their population, their institutions of knowledge creation, and their digital infrastructure for communication and knowledge management". Marsal-Llacuna et al. [37] state that initiatives aimed at creating smart cities tend to enhance urban performance by using ICTs with the aim of providing more efficient services to citizens, improving existing infrastructure, increasing cooperation between various economic actors, and encouraging innovative business models in all sectors. Harrison et al. [38] advocate the position that smart cities use operational data related to the daily functioning of the city in order to optimize the performance of city services. Zubizarreta et al. [39] (p. 04015005–7) consider smart cities to be "not only an aggregation or a merger of some applications, they represent a new cultural idea of cities. Technology is a driver, a facilitator for the city development, but if there is no strategy and a purpose that technology must follow, the risk is disorder." According to Neirotti et al. [40], the concept of a smart city goes beyond the application of digital technologies but takes into account some aspects related to the soft components necessary for the realization of the socio-economic development of the city, such as human capital. Therefore, the concept of a smart city does not only include the application of ICTs but also addresses the needs of people and communities [41]. Smart city initiatives imply the implementation of successful projects aimed at improving the quality of life of citizens, economic prosperity, and sustainable development [42].

Since numerous definitions of smart city highlight the importance of city's sustainability and inhabitants' quality of life in that city in order to be perceived as smart, these concepts are further explained in Table 1.

Table 1. Related research on urban sustainability, smart city and quality-of-life concepts.

Urban Sustainability
"Urban sustainability refers to building and maintaining cities that can continue to function without running out of resources." [43]
"Urban sustainability focuses on the persistence of a desirable outcome of urban environments over time; it is frequently defined by aspects like intergenerational justice, intragenerational equity, natural resource protection, economic viability and diversity, societal self-sufficiency, social well-being, and fulfillment of fundamental human needs." [44]
"Urban sustainability refers to creating and managing cities and urban spaces in a way that considers their social, economic, and environmental impacts; the goal is to create resilient environments that sustain the well-being of current populations while safeguarding the capacity of future generations to achieve an equivalent or enhanced quality of life." [45]
Smart city
"A smart city is defined as a city that monitors and integrates critical infrastructure and services through sensor and IoT devices." [46]
"A smart city is defined as an urban environment that uses technology to increase the benefits and reduce the disadvantages of urbanization for residents." [47]
"Smart cities are cities where ICTs are widely used in vital infrastructure and services, so 'technology' is a key tool used to carry out smart city projects and, in addition, great importance is attached to improving the quality of life of residents." [48]
Quality of life
"Quality of life is based on one's perception of one's position in life with respect to one's goals, expectations, standards, and concerns; it is also influenced by one's culture and value system." [49]
"Quality of life is generally intended as the satisfaction of people with their lives for their personal well-being." [50]
"Quality of life is a multidimensional concept including psychological, economic, social, and physical well-being." [51]

Source: Authors' presentation.

Therefore, the reviewed definitions in Table 1 show that urban sustainability, smart city, and quality of life represent interconnected yet conceptually distinct domains. In essence, urban sustainability is typically understood as the capacity of cities to balance economic development, social inclusion and environmental protection over the long term, often framed through the 'triple bottom line' or similar multidimensional approaches. Smart cities, in contrast, emphasize the use of digital technologies, data and innovative governance arrangements to improve the efficiency, resilience and inclusiveness of urban systems. While smart city initiatives are frequently motivated by sustainability objectives, the two concepts are not synonymous: smart solutions can support, but do not automatically guarantee, sustainable outcomes. Quality of life represents yet another outcome-oriented concept, focusing on individuals' and households' perceived well-being and satisfaction with different aspects of urban life, such as housing, mobility, environment, public services and social relations. In this paper, we treat quality-of-life indicators as residents' subjective evaluations of how urban sustainability and smart city policies are experienced on the ground. Our composite index therefore captures perceived smart-city sustainability performance, rather than an objective measure of smartness or sustainability alone.

Further exploring the concept of smart cities requires an understanding of the multidimensionality inherent in them [52]. Considering the complex nature of smart cities,

it is necessary to create a multidimensional framework that includes environmental sustainability, social inclusion, and inclusive economic growth [53]. The literature mainly identifies six basic dimensions of smart cities [54]: smart economy, smart environment, smart governance, smart living, smart mobility, and smart people. In this study, we adopt this six-dimensional smart city framework as it offers a balanced representation of both hard and soft components of urban development, integrating infrastructure and technology with human and social capital. This classification has been widely used in European smart city benchmarking initiatives and academic studies, which facilitates comparability with existing empirical work and ensures conceptual continuity in the European context. Furthermore, the six dimensions closely mirror the structure of the Quality of Life in European Cities (Urban Audit Perception) Survey, whose modules cover economy and employment, mobility, environment, governance and public services, housing and livability, and subjective well-being. This alignment enables a coherent aggregation of perception-based indicators into conceptually consistent domains. Furthermore, the selected framework resonates with the priority areas of the Urban Agenda for the EU, such as sustainable urban mobility, energy and climate transition, social inclusion, and affordable housing, reinforcing the policy relevance of the proposed smart city sustainability index for European cities. The smart economy refers to the application of ICTs during the production process or service provision process, including the creation of new business models. The abundance of resources available to smart cities, reflected in infrastructure and human capital, enables the development of a more competitive business environment [35]. The smart environment encompasses the application of ICTs to create innovative solutions and/or improve processes related to energy consumption, pollution control, waste disposal, and similar urban services to improve environmental conditions [17]. The smart governance dimension is aimed at improving public services by applying modern technological solutions and facilitating decision-making and planning at all levels. The smart living dimension refers to improving the livability conditions through processes aimed at improving the overall well-being of the residents, with the aim of increasing the attractiveness of the city. These processes include initiatives aimed at improving the material conditions of residents, as well as ensuring adequate quality of health and educational services. Smart mobility includes initiatives related to improving transportation in the city and reducing traffic congestion and commuting time, as well as ensuring good connectivity between different parts of the city and adequate accessibility to all parts of the city through the application of technology. The smart people dimension includes the development and improvement of human and social capital of the city through the provision of adequate educational opportunities based on ICTs [17]. However, in addition to the development of human and social capital, this dimension includes initiatives aimed at increasing the city's attractiveness for talented and creative individuals, which will further increase the city's human and social capital [35]. It is precisely this multidimensional nature of smart cities that makes it difficult to evaluate the urban performance of cities, since it is not enough to monitor only one indicator, but it is necessary to monitor indicators of several dimensions. Composite indices appear as a suitable tool for evaluating multidimensional phenomena, since they can simplify complex phenomena and present them with a single, easy-to-understand index that will include all evaluated dimensions. The creation of composite indices by applying the methods of multi-criteria analysis allows obtaining objective evaluations and enables the comparison of units, both spatially and over time. Therefore, the goal of this work is to develop a methodological framework for creating composite indexes of urban performance of smart cities based on multi-criteria analysis.

3. Smart Cities: Methodological Framework

3.1. Approaches for Measuring Urban Performance

Assessment of the achieved level of urban sustainability must be an integral part of the development of smart cities, and when evaluating urban performance, it is necessary to integrate sustainability and the framework of smart cities [20]. Traditional approaches to the evaluation of urban performance have mostly focused on the economic aspects of performance, neglecting the social dimension. Also, many earlier studies of sustainable development were mainly limited to searching for a balance between the economic and ecological dimensions, which unjustifiably marginalized the social sphere of sustainability [55]. However, when it comes to smart cities, the evaluation of urban performance represents more than the evaluation of economic performance and requires analyzing the satisfaction of citizens with solutions in smart cities, that is, whether the transformation of the city into a smart city has benefited the direct users of city services [30]. The development of smart cities should be people-focused, serving the needs of local citizens with the broader goal of meeting their needs and preferences to improve their well-being and quality of life [56]. Nevertheless, although citizens represent the most important actors in every phase of the development of smart cities, very often their actual needs are not adequately taken into account during the implementation of city development projects [57]. When creating smart cities, city authorities have a limited budget at their disposal; therefore, it is necessary to select priority services from a wide range of smart city services to ensure optimal allocation of resources, while the selection of priority areas should be made in accordance with the needs and preferences of citizens [58]. The participation of citizens and respect for the opinions and views of citizens enable better service provision and a sustainable future for cities [59]. Hollands [60] (p. 316) states that "a smart progressive city needs and requires the input and contribution of these various groups of people and cannot simply be labeled as smart by adopting a sophisticated information technology infrastructure or through creating self-promotional websites". Several empirical studies take into account citizens' perspectives, since citizens are the ones who should benefit from smart city services [56]. Macke et al. [22] evaluate the perception of quality of life in a smart city and analyze the main elements of citizens' satisfaction on the example of the city of Curitiba, in Southern Brazil. Stanković et al. [61] performed a ranking of the European cities according to their smart and urban development indicators based on the data collected through four cycles of the Eurostat's Urban Audit Perception Survey. Vidiasova and Cronemberger [62] examined the differences between perceptions of authorities and citizens in local government initiatives towards smart city development in Saint Petersburg and revealed that there is a gap in the way the two groups understand smart city endeavors. Georgiadis et al. [63] examined the citizens' perception of the smart city concept among the Greek and Cypriot citizens. Smart cities in the study of Saeed et al. [64] were evaluated across eight major urban centers of Punjab (Lahore, Rawalpindi, Faisalabad, Multan, Sialkot, Gujranwala, Sargodha, and Bahawalpur) using a multidimensional composite index that integrated 44 spatial, economic, environmental, infrastructural, and social indicators derived from remote sensing (e.g., Landsat, Sentinel, MODIS), GIS analyses, official statistics, and expert surveys weighted through the Analytical Hierarchical Process (AHP) to capture each city's overall livability and sustainability performance. A summary of the mentioned studies is presented in the following table (Table 2).

Table 2. Overview of Smart City Evaluation Studies.

Reference	Method Used	Sample	Contribution
[22]	Evaluation of perceptions of quality of life (QoL) in a smart city; analysis of key elements of citizen satisfaction.	Citizens of Curitiba, Southern Brazil.	Demonstrates how QoL perceptions can reveal factors shaping citizen satisfaction in a smart-city context.
[61]	Ranking of European cities based on smart and urban development indicators using data from four cycles of Eurostat's Urban Audit Perception Survey.	European cities included in the Urban Audit Perception Survey.	Provides a comparative ranking of urban and smart-development performance across Europe using standardized perception-based indicators.
[62]	Comparative analysis of authorities' vs. citizens' perceptions of smart city initiatives.	Authorities and citizens in Saint Petersburg.	Identifies a perception gap between local government and citizens regarding smart-city initiatives, highlighting governance and communication challenges.
[63]	Survey-based assessment of citizens' understanding and perception of the smart city concept.	Citizens in Greece and Cyprus.	Reveals how residents conceptualize smart cities, contributing to knowledge on public awareness and adoption of smart-city ideas.
[64]	Multidimensional composite index integrating 44 spatial, economic, environmental, infrastructural, and social indicators; based on remote sensing (Landsat, Sentinel, MODIS), GIS analyses, official statistics, expert surveys, and AHP weighting.	Eight major urban centers in Punjab: Lahore, Rawalpindi, Faisalabad, Multan, Sialkot, Gujranwala, Sargodha, Bahawalpur.	Provides a holistic, data-rich evaluation of smart-city livability and sustainability using advanced spatial, statistical, and expert-based methods.

Source: Authors' presentation.

It can be concluded that the evaluation of the urban performance of smart cities based on the perception of citizens is an area that is not yet sufficiently developed and exploited. However, in 2016, during the United Nations Conference, heads of state, government leaders, ministers, and high-level representatives committed to the New Urban Agenda—an initiative that is, among others, grounded in a smart-city framework that leveraged digitalization, clean energy, and advanced transport technologies to promote environmentally sustainable choices, enhance public service delivery, and support long-term economic growth [65] (p. 19). Similarly, the Urban Agenda for the EU represents a strategic effort to harness the potential of urban areas in achieving better regulation, funding, and knowledge, thus supporting the EU goals and priorities, such as the European Innovation Partnership 'Smart Cities and Communities' [66,67]. Moreover, the EU Missions framework focuses on smart cities by integrating innovative, digital, and sustainable solutions to achieve climate neutrality by 2030. The aim is to make cities more sustainable, livable, and resilient, setting examples for all European cities to follow in achieving climate goals and advancing the digital transition [68]. Therefore, initiatives aimed at the development of smart cities must

be evaluated in order to assess the level of urban performance of smart cities and to provide information on how well the needs of citizens are met.

In order to measure the urban performance of smart cities, it is necessary to develop an index that enables the evaluation of the success of urban development policies. When creating an index of the urban performance of smart cities, Petrova-Antonova and Ilieva list several criteria to consider [15]: (i) measurability—the indicator must be measurable, preferably objectively; (ii) reliability—the indicator must be defined clearly and unambiguously; (iii) relevance—the indicator must correspond to the specific dimension of smart cities being measured; (iv) intuitiveness—the resulting index must be comprehensible to end users; (v) exclusiveness—an indicator must measure only the dimension for which it is defined. However, when creating an index, knowing the characteristics of the index is not enough; it is necessary to apply an adequate methodology for ranking the urban performance of smart cities [69]. When creating composite indices, the key issues are related to the problem of weighting and aggregation. There are several approaches to deriving indicator weights, generally categorized as subjective or objective. Given the shortcomings of each of these approaches, the authors opted to construct a composite index using the Benefit-of-the-Doubt (BoD) approach, a variant of Data Envelopment Analysis (DEA). DEA addresses the weighting issue by allowing each decision-making unit (DMU) the freedom to select the most favorable weights, thereby ensuring the absence of a priori bias.

3.2. Data Preparation

The analysis in this study relies on the 2023 edition of the Quality of Life in European Cities Survey, also known as the Urban Audit Perception Survey, conducted on behalf of the European Commission's Directorate-General for Regional and Urban Policy [70]. This survey represents the sixth round of the triennial perception survey series that has been carried out since 2007, providing comparable information on how citizens evaluate various aspects of urban life across European cities [71]. According to the evaluation report, the 2023 survey was conducted between January and April 2023 in 83 cities from EU Member States as well as candidate and associated countries, including EFTA states, the Western Balkans, Türkiye, and the United Kingdom. The survey sample in each city is designed to be representative of the adult resident population. The questionnaire covered multiple domains of urban life, including [71]: overall satisfaction with living in the city, housing and affordability, employment opportunities, urban environment, green areas, air quality, transport and mobility, cultural and recreational facilities, safety and security, governance, trust in local authorities, participation in decision-making, and perceptions of discrimination, inclusiveness, and social cohesion. Respondents evaluated their satisfaction using a four-point scale with the following categories: very satisfied, rather satisfied, rather unsatisfied, and not at all satisfied; the option do not know/no answer was also available. For analytical purposes, responses were quantified on a Likert-type scale, assigning a value of 1 to not at all satisfied and 4 to very satisfied. The category does not know/no answer was excluded from the analysis. The indicators examined in this study were subsequently derived as the weighted arithmetic mean of individual responses for each item [61]. Specifically, for each survey item and each city, the indicator value was derived from the distribution of responses across the four-point Likert scale. Let v_s denote the numerical score associated with response category s $(s = 1, 2, 3, 4)$, and let p_{ijs} denote the percentage of respondents in city i who selected category s for indicator j. The city-level value of indicator j for city i was then computed as a weighted average:

$$y_{ij} = \frac{\sum_{i=1}^{4} v_s p_{ijs}}{\sum_{i=1}^{4} p_{ijs}}$$

The denominator corresponds to the total share of valid responses (excluding "don't know" and item non-response), so that y_{ij} represents the average satisfaction score for indicator j in city i on the original 1–4 scale.

Indicator selection followed a two-step procedure. First, we identified survey items that conceptually match the six dimensions of the smart city framework (smart mobility, smart living, smart environment, smart economy, smart governance and smart people), focusing on satisfaction with public transport, public spaces and facilities, environmental quality, job opportunities and housing, local public administration, neighborhood quality and overall life satisfaction. Second, we retained only those items that are available for all cities in the sample and are measured on a consistent four-point Likert scale. The final set of indicators and their allocation to the six dimensions are summarized in Table 3. In order to prepare data for the application of the BoD approach, individual survey indicators were grouped into six dimensions reflecting the widely acknowledged smart city framework: people, government, economy, mobility, environment, and living [72]. The individual indicators were aggregated using the Simple Additive Weighting (SAW) method. Within each dimension, all indicators were assumed to have equal importance and were therefore assigned identical weights. The SAW method is widely applied in multi-criteria analysis, as it provides a transparent and intuitive procedure for combining multiple indicators into a single measure [73]. In this approach, the values of individual indicators are first normalized to ensure comparability. In line with standard implementations of the SAW method, all indicators were normalized using max normalization. The normalized scores are then multiplied by the assigned weights and finally summed to obtain the composite value for the dimension. Since equal weighting was applied, each indicator contributed proportionally and uniformly to the final dimension score, thus avoiding subjective prioritization.

Table 3. Perception-based indicators of smart city performance and their allocation to the six dimensions.

Dimension	Indicator	Description
Mobility	I11 Public transport in the city, for example, bus, tram or metro	Overall satisfaction with public transport in the city (bus, tram, metro)
	I12 Public transport: Affordable	Satisfaction with the affordability of public transport
	I13 Public transport: Safe	Perceived safety when using public transport
	I14 Public transport: Easy to get	Perceived ease of accessing public transport
	I15 Public transport: Frequent (comes often)	Satisfaction with how often public transport comes
	I16 Public transport: Reliable (comes when it says it will)	Satisfaction with the reliability/punctuality of public transport
Living	I21 Schools and other educational facilities	Satisfaction with schools and other educational facilities in the city
	I22 Health care services, doctors and hospitals	Satisfaction with health care services, including doctors and hospitals, in the city
	I23 Green spaces such as public parks or gardens	Satisfaction with green spaces in the city, such as public parks or gardens
	I24 Sports facilities such as sport fields and indoor sport halls in the city	Satisfaction with sports facilities (sports fields and indoor sport halls) in the city
	I25 Public spaces in this city such as markets, squares, pedestrian areas	Satisfaction with public spaces such as markets, squares and pedestrian areas
	I26 Cultural facilities such as concert halls, theaters, museums and libraries in the city	Satisfaction with cultural facilities (concert halls, theaters, museums, libraries)
	I27 Generally speaking, most people in this city can be trusted	Perception that most people in the city can be trusted
	I28 I feel safe walking alone at night in my city	Perception of safety when walking alone at night in the city

Table 3. *Cont.*

Dimension	Indicator	Description
Economy	I31 In this city it is easy to find a good job	Perception on whether it is easy to find a good job in the city
	I32 The financial situation of your household	Satisfaction with the household's financial situation
	I33 Your personal job situation	Satisfaction with one's personal job situation
	I34 In this city, it is easy to find good housing at a reasonable price	Perception that it is easy to find good housing at a reasonable price
Environment	I41 The quality of the air in the city	Satisfaction with air quality in the city
	I42 The noise level in the city	Satisfaction with the noise level in the city
	I43 The cleanliness in the city	Satisfaction with cleanliness in the city
People	I51 The neighborhood where you live	Satisfaction with the neighborhood where the respondent lives
	I52 The life you lead	Satisfaction with the life the respondent leads
	I53 I'm satisfied to live in this city	Overall satisfaction with living in the city
Governance	I61 I am satisfied with the amount of time it takes to get a request solved by my local public administration	Satisfaction with the time needed for local public administration to resolve requests
	I62 The procedures used by my local public administration are straightforward and easy to understand	Perception that local public administration procedures are straightforward and easy to understand
	I63 The fees charged by my local public administration are reasonable	Perception that fees charged by the local public administration are reasonable
	I64 Information and services of my local public administration can be easily accessed online	Perception that information and services of local public administration are easily accessible online
	I65 There is corruption in my local public administration	Perception of corruption in the local public administration (to be reverse-coded so higher values indicate less perceived corruption)

Source: Authors' presentation.

Accordingly, the 29 perception-based indicators were synthesized into the following categories:

- Mobility—representing smart mobility, this dimension captures perceptions of public transport in terms of affordability, safety, accessibility, frequency, and reliability.
- Living—a proxy for urban livability and housing conditions, this dimension includes satisfaction with schools and educational facilities, health care, green spaces, sports facilities, public spaces, and cultural amenities, as well as indicators of trust and perceived safety in the city.
- Environment—reflecting the smart environment, this dimension incorporates perceptions of air quality, noise levels, and cleanliness.
- Economy—representing a smart economy, this dimension covers perceptions of job opportunities, household financial situation, personal employment status, and the affordability of housing.
- Governance—linked to smart government, this dimension captures satisfaction with local public administration procedures, efficiency, online accessibility of services, reasonableness of fees, and perceptions of corruption.
- People—a proxy for smart people, this dimension includes indicators of subjective well-being and social cohesion, measured through satisfaction with the neighborhood, quality of life, and living in the city overall.

Each indicator is assigned to a single dimension according to its primary conceptual focus (e.g., satisfaction with public transport is classified under smart mobility, satisfaction with health and education services under smart living, and satisfaction with air quality and noise under smart environment). The resulting set of indicators forms the building blocks

for the six composite dimension scores that serve as outputs in the BoD model. Table 3 provides an overview of all indicators used in the analysis.

To provide an overview of the data used in the analysis, Table 4 reports descriptive statistics (mean, standard deviation, minimum and maximum) for the variables included in the six smart city dimensions.

Table 4. Descriptive statistics of perception-based indicators by smart city dimension.

Dimension			**Mobility**					**Living**						
Indicator	I11	I12	I13	I14	I15	I16	I21	I22	I23	I24	I25	I26	I27	I28
Mean	2.94	2.90	3.22	3.22	3.01	2.98	2.97	2.85	3.03	2.90	2.94	3.13	2.70	2.85
Std.dev.	0.33	0.26	0.25	0.25	0.32	0.33	0.24	0.36	0.32	0.24	0.23	0.26	0.27	0.30
Min	1.87	2.35	2.30	2.35	1.82	1.77	2.42	2.12	2.04	2.11	2.11	2.36	1.90	2.15
Max	3.71	3.63	3.62	3.60	3.56	3.62	3.53	3.58	3.49	3.33	3.28	3.63	3.22	3.37
Dimension		Economy			Environment			People			Governance				
Indicator	I31	I32	I33	I34	I41	I42	I43	I51	I52	I53	I61	I62	I63	I64	I65
Mean	2.38	2.84	2.98	2.10	2.67	2.70	2.63	3.29	3.13	3.34	2.56	2.63	2.59	2.98	2.51
Std.dev.	0.36	0.23	0.20	0.34	0.37	0.27	0.36	0.27	0.36	0.19	0.19	0.24	0.27	0.25	0.36
Min	1.35	2.22	2.48	1.46	1.85	2.02	1.40	2.02	1.40	2.75	2.64	2.66	1.69	2.00	1.72
Max	3.01	3.27	3.32	2.83	3.35	3.10	3.37	3.10	3.37	3.62	3.55	3.74	3.12	3.12	3.35

3.3. Data Envelopment Analysis

The BoD approach is a methodological extension of DEA for constructing composite indices. DEA was originally introduced by Charnes, Cooper, and Rhodes [74] as a non-parametric method to measure the efficiency of DMUs by enveloping observed data points in an optimal frontier [75]. Building on this foundation, Melyn and Moesen [76] first proposed the BoD model to create a single synthetic indicator of macroeconomic performance when reliable weight information was lacking [77]. In their seminal work, each country's overall performance was evaluated relative to a benchmark composed of best-observed achievements across multiple dimensions [77]. The term "benefit of the doubt" reflects the idea that each entity (e.g., city or country) is given the most favorable weighting of criteria, effectively granting it the benefit of the doubt in areas where its performance is stronger. Cherchye et al. [75] later formalized and popularized BoD for composite indicators, demonstrating how DEA can address key issues in index construction, such as normalization and weighting controversies. Since its introduction, BoD has been applied in diverse contexts, from evaluating human development and social inclusion to benchmarking city smartness and sustainability, wherever a cross-sectional comparison of units across multiple criteria is needed [78].

At its core, the BoD method is an application of DEA optimization to composite index construction. The approach treats each evaluated unit (e.g., a city) as a DMU that consumes a fixed "input" (often a single nominal input like a unity or budget) to produce multiple "outputs" (the various indicator scores representing performance on different criteria). BoD constructs an efficiency frontier by finding the highest possible composite score each DMU could attain under the most favorable weighting of indicators, subject to the constraint that no other unit exceeds a score of 1 under that same weighting [77]. In formal terms, the composite indicator for a specific unit is defined as the ratio of its actual performance to its benchmark performance, where the benchmark is a weighted combination of best-observed performances across all units [79]. This leads to a linear programming model solved for

each unit: the weights on each indicator are endogenously chosen to maximize a unit's weighted sum of indicators, with constraints that no unit's weighted sum can exceed 1 (thus defining a frontier where the "best" possible score is 1) [80]. These optimal weights are unit-specific and highlight the criteria in which the unit excels, effectively tailoring the index to each unit's strengths. Let $j = 1, 2, \ldots, n$ index the cities (DMUs) and $r = 1, 2, \ldots m$ index the output dimensions. Denote by y_{rj} the value of output r for city j. Within the BoD framework, the composite index for a given city j_0 is obtained by solving the following output-oriented CRS DEA problem:

$$\max_{u_1, u_2 \ldots u_m} \theta_{j_0} = \sum_{r=1}^{m} u_r y_{rj_0}$$

s.t.

$$\sum_{r=1}^{m} u_r y_{rj} \leq 1, \; j = 1, 2, \ldots, n$$
$$u_r \geq 0, \; r = 1, 2, \ldots, m$$

where u_r denotes the non-negative weight assigned to output r and θ_{j_0} is the BoD score (composite index) for city j_0.

A key feature of BoD is its endogenous weighting scheme. Unlike conventional composite indices that use fixed weights (equal weights or weights from expert judgment), BoD lets the data "decide" the weights for each unit [77]. This means each city or DMU is evaluated under its own optimal weights, emphasizing its advantages. The flexibility of these "benefit-of-the-doubt" weights fills the informational gap when there is no consensus on the "correct" weights [75]. As a result, the composite score is units-invariant (insensitive to units of measurement) and does not require a prior normalization step, because DEA's linear program inherently normalizes through the constraints [75]. The BoD index for each unit lies between 0 (worst possible) and 1 (the frontier), with higher values indicating that the unit comes closer to the performance of a hypothetical composite benchmark constructed from the best achievements in the sample. Intuitively, a BoD score can be interpreted as an efficiency rating or "smartness score" for a city, representing how well it turns inputs (if any) into outputs (indicators) relative to peer best practices. In this study, the BoD approach is implemented as an output-oriented DEA model under constant returns to scale (CRS). Each city is regarded as a DMU that uses a single fixed input to 'produce' the six output indicators corresponding to the smart-city dimensions. The choice of an output orientation reflects our aim to compare cities in terms of their performance levels under comparable resource conditions, whereas the CRS assumption follows the standard practice in BoD-based composite indicators, where the focus lies on relative performance rather than scale effects. In the empirical application, each of the analyzed European cities is treated as a DMU. The six smart city dimension scores (mobility, living, environment, economy, governance and people), computed as described in Section 3.2, are used as the outputs in the BoD model, while a single dummy input with value 1 is assigned to all cities. The BoD score reported for each city is the optimal value of the output-oriented CRS DEA problem corresponding to that city's input–output vector, obtained using the Efficiency Measurement System (EMS) software (https://share.google/1V8XM1vM8bNehzXl2, accessed on 1 September 2025).

4. Results

4.1. From Perception Indicators to BoD Efficiency Scores

Before the empirical findings are presented, a brief summary is provided of how the composite smart-city scores were obtained from the original perception-based indicators, in line with the BoD framework described in Section 3.

Step 1: City-level indicators. For each survey item listed in Table 3, individual responses on the 1–4 satisfaction scale were first aggregated to the city level as weighted arithmetic means. Concretely, for each indicator, the proportion of respondents selecting each category on the 1–4 Likert scale is multiplied by the corresponding score, and these products are summed, producing a single average value per indicator and per city. The descriptive statistics in Table 4 summarize the distribution of these city-level indicators.

Step 2: Normalization and dimension scores. To make indicators comparable, each city-level value was normalized using max normalization so that the best-performing city on a given indicator attains a score of 1 and all other cities obtain values in the [0, 1] interval proportional to their performance. Within each of the six smart-city dimensions (mobility, living, environment, economy, governance and people), the normalized indicators were then combined using the Simple Additive Weighting method with equal weights.

Step 3: DEA model inputs and outputs. In the BoD model, each city is treated as a DMU that uses a single fixed input (set to 1 for all cities) to "produce" the six-dimensional scores as outputs. As detailed in Section 3.3, the output-oriented CRS BoD formulation then searches, for each city, for the most favorable set of non-negative output weights that maximizes its weighted sum of dimension scores, under the constraint that no city exceeds a composite score of 1 when the same weights are applied to all cities.

Step 4: Optimization and software. The output-oriented constant-returns-to-scale BoD problem was solved for each city using the EMS software. For each city, EMS returns a BoD efficiency score $\theta_i \in [0, 1]$, together with the associated optimal output weights. These values of θ_i are reported in Table 5 and interpreted as the composite smart city performance scores used in the subsequent analysis.

Table 5. City efficiency.

City	Score	Rank	City	Score	Rank
Aalborg	1.0000	1	Essen	0.9447	41
Luxembourg	1.0000	1	Burgas	0.9433	42
Cluj-Napoca	1.0000	1	Brussels	0.9423	43
Zurich	1.0000	1	Nicosia	0.9421	44
Groningen	0.9924	5	Bucharest	0.9417	45
Geneve	0.9856	6	Dortmund	0.9412	46
Graz	0.9818	7	Strasbourg	0.9411	47
Copenhagen	0.9815	8	Sofia	0.9390	48
Antalya	0.9813	9	Miskolc	0.9387	49
Prague	0.9802	10	Glasgow	0.9382	50
Oslo	0.9796	11	Amsterdam	0.9377	51
Bialystok	0.9769	12	Kosice	0.9375	52
Vienna	0.9712	13	Bratislava	0.9334	53
Tallinn	0.9696	14	Berlin	0.9301	54
Oulu	0.9690	15	Bordeaux	0.9286	55
Cardiff	0.9679	16	Warsaw	0.9223	56
Rostock	0.9671	17	London	0.9216	57
Liege	0.9665	18	Budapest	0.9207	58
Munich	0.9658	19	Stuttgart	0.9147	59
Stockholm	0.9654	20	Krakow	0.9140	60

Table 5. *Cont.*

City	Score	Rank	City	Score	Rank
Piatra Neamt	0.9643	21	Braga	0.9103	61
Malmo	0.9643	22	Marseille	0.9085	62
Leipzig	0.9620	23	Malaga	0.9067	63
Valletta	0.9616	24	Lille	0.9063	64
Reykjavik	0.9616	25	Paris	0.9062	65
Antwerp	0.9593	26	Verona	0.8984	66
Gdansk	0.9581	27	Bologna	0.8979	67
Belfast	0.9580	28	Madrid	0.8967	68
Ankara	0.9578	29	Riga	0.8876	69
Manchester	0.9569	30	Barcelona	0.8842	70
Rennes	0.9539	31	Diyarbakir	0.8835	71
Helsinki	0.9533	32	Zagreb	0.8817	72
Newcastle upon Tyne	0.9519	33	Istanbul	0.8702	73
Ljubljana	0.9514	34	Lisbon	0.8532	74
Ostrava	0.9495	35	Heraklion	0.8410	75
Hamburg	0.9491	36	Turin	0.8403	76
Dublin	0.9486	37	Athens	0.8241	77
Vilnius	0.9474	38	Rome	0.8015	78
Oviedo	0.9458	39	Naples	0.7974	79
Rotterdam	0.9448	40	Palermo	0.7849	80

Source: Authors' calculation.

4.2. BoD Efficiency Scores for European Cities

The results of the city smartness evaluation obtained through the BoD approach are presented in this section. By applying this variant of DEA, each city was assessed relative to the best practices observed in the dataset, thereby constructing a composite indicator of smartness that reflects performance across multiple dimensions. The BoD framework enabled each city to endogenously determine the most favorable set of indicator weights, ensuring that no unit was disadvantaged by an a priori weighting scheme and allowing for a fair benchmarking process.

The BoD efficiency scores θ_i, obtained from the DEA optimization described in Section 4.1 (Step 4), are reported in Table 5 for all analyzed cities. These scores represent the composite smart-city index and form the basis for the ranking and comparative analysis discussed below. The composite scores for each city, bounded between 0 and 1, indicate the extent to which a city approaches the efficiency frontier defined by the best-performing peers. Cities with scores equal to 1 are positioned on the frontier and can be considered "efficient" in the sense that no combination of other cities' performances dominates them, while scores below 1 highlight relative inefficiencies and opportunities for improvement.

5. Discussion

The contemporary composite index of smart cities derived from the Urban Audit Perception Survey for 2023 indicates that European cities are progressing toward greater urban sustainability, with cities such as Aalborg (Denmark), Luxembourg (Luxembourg), Cluj-Napoca (Romania), and Zurich (Switzerland) standing out as exemplary cases, while Rome, Naples, and Palermo (Italy) lag. Northern and Western European cities, such as Zürich, Copenhagen, and Vienna, lead the ranking with the highest composite scores. Southern European cities, including Madrid, Lisbon, and Athens, demonstrate moderate performance, while Eastern and Balkan cities like Cluj-Napoca, Prague, and Ljubljana

show rapid progress, narrowing the gap with Western peers. Among Eastern European cities, Cluj-Napoca performs exceptionally well, thus achieving a perfect score (1.000) and ranking alongside leading Western cities like Zürich and Luxembourg, highlighting its rapid progress in terms of city smartness. Conversely, Rome and Naples in Southern Europe score unexpectedly low, given their size, cultural prominence, and government efforts toward higher smart city performances [81], reflecting the need for improvement. The pattern whereby Southern European cities obtain lower composite scores than most Northern and Western European cities is consistent with the broader literature on regional disparities within the European Union. Several studies underline that Southern Europe has been more severely affected by the consequences of the global financial crisis and subsequent periods of fiscal consolidation, which have constrained local government budgets and limited the scope for investment in public transport, environmental infrastructure and social services [82]. At the same time, higher structural unemployment, more precarious labor markets and pronounced housing affordability problems have been documented in many Southern European metropolitan areas. These structural conditions are directly related to the domains captured by our smart-city framework, namely satisfaction with public services and administration (governance), mobility, environmental quality, economic opportunities and housing. Obtained perception-based indicators appear to reflect these differences in the socio-economic and institutional context. Southern European cities in the sample systematically report lower levels of satisfaction with public transport, cleanliness, noise and air quality, as well as with job opportunities and the affordability of housing, while differences in the 'people' and 'living' dimensions are somewhat less pronounced [83–85]. This suggests that the lower BoD scores of Southern cities should not be interpreted as a lack of 'smartness' in a technological sense, but rather as evidence that citizens in these cities face more severe constraints in accessing good-quality public services and economic opportunities.

The EMS output also provides the endogenous weights attached to the six smart-city dimensions. For most leading cities, the model assigns relatively high weights to the 'soft' dimensions, such as smart living, smart people and smart governance, combined with a positive, but more moderate, contribution of the 'harder' dimensions—smart mobility and smart environment. This suggests that overall performance is not driven solely by infrastructure and technology but is strongly influenced by perceived quality of life, trust and the functioning of local government. Cluj-Napoca, the city with the highest composite score in our sample, is a typical example of this profile. The BoD solution for Cluj-Napoca places the largest weights on dimensions capturing satisfaction with local public administration, the availability and quality of local public services, safety, neighborhood quality and overall quality of life. The city achieves some of the highest perceived values precisely in the smart governance, smart living and smart people dimensions, while mobility and environmental quality are at or above the sample average but less decisive for reaching efficiency. Similar patterns can be observed in other top-ranked cities (e.g., Aalborg, Luxembourg, Zürich), where very high levels of satisfaction with quality of life, trust and local government performance are crucial for their position on the efficient frontier. By contrast, cities with the lowest BoD scores (such as Naples, Palermo, Athens and Rome) show substantial negative deviations in the mobility, environment and economy dimensions. This is consistent with lower levels of satisfaction with public transport, cleanliness, noise, air quality, job opportunities and affordable housing reported in the descriptive statistics. For these cities, the EMS output indicates larger slacks precisely in these dimensions, suggesting that potential improvements in overall efficiency would primarily require progress in these aspects of urban sustainability. Taken together, the results indicate that the most successful European smart cities distinguish themselves through a combination of strong 'soft' dimensions—trust,

safety, quality of life and effective, accessible local government—and solid performance in mobility and environmental quality. In contrast, cities with lower scores are constrained by perceived deficits in public services, transport and the urban environment, which points to key directions for future smart-city policy interventions. In the Balkans, Ljubljana performs above the regional average, showing strong governance toward a smart city compared to neighboring cities such as Zagreb or Sofia, which remain below the EU median. This pattern highlights persistent regional disparities across Europe, with a few cities bucking the trend. As the survey and, consequently, the composite index of smart cities derived from it capture residents' satisfaction across multiple dimensions of urban life, including infrastructure, services, safety, environmental quality, and personal circumstances, it serves as a unique and comprehensive indicator of urban sustainability. Moreover, by collecting residents' perspectives on pressing urban challenges, such as housing, employment, integration, and climate-related issues, the survey highlights areas where policy interventions can be most effectively directed to enhance overall urban livability.

The new composite index based on the Urban Audit Perception Survey data indicates that overall European cities remain very high in terms of sustainability. This mirrors broader quality-of-life trends: recent reports show continued progress in domains like employment and public services, especially in Eastern EU cities that are closing the gap with their Western counterparts [86]. Moreover, according to the Urban Audit Perception Survey methodology, cities such as Zurich, Copenhagen, Aalborg, Luxembourg, Groningen, and Vienna, as exemplary, regularly score among the highest in Europe on cultural amenities, green spaces, and safety. Such consistent top rankings reflect their comprehensive urban performance. Comparing study results to quality-of-life methodology of ranking cities, Aalborg, Luxembourg, Cluj-Napoca, and Zurich stand out as the smartest cities in different categories. For example, according to the quality-of-life report, Aalborg stands out as one of Europe's top-performing mid-sized cities, excelling in housing affordability, transparent and efficient governance, and digital public services. Its citizens report high satisfaction with jobs, financial stability, and environmental conditions, reflecting a well-balanced model of livability and sustainability. These results confirm Aalborg's position as a benchmark for smart, citizen-centered urban governance in Northern Europe. Luxembourg as a city consistently ranks among Europe's best-performing capitals, excelling in cleanliness, public spaces, and digital governance. Its residents report exceptionally high satisfaction with financial stability, employment, and local services, underscoring a well-managed and prosperous urban environment. These results highlight Luxembourg as a model of balanced economic strength and high-quality urban living in Western Europe. Cluj-Napoca stands out as a leading Eastern European city, combining rapid urban development with high citizen satisfaction. It ranks among the top European cities for overall quality of life, trust in local administration, and transport accessibility. These results underscore Cluj-Napoca's transformation into a well-managed and forward-looking urban hub, bridging the gap between Western and Eastern Europe through innovation, good governance, and citizen-focused policies. Lastly, Zurich residents reported the highest satisfaction with living in the city, financial situation in the household, public transport, cultural amenities, health care, air quality, and local administration service [87].

The study findings are consistent with past Urban Audit reports, which similarly found Copenhagen and Zurich at the top for satisfaction with living in the city [88]. Previous research shows that citizen satisfaction hinges on factors like health and safety, public transport, social inclusion, and environmental quality [89]. Roszkowska and Wachowicz's [89] BTOPSIS analysis also revealed significant regional and intra-country disparities in urban quality of life, with Zürich, Groningen, and Aalborg consistently ranking highest, while Tirana, Skopje, and Palermo remained the lowest-ranked cities. The method's

strength lies in capturing multidimensional factors and uncertain responses often omitted in traditional approaches. In contrast, the QSL single-question analysis confirmed similar patterns—higher satisfaction in northern and western European cities and lower levels in southern and Balkan cities—but tended to present a more optimistic picture by merging categories and excluding non-responses.

The multidimensional nature of the created smart city index is critical. The Urban Audit Perception Survey explicitly asks residents about many aspects of city life, from infrastructure and services to safety, environment, and personal factors. It is a perception-based survey that measures different aspects of urban life separately and does not capture city smartness by aggregating them into a single score. The research of Lai and Cole [90] indicates that while numerous indices attempt to measure smart city performance, their credibility, reliability, and methodological quality vary widely. Overall, the Cities in Motion Index (CIMI) demonstrates the best balance of these qualities, highlighting the need for future smart city indices to adopt refined indicators, clearly defined domains, and context-sensitive measurement frameworks to ensure fair and meaningful international comparisons. According to this index, governance, urban planning, technology, environment, international profile, social cohesion, human capital, mobility and transportation, and economy are weighted as significant factors of a smart city's performance. In an assessment of the sustainability and quality of life of 183 worldwide cities, the highest-ranked European cities for 2025 are Paris (3rd) and Berlin (5th), while Zurich is ranked at 14th place [91]. Both are measuring urban smartness, but while CIMI assesses city smartness through objective, data-driven measures of infrastructure, governance, economy, and sustainability, the composite index of smart cities created within this research evaluates it from a citizen-centered perspective, emphasizing perceived livability and well-being. Taken together, they reflect complementary approaches—structural efficiency versus experiential satisfaction. The most similar to the created composite index in this study is the IMD Smart City Index (SCI). SCI employs a perception-based methodology that combines residents' survey data with structural and technological indicators across five key domains for 143 cities worldwide, using fixed weights and the region-level Subnational Human Development Index-adjusted normalization to ensure cross-city comparability [92]. On the other hand, the composite index applies a data-driven approach using the BoD (DEA) method, which endogenously determines indicator weights to evaluate performance across six sustainability-oriented dimensions. While the SCI emphasizes citizens' quality of life and technological integration, the composite index in this study provides a more flexible, efficiency-based assessment of urban sustainability and smart city performance. In the case of the SCI (2025) results, leading European cities such as Zurich, Oslo, Geneva, London, and Copenhagen consistently occupy top positions, reflecting strong performance in governance quality, urban mobility, and technological infrastructure [92]. In contrast, the composite index identifies Zurich, Geneva, and Copenhagen as the most advanced in terms of sustainable urban development. Collectively, both indices converge on Nordic and Western European cities as leaders but differ in emphasis. While the SCI prioritizes technological integration and perceived livability, the smart city index underscores environmental resilience and social inclusiveness as key determinants of urban performance. Aligned to the paper results, Bove and Ghiraldelli [64] propose nine livability-based alternative indicators—including life expectancy, mental health, air quality, green space access, housing affordability, and social cohesion—to better reflect urban quality of life and sustainability of the smart city. Unlike traditional smart city indices that emphasize technology and economics, these alternatives also focus on human well-being and environmental resilience. The goal is to create a more balanced, people-centered view of what makes a city truly "smart".

6. Conclusions

The results of the study contribute to the ongoing discussion on how smart cities, urban sustainability and quality of life are related. Conceptually, we argued that smart city policies and sustainability objectives should ultimately be reflected in residents' quality of life, and that perception-based indicators therefore capture an important outcome dimension of 'smartness'. The empirical analysis supports this view in two ways. First, the BoD results show that cities that residents perceive as high-performing are not necessarily those with the most advanced technological infrastructures but those that combine good transport and environmental conditions with very high satisfaction in governance-, living- and people-related domains. The relatively high weights assigned to smart living, smart governance and smart people dimensions indicate that citizens' overall assessment of city performance is strongly shaped by the functioning of local public administration, the quality and accessibility of public services, perceived safety, trust in others and satisfaction with everyday life. This finding is consistent with the people-centered perspective on smart cities, which emphasizes that digital technologies and data should be instruments for improving livability and inclusive governance rather than ends in themselves. Second, the observed regional differences suggest that perception-based smart city performance is deeply embedded in broader socio-economic trajectories. Lower composite scores in many Southern European cities are not simply 'technical underperformance' but reflect the legacy of the financial crisis, fiscal constraints, labor market difficulties and housing pressures documented in the literature on European regional disparities. In this sense, our perception-based index provides a lens on how long-term structural conditions and governance models translate into citizens' evaluations of urban life. The study thus adds to the literature by showing how a BoD-based composite indicator, built entirely from perception data, can reveal both multidimensional strengths and structural weaknesses in the lived experience of smart and sustainable cities.

The empirical patterns identified in this paper have several implications for urban policymakers and for European smart city initiatives. First, the prominence of governance-, living- and people-related dimensions in the BoD weights suggests that investments in digital and physical infrastructure need to be accompanied by efforts to improve the responsiveness, transparency and accessibility of local public administration. Cities that score highly in the index are those where residents experience public services as efficient and accessible, where information can be obtained online, and where procedures are perceived as straightforward and fair. Strengthening these aspects of local governance appears to be as important for perceived smart city performance as upgrading transport networks or environmental infrastructure. Second, the analysis points to specific policy domains where improvements could yield substantial gains in perceived performance. For many lower-performing cities, especially in Southern Europe, the largest slacks are found in the mobility, environment and economy dimensions. This indicates that targeted interventions to enhance public transport reliability and affordability, reduce noise and air pollution, improve cleanliness and support access to decent jobs and affordable housing are likely to have the greatest impact on residents' assessments of their city. The index can thus be used as a diagnostic tool to identify which dimensions most constrain each city's overall performance from a citizen perspective. Third, regional patterns suggest that similar challenges tend to concentrate geographically. Groups of cities in Southern and parts of Central and Eastern Europe share combinations of lower scores in mobility, environment and economic opportunity. For these clusters, common policy platforms and shared learning, for example, within EU Urban Agenda partnerships or city networks, could be particularly valuable. Conversely, leading cities in Northern and Western Europe provide examples of how integrated investments in infrastructure, governance and quality-

of-life policies can generate high and balanced performance across dimensions. Finally, at the European level, the proposed index complements existing objective smart city and urban sustainability indicators by bringing in the residents' voice. It can support EU initiatives by highlighting where citizens' perceptions of urban conditions diverge from objective metrics, thereby helping to prioritize areas where policy efforts need to be better aligned with residents' expectations.

A key contribution of this work is showing the added value of citizens' perceptions in assessing city performance. Unlike many smart-city indices that rely solely on objective data (e.g., infrastructure counts or economic metrics), this composite index incorporates residents' subjective evaluations, weighting each city's indicators according to local strengths. This aligns with recent scholarly calls to listen to residents when shaping urban policy for sustainable development. In practice, this perception-based index converges broadly with objective measures in identifying leading cities (e.g., Nordic and Western capitals), but it also highlights different priorities. For example, the IMD Smart City Index (SCI) 2025, which blends survey and fixed-weight objective data, ranks Zurich, Oslo, and Copenhagen at the top, echoing study findings. However, the SCI gives more weight to technology integration and hardware, whereas the composite index, through the BoD approach, emphasizes outcomes like environmental resilience and social well-being. In other words, objective indices and perception-based indices are complementary. The former measures a city's structural assets, while the latter captures experiential satisfaction. Creating a composite index ensures that planning does not overlook what matters most to people. For example, this citizen-centric perspective can reveal latent issues, such as perceptions of safety or housing quality, that raw data might miss. As such, incorporating public satisfaction into benchmarking yields a more context-sensitive picture of urban sustainability and city smartness.

This study demonstrates the utility of a citizen-centered composite index for urban sustainability. By synthesizing resident satisfaction across multiple domains, the index paints a comprehensive picture of smart-city performance. It confirms that Northern and Western European cities tend to lead in balanced urban sustainability, while also spotlighting areas for improvement in other regions. Crucially, the findings underscore that "smartness" is not just about technology or GDP, but about how well city services and environments serve the everyday needs of people. The proposed index thus equips city leaders with a tool based on the data-driven rigor of the lived experiences of citizens, guiding policy toward more equitable, livable, and sustainable urban futures.

This study has several limitations that should be acknowledged. First, the index is built exclusively on perception-based data. Residents' responses may be influenced by cultural response styles, short-term political or economic events, media narratives or individual expectations, which can introduce biases that are not directly linked to objective conditions. While this is precisely what makes perception data valuable for capturing the lived experience of urban policies, it also implies that our index measures perceived rather than 'true' smart city sustainability performance. Second, the reliance on a single survey wave means that we cannot analyze temporal dynamics or disentangle cyclical fluctuations from structural differences across cities. Third, the BoD approach, by construction, allows cities to choose the most favorable set of weights within common constraints. This endogenous weighting is a strength in terms of avoiding arbitrary weights, but it may also lead to very small implicit weights for dimensions where a city performs poorly. We partially address this by examining the average weight profiles and by comparing our results with an equally weighted index, but further work could explore alternative formulations that impose minimum weights or incorporate external value judgments. Finally, our conceptualization deliberately focuses on perceived smart city sustainability performance,

which sits at the intersection of smart city policies, urban sustainability objectives and quality-of-life outcomes. We do not claim to provide a full measure of environmental or economic sustainability, nor a comprehensive smart city technology index. Instead, we offer a people-centered complementary perspective that can be used alongside objective indicators and more technology-focused benchmarks.

The framework proposed in this paper also opens several avenues for future research. First, the analysis could be extended in a longitudinal perspective by exploiting multiple waves of the Quality of Life in European Cities survey. A panel of cities over time would make it possible to study the dynamics of perceived smart city sustainability performance, identify trajectories of improvement or decline, and relate them more directly to the timing of specific policies or investments. Second, future work could develop hybrid indices that combine perception-based and objective indicators. Linking residents' satisfaction with transport, environment, governance and economic opportunities to measurable changes in emissions, service provision or infrastructure quality would allow a richer understanding of when and why objective improvements do, or do not, translate into higher perceived performance. Third, the spatial dimension deserves further investigation. Building on the descriptive regional patterns identified here, future research could apply formal clustering and spatial econometric techniques to examine how spatial dependence, regional context and inter-city networks shape perceived smart city sustainability. This could shed more light on spillover effects and on the role of national or EU-level policies.

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