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METHODOLOGYCAL APPROACH TO EMPIRICAL ANALYSIS OF URBAN INFRASTRUCTURE SUSTAINABILITY DETERMINANTS

МЕТОДИЧНИЙ ПІДХІД ДО ЕМПІРИЧНОГО АНАЛІЗУ ДЕТЕРМІНАНТ СТАЛОСТІ МІСЬКОЇ ІНФРАСТРУКТУРИ

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In the context of rapid urbanization and global environmental challenges, the issue of sustainable urban development is critical. This article presents a comprehensive methodology to identify empirical determinants of urban infrastructure sustainability. The research proposes a nine-stage algorithm based on a balanced panel data set covering seven European cities (Stockholm, Helsinki, Zurich, Milan, Prague, Brussels, and Kyiv) from 2015 to 2020. The analysis integrates 56 infrastructure indicators grouped into 11 functional components. Statistical methods include Pearson correlation analysis and significance verification using Student's t-test. Findings identify key sustainability drivers and establish 12 practical management levers for municipal policy. This framework enables local governments to convert theoretical sustainability goals into measurable Key Performance Indicators (KPIs) and evidence-based investment priorities.

Keywords: urban sustainability, urban infrastructure, panel data, correlation analysis, management levers, municipal policy.

У статті представлено та науково обґрунтовано комплексну методику емпіричного аналізу детермінант сталості міської інфраструктури в умовах сучасних викликів глобальної урбанізації та кліматичних змін. Авторами розроблено дев'ятиетапний алгоритм дослідження, що базується на поєднанні методів системного підходу, економіко-статистичного аналізу та економетричного моделювання панельних даних. До аналізу залучено сім європейських міст, а саме Стокгольм, Гельсінкі, Цюрих, Мілан, Прага, Брюссель та Київ. Сформовано унікальну панель даних, що охоплює 56 показників міської інфраструктури, структурованих за одинадцятьма функціональними компонентами: транспортна мережа, екологічний стан, територіальний розвиток, житлова інфраструктура, охорона здоров'я, громадська безпека, поводження з відходами, водозабезпечення, енергоефективність, освіта та фінансовий потенціал міста. Емпіричну базу дослідження складають дані за період 2015–2020 років, що формує збалансовану панель із 42 спостережень. Центральне місце в методиці займає процедура статистичної фільтрації детермінант. На основі розрахунку коефіцієнтів парної лінійної кореляції Пірсона та перевірки їх значущості за допомогою t-критерію Стьюдента та p-value проведено відбір факторів, що мають найбільш суттєвий вплив на інтегральний рівень урбаністичної сталості. Це дозволило виключити статистично незначущі параметри та зосередити увагу на ключових драйверах розвитку сталої інфраструктури урбанізованих територій. Наукова новизна запропонованого підходу полягає у переході від статичного ранжування міст до динамічного аналізу причинно-наслідкових зв'язків детермінант їхнього розвитку. Завершальний етап методології передбачає розробку 12 управлінських важелів міської політики, ранжованих за пріоритетністю. Систематизація цих важелів забезпечує підґрунтя для формування інвестиційних пріоритетів для міської влади. Практична цінність дослідження полягає у створенні доказової бази для обґрунтування проєктів сталого розвитку та заявок на міжнародне фінансування.

Ключові слова: урбаністична сталість, міська інфраструктура, панельні дані, кореляційний аналіз, управлінські важелі, муніципальна політика.

Statement of the problem. In the modern era of rapid urbanization and intensifying global environmental challenges, the concept of sustainable development has transitioned from a theoretical ideal to an urgent necessity for municipal governance. Cities today consume over 75% of global primary energy and are responsible for approximately 50-60% of global greenhouse gas emissions [1]. Within this context, urban infrastructure – comprising transport, energy, water, waste management systems etc. – acts as the primary determinant of a city's ability to balance economic growth with environmental preservation and social well-being.

However, a significant gap remains between the high-level goals of international sustainability agendas and the practical tools available to city managers. Most existing evaluation frameworks, such as international city rankings, provide a "static" snapshot of a city's performance. These rankings often fail to account for the dynamic, causal relationships between specific infrastructure investments and long-term sustainability outcomes. Furthermore, for cities like Kyiv, there is a lack of rigorous empirical benchmarking against recognized global sustainability leaders. This leads to a situation where municipal authorities often prioritize projects based on expert intuition or political urgency rather than data-driven evidence.

The problem, therefore, lies in the absence of a standardized empirical methodology that can translate vast amounts of urban infrastructure data into a clear hierarchy of sustainability determinants. Without such a methodology, it is impossible to identify which infrastructure "levers" are most effective for improving a city's sustainability index, leading to inefficient resource allocation and missed opportunities for systemic urban transformation.

Analysis of recent research and publications. Recent empirical studies on urban infrastructure sustainability in European cities demonstrate a highly diverse methodological landscape. A review of contemporary literature shows that researchers predominantly rely on specific analytical frameworks, such as integrated modeling, multi-criteria decision-making (MCDM), and indicator-based assessments, to evaluate various dimensions of the urban environment.

Many researchers focus on the sustainability of urban transport networks. Zito et al. developed a normalized transport sustainability index, successfully applying an indicator-based approach to compare urban transport sustainability across Europe [2]. Building on this, Alonso et al. conducted a comparative analysis of passenger transport sustainability using a rigorous benchmarking approach to evaluate efficiency and environmental impact [3]. More recently, reflecting the shift towards green mobility, Menendez Agudin et al. evaluated electric vehicle charging infrastructure [4]. By utilizing a KPI-based assessment combined with k-means clustering, their research classified cities' performance and identified critical infrastructure gaps hindering the spread of electric cars.

The evaluation of core environmental utilities and ecological zones is another critical research vector. Nijkamp et al. utilized meta-analysis alongside probit and rough set analysis to evaluate the impact of renewable energy initiatives on sustainable city performance, establishing early empirical links between energy policies and urban sustainability [5]. Rodrigues et al. expanded on utility management by focusing on environmental sustainability rankings concerning energy, water, and waste [6]. Through exploratory factor and principal component analysis (PCA), they identified the underlying statistical structures driving utility efficiency.

Several scholars have attempted to capture the holistic economic and social performance of cities. Spiekermann et al. applied integrated modeling (combining land use, transport, and environmental models) alongside MCDM and cost-benefit analysis to assess long-term urban strategies and their sustainability effects [7]. Stanković et al. evaluated smart city performance across economic, social, and environmental dimensions using classical MCDM techniques [8]. Advancing the complexity of these financial evaluations, Özekenci recently assessed economic performance and fiscal sustainability through a highly advanced MCDM framework aiming to eliminate subjective weighting biases [9].

Highlighting previously unresolved parts of the overall problem. While the aforementioned authors have made significant contributions to understanding specific sustainability vectors (e.g., transport clusters, ecological zones, or smart city indices), a methodological gap persists. Current international sustainability frameworks often fail to provide a sufficiently deep assessment of the technical and functional state of municipal infrastructure. Also, there is a pervasive lack of structured decision-making frameworks within municipal authorities. This methodological deficiency leads to fragmented policy-making and inefficient resource distribution. Consequently, cities often miss vital opportunities to synchronize critical infrastructure upgrades with broader urban development goals, leaving systems disjointed and under-optimized.

Formation of the objectives of the article. The purpose of this scientific article is to bridge the gap between theoretical urban sustainability concepts and practical municipal management. The study aims to construct a nine-stage empirical methodology based on multi-year panel data from European cities, designed to mathematically identify key infrastructure determinants. The ultimate objective is to provide city administrations with a scientifically validated toolkit of management levers and KPIs for optimizing sustainable urban infrastructure development.

Summary of the main research material. To achieve the stated objective and bridge the gap between theoretical concepts and practical municipal management, a comprehensive nine-stage empirical methodology was developed and implemented (Fig. 1). This framework systematically transitions from raw data collection to the formulation of actionable municipal policies.

Stage 1. Formation of the research sample. The empirical analysis is based on a targeted sample of seven European cities: Stockholm, Helsinki, Zurich, Milan, Prague, Brussels, and Kyiv. The selection was guided by dual criteria: systematic representation in prominent international sustainability rankings (e.g., IESE Cities in Motion Index, European Green City Index) and baseline demographic comparability. Crucially, the inclusion of Kyiv facilitates the benchmarking of an Eastern European transitional urban economy against recognized global sustainability leaders. To neutralize Kyiv's territorial anomaly (835.6 km² compared to the ~100–300 km² average of the other sample cities), the methodology strictly utilizes specific indicators (e.g., per capita or per square kilometer) and panel data models with fixed effects to control for unobserved heterogeneity.

Stage 2. Operationalization of indicators. To comprehensively capture the multidimensional nature of urban sustainability, a highly granular indicator framework was constructed. It encompasses 56 specific infrastructure metrics structured into 11 functional components: transport networks, environmental state, territorial development, housing infrastructure, healthcare, public safety, waste management, water supply, energy efficiency, education, and municipal financial potential.

The dependent variable utilized in this study – the Integral Sustainability Score – was constructed by aggregating nine authoritative international urban indices: the IESE Cities in Motion Index, Mercer Quality of Living City Ranking, The Global Liveability Index, Global Power City Index, Smart City Index, City Ranking – Infrastructure, The World's Best Cities, Sustainable Cities Index, and the European Green City Index. To ensure a comprehensive and unbiased evaluation of

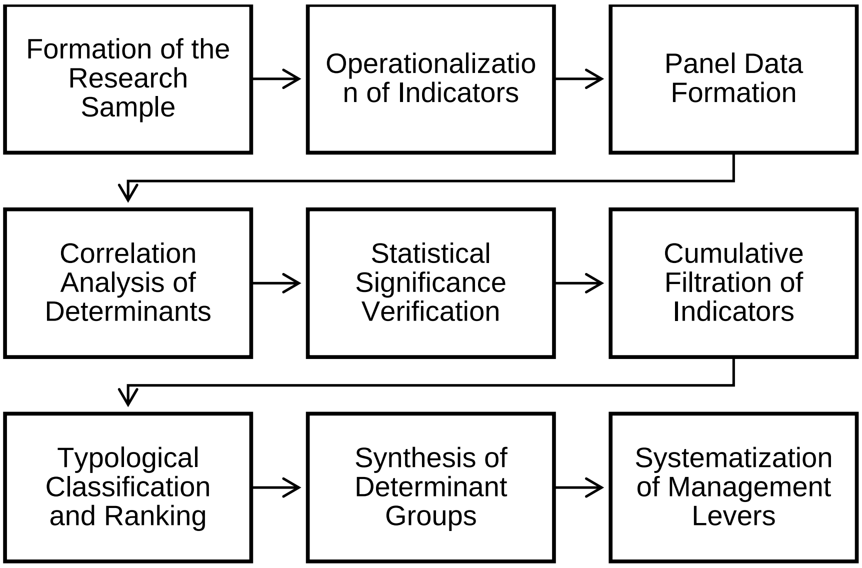

Figure 1. Methodology of empirical analysis of urban infrastructure sustainability determinants

Source: formed by the authors

each city's developmental level, the indicator was derived by calculating the arithmetic mean of these standardized indices.

Crucially, data reversal transformation was applied to the raw ranking data. In the original indices, a rank of 1 represents the superior position; however, to facilitate a standardized and intuitive interpretation of the statistical analysis, these ranks were mathematically inverted. This inversion ensures that a higher numerical *Score* consistently represents a superior sustainability position.

Stage 3. Panel data formation. Moving beyond traditional static assessments, a balanced panel data set was constructed to capture dynamic developmental trends. The empirical base spans a continuous six-year period (2015–2020) across the 7 cities, yielding a robust sample of $n=42$ observations ($N=7, T=6$). This temporal depth is essential for identifying sustained infrastructural impacts rather than temporary fluctuations.

The selection of the six-year chronological framework (2015–2020) for the panel data is primarily dictated by the fundamental necessity to ensure the high validity, reliability, and comparability of the statistical observations. This specific timeframe was deliberately chosen to capture a period of standard, uninterrupted urban development, thereby avoiding severe structural breaks in the time series caused by recent global and regional macroeconomic shocks.

Specifically, the restriction of the timeline to the year 2020 is justified by three critical factors regarding data integrity:

1. The COVID-19 pandemic anomaly. The years immediately following 2020 (2021–2022) were heavily distorted by global pandemic lockdowns. These restrictions caused unprecedented statistical anomalies in urban infrastructure usage, including drastic artificial reductions in public transport ridership, highly skewed municipal energy consumption patterns, and temporary, non-structural drops in greenhouse gas emissions [10]. Including these years would mathematically distort the long-term causal relationships between infrastructure investments and sustainability.
2. The war in Ukraine. The full-scale military invasion of Ukraine in 2022 fundamentally altered the infrastructural landscape of Kyiv. The catastrophic physical damage to energy grids, water supply networks, and transport systems renders post-2021 data entirely incomparable to the stable development trajectories of Western European cities [11].
3. Closure of statistical data. Due to the introduction of martial law, official state and municipal statistical data regarding critical infrastructure in Ukraine has been restricted or completely classified for national security reasons. Consequently, gathering a fully balanced and transparent dataset for Kyiv post-2021 is currently impossible.

Therefore, the 2015–2020 period is the most recent and robust temporal window that allows for the construction of a strictly balanced panel ($N=7, T=6$), ensuring that the benchmarking of Kyiv against European sustainability leaders remains mathematically and methodologically valid.

Stage 4. Correlation analysis of determinants. Correlation analysis is a key statistical method for investigating the stochastic dependence between random variables, allowing for the identification of the presence, direction, and strength of relationships between urban infrastructure indicators and the integral level of sustainability. Computational procedures were implemented in the MS Excel software environment utilizing the Data Analysis tool.

To measure the strength and direction of the linear statistical relationship between the independent variables (infrastructure indicators) and the dependent variable (Score – integral sustainability indicator), the Pearson pairwise linear correlation coefficient was calculated.

Stage 5. Statistical significance verification. Following the preliminary identification of linear relationships in Stage 4, a secondary, rigorous statistical filter was applied to the dataset. The primary objective of this stage was to eliminate spurious correlations relationships that appear mathematically strong but are actually the result of random sample fluctuations, and to scientifically validate the true determinants of urban sustainability.

To achieve this, the statistical significance of each calculated Pearson correlation coefficient (r) was tested using Student’s t-test. Because the coefficient *r* is calculated based on sample data, it is necessary to verify whether the identified relationship reflects a true pattern in the general population or is merely the result of random fluctuations [12].

For each calculated *t-statistic*, a two-tailed probability (*p-value*) was determined based on Student's t-distribution with $df=40$ degrees of freedom. In this study, the critical level of significance was strictly set at $\alpha=0.05$. This threshold enables the mathematically justified elimination of statistically insignificant variables.

Stage 6. Cumulative filtration of indicators. Based on the synthesis of correlation strength (r) and its statistical significance ($p<0.05$), the entire array of 55 indicators underwent a cumulative filtering procedure. Variables that failed to demonstrate a statistically significant impact (for instance, *Cars_per_1000* with $p=0.9781$) were excluded from further analytical stages.

The selection algorithm for the final analytical model dictates that an indicator receives a "YES" designation and is subsequently included in the multivariate modeling stage, only upon the simultaneous fulfillment of TWO specific criteria:

1) Correlation strength. The absolute value of the correlation coefficient must indicate at least a "moderate" relationship ($|\mathrm{r}| \geq 0.30$).

2) Statistical reliability. The calculated p-value must be strictly less than the critical significance level (p > 0,05).

This cumulative (rather than alternative) filtration protocol ensures the high quality of the variables selected. By combining requirements for both explanatory power (strength of association) and reliability (statistical evidence), the model eliminates variables that might show a high correlation purely by chance, or those that are statistically significant but too weak to serve as meaningful predictors.

Stage 7. Typological classification and ranking. Following the filtration process, the remaining 30 statistically significant indicators were subjected to a hierarchical ranking based on the absolute magnitude of their Pearson correlation coefficient ($|r|$) [13]. This classification allows for the identification of the "weight" each infrastructural element carries in determining the city's global sustainability standing.

The determinants are stratified into three priority levels:

– Level I – Strategic Determinants (*** strong/very strong correlation, $|r|\geq 0.70$). These variables represent the fundamental drivers of urban sustainability. Their high correlation suggests that changes in these indicators are almost always accompanied by significant shifts in the city's international ranking. (e.g., *GDP per inhabitant*, *Total Land Area*).

– Level II – Tactical Determinants (** moderate correlation, $0.50\leq|r|<0.70$). These are influential factors that provide a consistent and predictable impact on the urban ecosystem. They often represent the core functional outputs of municipal infrastructure. (e.g., *Volume of Treated Wastewater per person*, *Household Waste Generation*).

Level III – Operational Determinants (* weak but significant correlation, $0.30\leq|r|<0.50$). While these indicators have a lower independent mathematical weight, their statistical significance ($p<0.05$) confirms they are valid components of the sustainability framework and should not be ignored in comprehensive policy planning.

Stage 8. Synthesis of determinant groups. In Stage 8, the methodology moves beyond pure mathematics to address the practicalities of public administration. The verified determinants are grouped based on their "managerial elasticity" - the degree of control municipal authorities exert over the indicator and the speed at which policy interventions can produce measurable results.

– Group A – Structural Levers (low elasticity). Attribution criteria: strong or very strong correlation and very high statistical significance ($p < 0.001$). These are foundational macroeconomic, geographic, or demographic indicators. While they often possess the highest correlation with sustainability (Level I), they are difficult to change in the short term. Municipalities treat these as strategic constraints or long-term baseline conditions (e.g., *Life Expectancy*, *City Territory*).

– Group B – Managerial Levers (high elasticity). Attribution criteria: moderate correlation and statistical significance ($p < 0.05$). This is the primary focus of the research. These variables exhibit moderate-to-strong correlation and are highly susceptible to direct municipal regulation, investment, and administrative reform. They represent the "active tools" of urban governance (e.g., *Water Loss Reduction*, *Waste Recycling Rates*, *Energy Efficiency*).

– Group C – Auxiliary Levers (supportive elasticity). Attribution criteria: weak correlation and statistical significance ($p < 0.05$). These variables serve as secondary tools that complement the primary managerial levers. They are often used for fine-tuning specific sectoral policies, such as public transport optimization or local environmental initiatives.

– Group D – Not significant. Attribution criteria: $p \geq 0.05$, which are completely excluded from further empirical analysis due to the lack of sufficient statistical evidence of a systematic relationship in the general population.

Stage 9. Systematization of the management levers. The final stage of the methodology transforms the empirical findings into a structured policy toolkit. By synthesizing the Group B determinants, 12 specific municipal management levers were formulated (tab. 1). The systematization provides a mathematical justification for:

1. Investment Prioritization. Directing capital toward infrastructure indicators with the highest proven impact on the city’s global Score.
2. Budgetary Allocation. Providing a data-driven basis for distributing resources between competing departments (e.g., comparing the sustainability "return" on water infrastructure vs. waste management).
3. KPI Development. Establishing evidence-based Key Performance Indicators for municipal departments based on the benchmark values of sustainability leaders (e.g., Stockholm or Zurich).
4. International Funding Justification. Using empirical evidence of "cause-and-effect" to support grant applications for sustainable development projects.

By moving from raw data collection (Stage 1) through rigorous statistical verification (Stages 4–6) to the formulation of actionable levers (Stage 9), this methodology ensures that urban development strategies are not based on subjective assumptions, but on empirically proven determinants of global competitiveness and sustainability.

Conclusions. This study has developed and implemented a rigorous 9-stage empirical methodological approach to identify the fundamental determinants of urban sustainability across a panel of seven diverse European cities. By integrating data from nine authoritative international rankings into a directionally aligned Integral Sustainability Score, the research moved beyond subjective benchmarking to establish a mathematically proven "cause-and-effect" framework between infrastructure performance and global competitiveness.

The application of a cumulative filtration protocol proved to be a critical diagnostic tool, effectively distilling 55 initial indicators into a concentrated set of 30 statistically significant determinants. This process revealed that nearly half of the commonly tracked urban metrics, including variables such as *Cars per 1000 inhabitants* or *Crimes Reported*, did not possess a statistically reliable link to the integral level of sustainability within the studied sample. Conversely, the identification of Level

Table 1

Systematization of the 12 management levers for investment prioritization

Priority of the investment	Investment directions	Indicators	r	p-value	Cumulative filtration	Priority
1	Water infrastructure	1. Treated wastewater per capita, m³/person 2. Water losses in water supply networks, %	1. r = 0.689 2. r = -0.669	<0.001 <0.001	YES YES	** **
2	Energy transformation	3. Green energy of the city, GWh 4. Green energy per capita, GWh/person	3. r = 0,643 4. r = 0,629	<0.001 <0.001	YES YES	** **
3	Economic development and welfare	5. GDP of the city, million USD 6. GDP per capita, USD/person	5. r = 0.651 6. r = 0,716	<0.001 <0.001	YES YES	** ***
4	Mobility and public transport	7. Travel by public transport per capita	7. r = 0,586	<0.001	YES	**
5	Waste Management	8. Volume of household waste, tons	8. r = -0,671	<0.001	YES	**
6	Employment and Public Health	9. Unemployed people of working age, persons 10. Hospitalizations, persons	9. r = -0,580 10. r = -0,579	<0.001 <0.001	YES YES	** **
7	Safety of the urban environment	11. Road injuries per 10000 inhabitants 12. Crime per 1000 inhabitants	11. r = 0,542 12.r = 0,526	<0.001 <0.001	YES YES	** **

Source: formed by the authors

I Strategic Determinants ($|r| \geq 0.70$) highlights that foundational factors like GDP per capita and land-use efficiency remain the primary anchors of a city’s global standing.

A key contribution of this research is the transition from abstract statistical correlation to practical municipal application through the lens of managerial elasticity. By categorizing verified determinants into Structural, Managerial, and Auxiliary levers, the study provides a roadmap for urban administrators to optimize their interventions.

The findings underscore that urban sustainability is not the result of isolated successes but of a synchronized optimization of high-elasticity infrastructure, particularly in the realms of water resource management, waste circularity, and energy efficiency. For municipal governments, these results provide a mathematical justification for shifting from broad, undifferentiated infrastructure spending toward targeted investments in high-impact "Managerial Levers" that yield the greatest return on sustainability.

While this study successfully utilizes a composite average of nine established global rankings to ensure objectivity, a critical direction for future research lies in the development of a dedicated, primary-data-driven urban infrastructure index.

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