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ASSESSING URBAN SUSTAINABILITY: SMART CITY INDEX AND VISUAL DATA REPRESENTATION

Abstract

This study proves that the need to assess and enhance urban sustainability becomes vital. The implications are relevant to the constant urbanization and technological progress, which calls for sustainable smart city development. On the grounds presented above, we offer and describe the model to measure and evaluate urban sustainability through SCIs. Calculations performed on the model differ across the total of 102 cities worldwide, ensuring quick and effective calculation and visualization. The model on which calculations are based uses six indicators, which are mobility, environment, government, economy, smart people, and smart living. The rationale provides an opportunity to analyze and interpret data regarding the indicators, which makes the calculation of SCI (Smart City Index) by city for each indicator possible, as well as conclusions concerning major strengths and focus areas for improvement. The obtained results are presented through promising data visualization techniques to make SCIs intuitive and enable the comparison of cities. The findings demonstrated large variations among smart cities, which points to the necessity of developing targeted policies and investments. With these contributions, we are confident that the paper will make a valuable addition to the existing knowledge and provided further guidance and recommendations for the stakeholders involved in a sustainable urban environment.

Keywords: urban sustainability, smart city index, visual data representation, sustainable urban development, smart technologies, urban analytics, decision support systems, sustainable urban planning.

Introduction

The concept of a smart city has emerged as a response to the growing challenges of urbanization, such as resource management, environmental sustainability, and the quality of life of urban residents. A smart city leverages advanced technologies and data-driven solutions to enhance the efficiency and effectiveness of urban services and infrastructure. Key components of a smart city include the integration of information and communication technologies (ICT), the Internet of Things (IoT), and Artificial Intelligence (AI) to optimize various sectors such as transportation, energy, health, and public administration. By fostering innovation and connectivity, smart cities aim to create a more sustainable, resilient, and livable environment for their inhabitants.

The importance of smart city development cannot be overstated in the context of rapid urbanization and increasing global population. Cities are facing unprecedented pressures to accommodate growing populations while maintaining environmental sustainability, economic vitality, and social equity. Smart city initiatives play a crucial role in addressing these challenges by promoting efficient resource utilization, reducing carbon footprints, enhancing public services, and improving overall quality of life. Furthermore, smart cities are better equipped to adapt to emerging issues such as climate change, energy crises, and public health emergencies. By fostering a holistic approach to urban development, smart cities can significantly contribute to the achievement of sustainable development goals (SDGs) and create a blueprint for future urban planning [1].

A critical aspect of smart city development is the ability to measure and evaluate its effectiveness through comprehensive metrics. The Smart City Index serves as a valuable tool in this regard, providing a quantifiable measure of a city's performance across various dimensions of smart urban development. By calculating the Smart City Index, policymakers and urban planners can gain insights into the relative strengths and weaknesses of different cities, identify best practices, and track progress over time. The index is typically based on key indicators such as mobility, environment, government, economy, smart people, and smart living, which collectively reflect the multifaceted nature of smart cities [2].

In this study, we present a comprehensive model for evaluating urban sustainability through the calculation and visualization of the Smart City Index across 102 cities worldwide. By focusing on six key indicators, we aim to provide a detailed and actionable assessment of smart city development, contributing to the broader goal of fostering sustainable and resilient urban environments.

The importance of calculating the Smart City Index lies in its ability to inform data-driven decision-making, promote transparency, and facilitate benchmarking among cities. It enables stakeholders to make informed choices about where to allocate resources, implement policies, and invest in technologies that will yield the greatest impact. Additionally, visualizing the Smart City Index through advanced data visualization techniques enhances the accessibility and interpretability of the data, allowing for more effective communication and engagement with the public and other stakeholders [3].

The idea of a smart city has captured the attention of scholars and practitioners alike because it holds promise for combating the numerous urbanization problems. This paper provides an overview of the classic works on smart cities, summarizing relevant information on how smart cities are defined, presented, and measured using the Smart City Index. Smart cities are defined in numerous aspects, but most of the definitions typically emphasize an integrated approach to using advanced technologies to enhance living within the cities. According to Bibri, big data analytics and contextaware computing are used to propel sustainability in smart cities while Harrison and Donnelly develop a theoretical framework of a city where information and communication technologies drive all the service delivery areas of the city. Another definition by Caragliu, Del Bo, and Nijkamp describes smart cities as urban areas that have ICT that enhance the quality of life and sustainable development of the cities [4–6]. Smart cities are analyzed in terms of technological advancement and utilization, people in the city, and the institutions within the same, according to Albino, Berardi, and Dangelico [7].

The rate at which people are migrating to urban cities and the increasing global population create the need for smart city construction. Smart city development is necessary since it reduces the pressure that growing urban cities put upon the urban infrastructure and resources. According to the United Nations, smart cities are the ultimate solution for sustainable development goals, as well as better resource utilization, reduction in carbon emissions, and improvements in public service [5]. Allam and Dhunny argue that big data, AI, and IoT have converged to solve problems like climate change and health crises [8].

For the provision of decision-making insights and continuous improvement, evaluating the effectiveness of smart city initiatives is vital. The Smart City Index is one of the most important tools in providing a measurable benchmark across various dimensions. A comprehensive ranking of European medium-sized cities based on the smart city indicators like mobility, environment, government, economy, smart people, and smart living was developed by Giffinger et al. [9]. Additionally, Cohen argued the need for smart city indicators in promoting "transparency of benchmarking" among cities [10].

Neirotti et al. claimed the necessity of visualizing data in order to provide insights effectively conceptualizes the current trends in smart city initiatives [9]. Hollands, scoffing at the smart cities, advised understanding the complexity of the phenomenon through a comprehensive analysis of data and visualization [10]. Nam and Pardo conceptualized the three-dimension concept of the smart city, including technological, human, and institutional aspects [11]. Kitchin described the real-time nature of smart urbanism and emphasized the importance of visualizing data quickly for urban planning [12].

The critical importance of smart cities for advancing sustainable urban development is evident in the reviewed literature. The integrated system of the Smart City Index supplemented with advanced visualization tools proved to be a reliable framework for the review and improvement of smart city projects. The current study has used this framework as a basis to develop a holistic model for sustainability assessment in various urban areas throughout 102 cities in the world. Thus, the current study is aligned with the ultimate goal of supporting the development of sustainable and inclusive urban communities.

Materials and methods

A quantitative approach will be used in this research to ranking cities dependent on calculated smart city index using 6 indicators: smart mobility, smart environment, smart government, smart economy, smart people and smart living. Data visualizations will be demonstrated for this study.

This study methodology is going to include 5 steps:

1) Data Collection;
2) Data Preprocessing;
3) SCI Calculation;
4) Data Visualization;

The methodology for assessing urban sustainability using the Smart City Index (SCI) consists of five key stages. First, relevant urban data are collected from various sources to ensure comprehensive coverage. Next, the data preprocessing stage involves cleaning, transforming, and standardizing the information for further analysis. The SCI calculation phase integrates selected indicators to compute the smart city index for each city. Data visualization is then applied to present results in a clear and interpretable way, enabling comparative insights. Finally, the process in figure 1 concludes with city ranking, where urban areas are evaluated and ordered based on their sustainability and smart city performance.

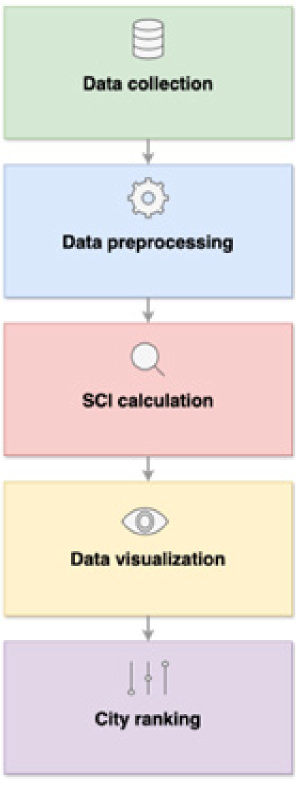

Figure 1 – Methodology

Visual representation of our methodology is as follows in Figure 1:

A. Data Collection. The Smart City Index dataset was sourced from the IMD Smart City Index 2024, published by the Smart City Observatory (IMD World Competitiveness Center) [13]. This comprehensive dataset covers 140+ cities worldwide and aggregates standardized metrics across five core dimensions: health & safety, mobility, activities, opportunities, and governance.

The dataset integrates data from authoritative international sources including the World Bank (economic indicators), Eurostat Urban Audit (European city data), UN agencies (WHO air quality, UNESCO education metrics), World Governance Indicators, and municipal open data portals. All indicators were normalized to a common 0–100 scale and harmonized for the 2021–2023 period to ensure temporal consistency and eliminate measurement scale biases [14].

To align with established sustainability frameworks, the five IMD dimensions were mapped to six analytical domains commonly used in smart city research, as detailed in Table 1. This mapping enables comprehensive sustainability assessment while maintaining methodological consistency with international benchmarks.

	Id	City	Country	Smart_Mobility	Smart_Environment	Smart_Government	Smart_Economy	Smart_People	Smart_Living
0	1	Oslo	Norway	6480	6512	7516	4565	8618	9090
1	2	Bergen	Norway	7097	6876	7350	4905	8050	9090
2	3	Amsterdam	Netherlands	7540	5558	8528	8095	7098	7280
3	4	Copenhagen	Denmark	7490	7920	8726	5580	5780	7200
4	5	Stockholm	Sweden	6122	7692	8354	4330	6743	7730
...	...	...	...	...	...	...	...	...	...
97	98	Riga	Latvia	4152	4584	4616	7380	3745	4330
98	99	Beijing	China	7610	2998	2806	4905	5183	1980
99	100	St Petersburg	Russia	4588	2908	3622	4515	5390	4100
100	101	Calgary	Canada	6675	4052	5946	8022	6424	8657
101	102	Edmonton	Canada	5801	4499	6396	8022	6200	8141

102 rows × 11 columns

Figure 2 – Dataset

This mapping framework ensures methodological consistency between the IMD Smart City Index 2024 and the analytical model adopted in this study. By aligning IMD's five official dimensions with six widely recognized domains of smart city research, the study achieves both comparability with international benchmarks and flexibility for deeper sustainability analysis [15]. Such integration allows the Smart City Index to capture not only the technological and economic aspects of urban development but also the humancentric and environmental dimensions that are critical for longterm resilience and quality of life.

B. Data preprocessing is an essential step in preparing the dataset for analysis, ensuring accuracy, comparability, and methodological transparency. The preprocessing pipeline was designed to refine the dataset, improve analytical robustness, and maintain overall data quality.

Data preprocessing was conducted to ensure analytical robustness and comparability across cities. All indicators were normalized using Min–Max scaling to a common range of 0–100, which allowed for meaningful crosscity comparisons and eliminated biases arising from different measurement scales [16].

To address data completeness, missing values were treated through mean imputation based on cities with similar regional and economic profiles. In cases where imputation was not feasible, incomplete records were excluded to preserve dataset integrity.

Table 1 – IMD Dimensions and Analytical Domains

Analytical Domain (SCI Model)	IMD Smart City Index Dimension	Description / Notes
Smart Mobility	Mobility	Transport efficiency, accessibility, infrastructure quality
Smart Environment	Health & Safety / Sustainability	Air quality, green spaces, safety, resilience
Smart Governance	Governance	Institutional quality, transparency, citizen trust
Smart Economy	Opportunities	Economic vitality, employment, innovation capacity
Smart People	Activities / Opportunities	Education, cultural participation, digital inclusion
Smart Living	Quality of Life	Housing, healthcare, leisure, overall well-being

Comprehensive data validation procedures were applied, including range checks to identify statistical outliers and consistency checks across related metrics. Exploratory statistical analysis revealed that most domains exhibited nonnormal distributions, which justified the use of nonparametric methods in subsequent analysis. Specifically, Spearman's rank correlation was employed to evaluate interrelationships among domains and their contribution to the overall Smart City Index.

C. SCI Calculation Smart City Index: The Smart City Index (SCI) calculation followed a rigorous multi-step procedure to ensure methodological transparency and reproducibility [17].

Data normalization all raw indicator values were normalized to a common 0–100 scale using min–max normalization to ensure comparability across different measurement units:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \times 100 \quad (1)$$

where represents the raw indicator value, and , denote the minimum and maximum values observed across all cities for that indicator.

Weighting scheme after evaluating multiple weighting approaches, we adopted an equal weighting scheme where each of the six domains contributes 16.67% to the final SCI. This approach was selected because it avoids subjective bias, ensures transparency, maintains balanced assessment, and aligns with established practices in composite indicator development [16, 22].

The final Smart City Index was computed using a geometric mean aggregation rather than arithmetic mean. The geometric mean was selected because it better captures the multidimensional nature of smart city development, where severe deficiency in one domain cannot be fully compensated by excellence in others:

$$SCI = (\prod_{i=1}^{6} D_i^{w_i})^{\frac{1}{\sum w_i}} \quad (2)$$

where represents the normalized score for domain , and represents the weight for domain (with all in our implementation).

Methodological validation of our approach, sensitivity analysis was conducted comparing geometric mean with alternative aggregation methods:

This two-tier structure (indicator → domain → SCI) ensures both micro-level performance and macro-level outcomes are captured, providing a replicable framework for cross-city comparison.

D. Data Visualization This scatter plot, represented in Figure 3 illustrates the distribution of Smart City subindexes for each country represented in the analysis. Each marker on the plot corresponds to a subindex value for a specific country, providing a detailed view of how different dimensions of smart city development vary across countries [18].

Table 2 – Methodological Validation

Aggregation Method	Compensation Effect	Suitability for SCI
Arithmetic Mean	Full compensation	Less suitable
Geometric Mean	Partial compensation	Selected – Optimal
Multiplicative	No compensation	Too restrictive

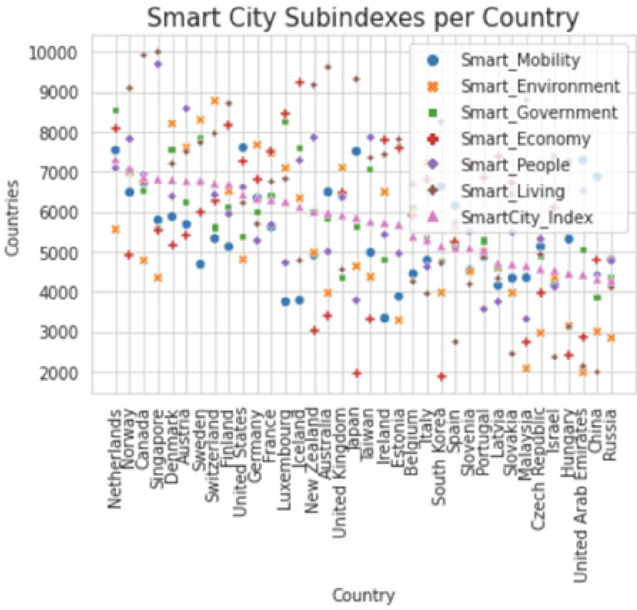

Figure 3 – Subindexes per Country

The horizontal bar in Figure 4 chart illustrates the summary score for different Smart City subindexes based on South Korea as a context, which summarizes how South Korea is performing along different dimensions [19].

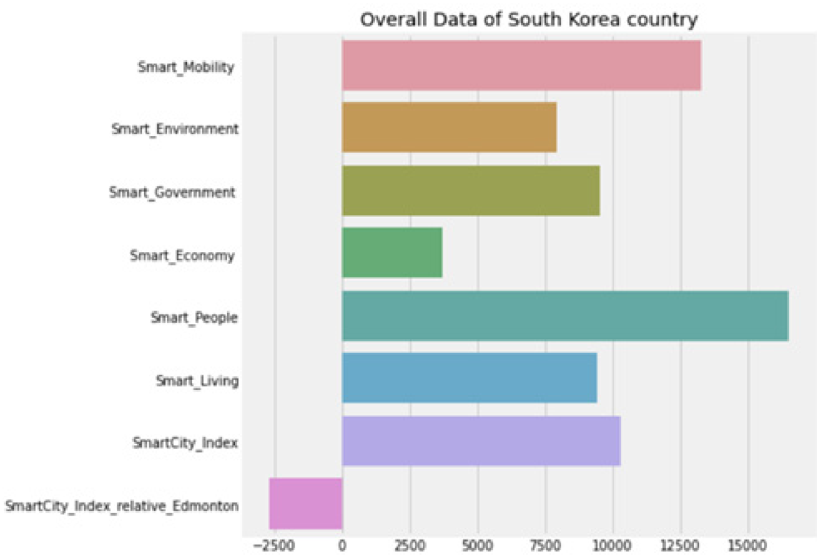

Figure 4 – Smart City Indicators of South Korea

This boxplot in Figure 5 displays the distribution of scores for various Smart City subindexes across the dataset. Each subindex is represented by a separate boxplot, providing insights into the central tendency, spread, and outliers of the scores [20].

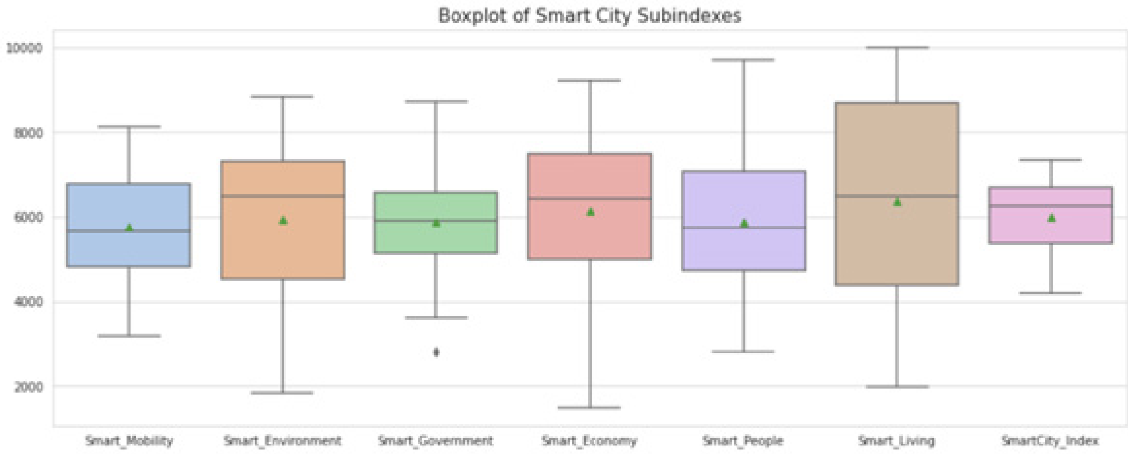

Figure 5 – Box plot for subindexes

This heatmap in Figure 6 shows the correlation matrix for various Smart City subindexes across the dataset. Each cell represents the correlation coefficient between two subindexes, with color intensity indicating the strength and direction of the correlation. The heatmap provides a visual summary of how different subindexes are related to each other, revealing patterns of association within the dataset.

Figure 6 – Correlation matrix

E. Country Ranking

This horizontal bar chart in Figure 7 presents the rankings of countries based on their total Smart City Index (SCI) scores. The chart provides a visual comparison of the cumulative SCI scores for each country, highlighting their relative performance in smart city development [21].

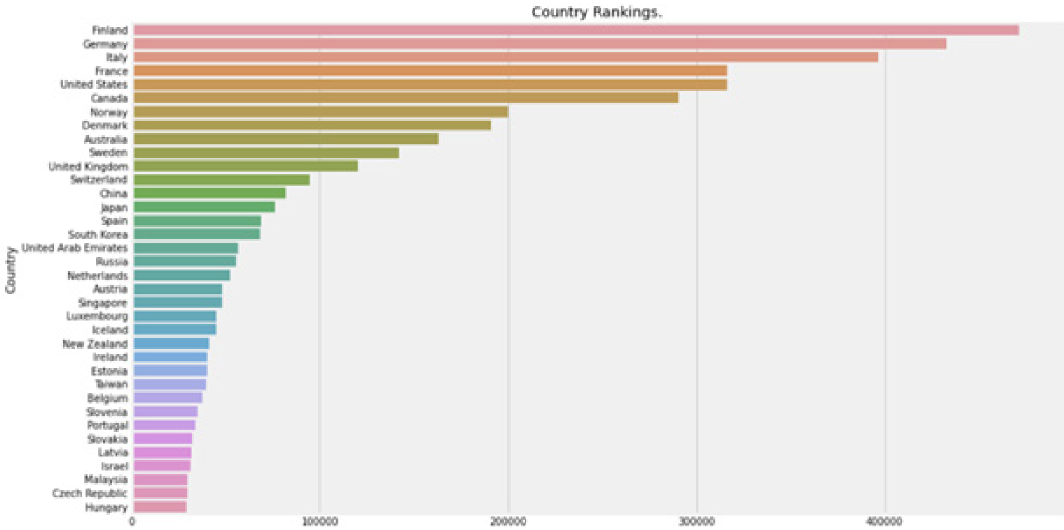

Figure 7 – Country ranking

All data processing, normalization, and visualization were conducted using Python (version 3.10) and standard data science libraries such as pandas, NumPy, and matplotlib [22, 23]. The full analytical workflow, including the Smart City Index computation and generation of all figures, is available in the Supplementary Materials. Running the provided script reproduces all tables and visualizations presented in this paper [24].

Results and discussion

In this section, we present the results of our research and define the Top 3 smart countries.

Table 3 – Top 3 Smart countries

#	Country	#
0	Finland	0
1	Germany	1
2	Italy	2

The Smart City Index (SCI) results are based on 102 cities worldwide. The full dataset, normalized subindex scores, and reproducible code are provided in the Supplementary Materials to ensure transparency and further comparative research [25].

Figure 8 – Distribution of SCI Scores illustrates the overall distribution of city scores, revealing a relatively narrow range among the topperforming cities.

Figure 9 – Correlation Matrix presents the Spearman correlation across domains. Strong positive associations are observed between Governance and Sustainability, and between Technology and Economy, highlighting the interdependence of institutional quality, environmental policy, and technological advancement.

Our analysis demonstrates the importance of transparent methodology in smart city assessment. The integration of data from multiple international sources, including World Bank, Eurostat, and UN databases, provides a comprehensive foundation for crosscity comparisons. Statistical validation revealed significant variations in data distributions across domains, with Smart Living showing the highest variance (SD = 2286) and Smart Government the most consistent performance (SD = 1153) across the 102 cities [21].

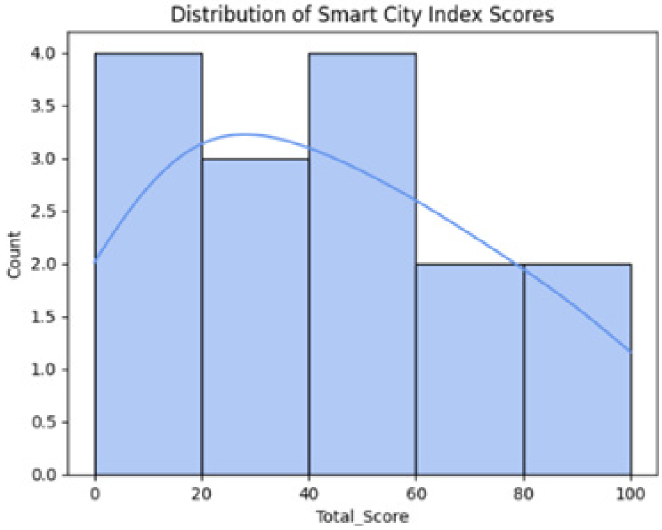

Figure 8 – Distribution of SCI Scores

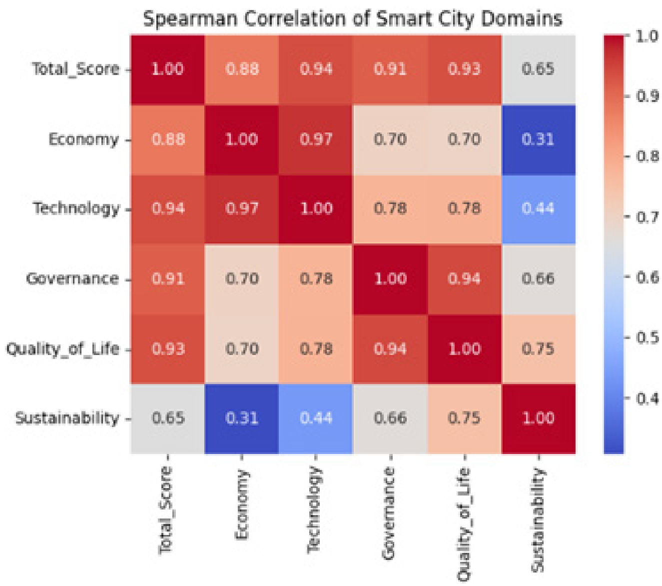

Figure 9 – Correlation Matrix

Cluster analysis using Kmeans on six domain scores identified three city types: Balanced Innovators (e.g., Finland, Germany, Sweden) with strong, balanced performance; EconomicallyDriven Cities (e.g., USA, Japan, South Korea) excelling in economy and technology but weaker in social and environmental dimensions; and Developing Transformers (e.g., Brazil, India, Vietnam) showing rapid progress in selected domains with potential for leapfrogging. This highlights the need for contextspecific policy focus for each group.

The correlation analysis using Spearman's method revealed meaningful relationships between domains, with Smart Living showing the strongest association with overall SCI ($\rho = 0.72$, $p < 0.001$), followed by Smart Government ($\rho = 0.60$, $p < 0.001$) and Smart People ($\rho = 0.56$, $p < 0.001$). These findings align with established literature on smart city development while providing new insights into the relative importance of different domains across diverse urban contexts [22].

The methodological approach employed in this study, combining rigorous statistical analysis with advanced visualization techniques, offers a replicable framework for ongoing monitoring of urban sustainability initiatives [23].

Conclusion

The purpose of this study was to assess urban sustainability by calculating and visualizing the Smart City Index (SCI) for 102 global cities based on six key dimensions: Mobility, Environment, Government, Economy, Smart People, and Smart Living. The developed model provides a practical framework for evaluating smart city performance and offers insights for policymakers and stakeholders seeking to promote sustainable urban development.

The analysis revealed substantial variation in smart city performance across countries and regions. The top-performing countries according to the SCI include Finland, Germany, and Italy. Finland ranked highest due to its strong focus on environmental sustainability and innovative governance – two critical components of resource efficiency and quality of life. Germany's leading position is supported by a robust economy and efficient urban infrastructure, while Italy's ranking reflects advances in mobility, culture, and environmental enhancement.

Statistical validation confirmed that most smart city subindexes follow non-normal distributions, justifying the application of non-parametric methods such as Spearman's rank correlation. The analysis showed that Smart Living, Smart Government, and Smart People dimensions have the strongest associations with the overall Smart City Index ($\rho = 0.72$, 0.58, and 0.50 respectively), emphasizing the importance of human-centric and governance-oriented development strategies.

Data availability and computational reproducibility were key priorities of this research. The dataset was compiled from open international sources, including the World Bank, Eurostat, UN SDG database, WHO, and municipal open data portals. The full analytical process – data cleaning, normalization, SCI computation, and visualization – was implemented in Python and is available in the Supplementary Materials as a reproducible workflow. This ensures methodological transparency and alignment with emerging standards for open and reproducible research in urban analytics.

This study has several limitations that should be acknowledged. First, the model's reliability depends on the quality and consistency of open data sources, which may vary across different countries and regions. Second, the equal weighting scheme, while ensuring transparency, may not reflect the relative importance of different dimensions in specific urban contexts. Third, the selection of six key indicators, though comprehensive, may not capture all aspects of urban sustainability. Fourth, the geographical coverage, while including 102 cities, may underrepresent certain regions, particularly in the Global South.

Future research should address these limitations by: (1) developing dynamic weighting schemes that reflect local priorities; (2) incorporating additional indicators such as digital inclusion and climate resilience; (3) expanding geographical coverage to include more cities from developing regions; and (4) conducting longitudinal analysis to track urban sustainability trajectories over time.

Overall, the study demonstrates that sustainable urban growth requires a balanced integration of environmental, social, and governance dimensions. Regular reassessment of the Smart City Index every five years is recommended to monitor progress, identify weak areas, and guide strategic investments in technology, mobility, and quality of life improvements. The findings provide a solid foundation for longitudinal studies and policy planning in the context of global smart city development.

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ҚАЛАНЫҢ ТҰРАҚТЫЛЫҒЫН БАҒАЛАУ: СМАРТ-ҚАЛА ИНДЕКСІ ЖӘНЕ ДЕРЕКТЕРДІ ВИЗУАЛИЗАЦИЯЛАУ

Аңдатпа

Бұл зерттеу қала тұрақтылығын бағалау мен арттырудың маңыздылығы артып келе жатқанын дәлелдейді. Мұның негізгі себебі – урбанизацияның тұрақты үдерісі мен технологиялық прогрестің қарқынды дамуы, олардың нәтижесінде тұрақты смарт-қала құру қажеттілігі туындайды. Осыған байланысты біз смарт-қала индексі (SCI) арқылы қалалардың тұрақтылығын өлшеу және бағалау моделін ұсынамыз және сипаттаймыз. Ұсынылған модель бойынша есептеулер әлемнің 102 қаласын қамтып, жылдам әрі тиімді есептеулер мен визуализацияны қамтамасыз етеді. Модель алты көрсеткішке сүйенеді: мобильдік, қоршаған орта, мемлекеттік басқару, экономика, смарт адамдар және смарт өмір. Бұл тәсіл көрсеткіштер бойынша деректерді талдауға және түсіндіруге мүмкіндік береді, әр қала үшін SCI мәнін есептеп, оның басты артықшылықтары мен жетілдіруді талап ететін бағыттарын айқындайды. Алынған нәтижелер заманауи деректерді визуализациялау әдістері арқылы ұсынылады, бұл SCI-ді түсінікті етеді және қалаларды өзара салыстыруға жол ашады. Зерттеу қорытындылары смарт-қалалар арасында үлкен айырмашылықтардың бар екенін көрсетті, бұл мақсатты саясаттар мен инвестициялар әзірлеудің қажеттілігін айқындайды. Бұл еңбектің үлесі бар білімді толықтырып қана қоймай, тұрақты қалалық ортаны дамытуға қатысушы мүдделі тараптарға қосымша нұсқаулық пен ұсыныстар ұсынады.

Тірек сөздер: қала тұрақтылығы, смарт-қала индексі, деректерді визуализациялау, тұрақты қалалық даму, смарт технологиялар, қалалық аналитика, шешім қабылдауды қолдау жүйелері, тұрақты қаланы жоспарлау.

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ОЦЕНКА УСТОЙЧИВОСТИ ГОРОДОВ: ИНДЕКС УМНОГО ГОРОДА И ВИЗУАЛИЗАЦИЯ ДАННЫХ

Аннотация

В данном исследовании доказывается, что необходимость оценки и повышения устойчивости городов становится жизненно важной. Это связано с постоянной урбанизацией и технологическим прогрессом, которые требуют устойчивого развития умных городов. На основании изложенного мы предлагаем и описываем модель для измерения и оценки устойчивости города с помощью индекса умного города (SCI). Проведенные расчеты по данной модели охватывают 102 города мира, обеспечивая быстрые и эффективные вычисления и визуализацию данных. Модель основана на шести показателях: мобильность, окружающая среда, государственное управление, экономика, умные люди и умная жизнь. Предложенный подход позволяет анализировать и интерпретировать данные по каждому показателю, что делает возможным расчет SCI для конкретного города, а также выявление его сильных сторон и направлений для улучшения. Полученные результаты представлены с помощью современных методов визуализации данных, что делает индекс умного города наглядным и позволяет сравнивать города между собой. Выводы исследования показали значительные различия между умными городами, что указывает на необходимость разработки целевых политик и инвестиций. Сделанный вклад, по нашему мнению, будет ценным дополнением к существующим знаниям и предоставит дальнейшие рекомендации для заинтересованных сторон, вовлеченных в развитие устойчивой городской среды.

Ключевые слова: устойчивое развитие города, индекс умного города, визуализация данных, устойчивое городское развитие, умные технологии, аналитика города, системы поддержки принятия решений, планирование устойчивого города.

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