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A TAXONOMIC ANALYSIS OF SMART CITIES AND SUSTAINABLE DEVELOPMENT IN POLAND AND SELECTED EUROPEAN COUNTRIES: A DYNAMIC APPROACH

Anna JANIGA-ĆMIEL

University of Economics in Katowice; anna.janiga-cmiel@ue.katowice.pl, ORCID: 0000-0002-7668-9225

Purpose: The primary objective of this study is to conduct a taxonomic analysis of smart city implementations within the framework of sustainable development in Poland and selected European countries. By adopting a dynamic approach, the research tracks evolutionary trajectories and temporal shifts, with particular emphasis on the comparative periods preceding and following the COVID-19 pandemic.
Design/methodology/approach: This paper examines the implementation of smart city solutions and their impact on sustainable development in Poland and selected European countries, with a specific focus on the pre- and post-COVID-19 pandemic periods. The data were sourced from the Eurostat database, in accordance with the thematic scope of the study and data availability, covering the years 2017, 2020, and 2024. The analysis employs selected Multidimensional Comparative Analysis (MCA) tools to, on the one hand, establish a ranking of development levels across the surveyed nations—thereby facilitating a comparative assessment of the units—and, on the other hand, apply a clustering method to identify groups of countries characterized by homogeneous dynamic development of the phenomenon.
Findings: The study evaluates the implementation of smart city solutions within the framework of sustainable development across selected European countries, with a specific focus on the COVID-19 pandemic period. Taxonomic analysis facilitates the effective measurement of how various factors influence the trajectory of this phenomenon
Research limitations/implications: A significant limitation of this study is the lack of longitudinal, comparable statistical data spanning an extended timeframe. Nevertheless, the proposed methodology facilitates cross-national and regional comparisons and serves as a robust foundation for future scholarly inquiry.
Originality/value: The taxonomic analysis of the investigated phenomenon is applicable for benchmarking diverse spatial units—ranging from nation-states to regional and local administrations—as well as for examining various multifaceted dimensions of the issue. The findings constitute a substantial contribution to the advancement of empirical research in this field.
Keywords: taxonomic analysis, Smart City, ICT adoption, sustainable development, COVID-19 pandemic.
Category of the paper: Research paper.

1. Introduction

Contemporary nation-states and urban environments are undergoing profound technological, social, and environmental transformations. These shifts are precipitated, inter alia, by globalization, urbanization, and the increasing integration of advanced technologies into the daily functioning of society. Furthermore, rapid urban expansion, demographic shifts, the depletion of natural resources, as well as the imperative of environmental preservation and climate change mitigation, compel us to confront an array of increasingly multifaceted challenges. These developments fundamentally influence the spatial organization of cities, the provision of public services, the accessibility of innovative solutions, and the level of social well-being. A pivotal strategic response to these issues is the Smart City concept, which is gaining prominence globally, including in Poland. The information society, by leveraging Information and Communication Technologies (ICT), plays an essential role in the realization of sustainable development goals. Digital tools facilitate the efficient analysis of environmental data, support the formulation of urban management strategies, and enable the rigorous monitoring of urbanization processes.

The evolution of the Smart City concept represents a primary trajectory for the transformation of contemporary urban centers, which must address challenges associated with globalization, urbanization, and the implementation of sustainable development principles. The digitalization of public services, the deployment of the Internet of Things (IoT), energy management systems, and intelligent transportation have become integral components of modern urban infrastructure. Notable implementations include, among others, the intelligent public transport system in Warsaw and the energy management platform in Barcelona. Their significance extends beyond improving the quality of life for residents; it also encompasses enhancing economic efficiency, mitigating environmental impact, strengthening social cohesion, and increasing urban resilience to crises, such as the COVID-19 pandemic.

The implementation of smart solutions facilitates enhanced responsiveness to citizen needs and fosters social engagement. It is essential to emphasize that the Smart City encompasses not only technological advancements but also a management philosophy rooted in social dialogue, innovation, and the pursuit of harmonious development across all dimensions of urban life.

Within the European context, there is a pronounced diversity in the implementation of smart city solutions, stemming from distinct economic, institutional, and cultural conditions. Individual countries and cities exhibit various models of smart technology adoption, resulting in disparities in digital infrastructure maturity, the quality of public services, and the degree of civic involvement. Poland, mirroring other nations in the Central and Eastern European region, is currently undergoing an intensive search for smart technology implementation models that support urban modernization while addressing the specific needs of local communities.

The integration of smart city solutions enables efficient resource management, the reduction of the anthropogenic impact on the environment, and the promotion of civic activity, which concurrently enhances urban competitiveness and attractiveness. A significant challenge remains the provision of equitable access to modern technologies for all social groups and the elimination of both infrastructural and social barriers (Bibri, Krogstie, 2017; Komninos, 2013; Makowski, Kidyba, 2018; Stawasz, Sikora-Fernandez, 2016; Szewczyk, 2020). A society that leverages technological resources while concurrently pursuing harmonious development—underpinned by ecological, social, and economic values—constitutes a cornerstone of contemporary urban policy. Consequently, the successful implementation of smart city solutions in Poland and other European nations is contingent upon a multitude of factors, including the degree of digitalization within public administration, the receptivity of local authorities to innovation, the engagement of the private sector, and the level of civic awareness and education. The operationalization of the smart city concept necessitates a thorough consideration of local contingencies, economic specificities, and social traditions. Such initiatives foster the development of robust, modern, and resilient urban centers capable of competing effectively in the international arena and addressing the challenges of the future. The article proposes an analysis utilizing Multidimensional Comparative Analysis (MCA) tools to, on one hand, establish a ranking of the developmental state of the investigated phenomenon, thereby facilitating a comparative analysis of the objects, and on the other hand, to apply a method for identifying clusters of homogeneous development among the studied entities.

In conclusion, it can be asserted that the urban transformation toward the smart city model represents one of the most significant trends of the 21st century. The implementation of intelligent solutions serves as a mechanism for enhancing the quality of life and remains a fundamental prerequisite for sustainable development. Furthermore, the COVID-19 pandemic accelerated the digitalization of urban services and shifted urban development priorities. The pre- and post-pandemic periods are critical for analyzing transformations in the adoption of smart city technologies.

This paper proposes a taxonomic analysis of smart city implementations against the backdrop of sustainable development in Poland and selected European countries, adopting a dynamic approach that accounts for the periods before and after the COVID-19 pandemic.

This framework enables, inter alia, an assessment of urban development levels and the formulation of future research trajectories and urban policy recommendations. The proposed comparative analysis encompasses multiple countries and employs a dynamic approach to track the evolution of the phenomenon over time. It presents a study that evaluates smart city initiatives and sustainable development through taxonomic instruments, while accounting for the structural changes induced by the COVID-19 pandemic.

The study consists of an introduction to the subject matter, an overview of the research methods employed, the presentation and discussion of empirical results, and the conclusions.

2. Methodology

2.1. Linear ordering method for the analyzed phenomenon

The selection of an appropriate methodology is contingent upon the nature of the data, the objectives of the analysis, and the required interpretability of the findings. In the field of smart cities and sustainable development, taxonomic methods facilitate not only the classification of countries based on their level of smart city implementation but also the identification of leaders and laggards. This identification provides a robust foundation for subsequent causal analyses and the formulation of policy recommendations. This study proposes the application of a taxonomic approach designed for the linear ordering of spatial units (entities). To rank these entities, a relative synthetic development index was employed, calculated according to the following formula (Pociecha, Podolec et al., 1988):

$$W_i = \frac{\sum_{j=1}^{k} z_{ij}}{\sum_{j=1}^{k} \max_i \{z_{ij}\}} \tag{1}$$

where:

$$z_{ij} = x_{ij}^* + \left| \min_i \{x_{ij}^*\} \right| \tag{2}$$

where x_{ij}^* - standardised variable.

The index assumes values within the interval [0, 1], where values approaching unity indicate a superior performance of the entity regarding the analyzed dimension (Pociecha et al., 1988). The application of this index facilitates a comparative assessment of development levels across entities, based on heterogeneous sets of diagnostic variables.

2.2. The centroid method

Numerical taxonomy, a branch of multivariate statistics, provides robust analytical tools for the simultaneous classification of entities based on multiple characteristics. This approach facilitates the formation of homogeneous clusters characterized by similar profiles (Pociecha et al., 1988). The specific hierarchical procedure employed in this study is an agglomerative technique, namely the centroid method (also referred to as the center of gravity method). The methodology commences with the derivation of a distance matrix. Initially, individual entities are treated as separate clusters; subsequently, clusters are merged based on the proximity of their centers of gravity. The cluster representative is the centroid, defined as the vector of mean values for all diagnostic features of the entities within that cluster. The merging criterion is typically the minimization of the distance between centroids, which is most frequently calculated using the Euclidean distance.

3. Data characteristics and source material

The smart city concept and sustainable development encompass a broad spectrum of diverse thematic dimensions. Due to the constraints regarding the availability of comprehensive statistical data, the empirical scope of this study was narrowed to three selected thematic groups. The analysis utilizes a final set of diagnostic variables covering the years 2017, 2020, and 2024, with a particular focus on the impact of the COVID-19 pandemic. The research data were sourced from the Eurostat database, ensuring that the selected indicators align with both the thematic framework and data availability requirements.

The diagnostic variables adopted for this study are measurable and provide a robust representation of the analyzed phenomenon. The final selection of diagnostic features was determined based on the calculated coefficients of variation and a formal verification through correlation analysis, utilizing the inverse correlation matrix (Chomątowski, Sokołowski, 1978; Grabiński et al., 1980; Janiga-Ćmiel, 2023, 2025; Malina, 2008; Młodak, 2006; Nowak, 1990; Panek, 2009; Pociecha et al., 1988; Strahl, 1990; Zeliaś, 2004). The study encompasses 25 European countries, categorized into the following thematic domains:

Thematic Domain I: Selected elements of ICT infrastructure:

X1 – Broadband internet coverage by technology [%].

X2 – Mobile broadband internet traffic (within the country) [%].

X3 – Level of internet access – households [%].

X4 – Number of individuals – frequency of internet use.

Thematic Domain II: Selected aspects of the quality of life:

Y1 – Gross domestic product (GDP) and main components (output, expenditure and income).

Y2 – Self-perceived health by sex, age and degree of urbanisation [%].

Y3 – Number of population change - Demographic balance and crude rates at national level.

Y4 – Self-reported unmet needs for medical examination by sex, age, main reason declared and degree of urbanisation.

Thematic Domain III: Investment areas in smart mobility and sustainability:

Z1 – Number of new zero-emission vehicles by type of vehicle and type of motor Energy.

Z2 – International trade in ICT goods.

Z3 – Share of energy from renewable sources [%].

Z4 – Number of climate related economic losses by type of event.

In the subsequent stage of the analysis, the variables will undergo standardisation to facilitate the derivation of a linear ordering of the countries regarding the investigated phenomenon.

4. Empirical results and discussion

4.1. Linear ordering within the three selected thematic domains

Utilizing the methodology delineated in Chapter 2, a ranking of the studied countries was established across three thematic domains. The results pertaining to the first domain—comprising selected elements of ICT infrastructure in European countries for the years 2017, 2021, and 2024—are summarized in Table 1.

Table 1.
Linear ordering of selected ICT infrastructure elements in European countries (2017, 2021, 2024).

2024	W	2020	W	2017	W
Netherlands	1	France	1	France	1
Spain	0.913	Spain	0.934	Germany	0.761
Denmark	0.890	Italy	0.910	Italy	0.707
Luxembourg	0.871	Netherlands	0.878	Finland	0.645
Italy	0.798	Germany	0.875	Poland	0.641
France	0.796	Luxembourg	0.856	Spain	0.568
Sweden	0.760	Denmark	0.853	Sweden	0.563
Austria	0.750	Finland	0.844	Austria	0.556
Finland	0.731	Austria	0.832	Netherlands	0.521
Malta	0.719	Poland	0.779	Denmark	0.510
Poland	0.718	Sweden	0.743	Luxembourg	0.366
Belgium	0.716	Cyprus	0.677	Belgium	0.359
Germany	0.716	Belgium	0.631	Estonia	0.311
Cyprus	0.708	Slovenia	0.547	Cyprus	0.297
Hungary	0.682	Hungary	0.542	Czechia	0.279
Romania	0.673	Estonia	0.524	Hungary	0.270
Czechia	0.607	Malta	0.501	Slovenia	0.270
Slovenia	0.551	Czechia	0.484	Romania	0.269
Estonia	0.526	Romania	0.482	Malta	0.262
Latvia	0.508	Latvia	0.448	Latvia	0.249
Portugal	0.375	Slovakia	0.441	Lithuania	0.205
Bulgaria	0.370	Lithuania	0.374	Croatia	0.199
Slovakia	0.313	Croatia	0.324	Slovakia	0.199
Lithuania	0.292	Portugal	0.322	Portugal	0.169
Croatia	0.194	Bulgaria	0.149	Bulgaria	0.086

Source: based on own research (https://ec.europa.eu/eurostat).

The linear ordering presented in Table 1 for the first thematic domain (2017, 2020, 2024) reveals significant disparities in digital development across the surveyed nations. These findings are intrinsically linked to the attainment of Sustainable Development Goals (SDGs), particularly those concerning resilient infrastructure and fostered innovation. Countries that have consistently prioritized ICT investment—most notably the Netherlands, France, Denmark, Luxembourg, and Germany—maintain superior positions. This reflects sustained efforts in digitizing public services, expanding broadband connectivity, and deploying innovative technological solutions. In these nations, advanced ICT infrastructure facilitates efficient resource management, mitigates environmental degradation (e.g., through the proliferation of remote services), and enhances both the quality of life and equitable access to services across all social strata.

Conversely, several Central and Eastern European countries, including Bulgaria, Croatia, Lithuania, and Slovakia, occupy the lower echelons of the ranking, indicating a decelerated pace of innovation and constrained access to modern technologies. This divergence poses a risk of exacerbating socio-economic inequalities within Europe, potentially hindering the realization of global sustainable development objectives, specifically those regarding equal opportunity and the reduction of the digital divide.

Furthermore, the COVID-19 pandemic served as a catalyst, significantly accelerating digitalization processes post-2020. The crisis necessitated intensified investment in ICT infrastructure, resulting in a marked increase in indicator values for countries capable of rapid implementation of remote solutions in education, public administration, and commerce. While digitally advanced nations consolidated their positions through agile adaptation, those with lower baseline indicators continue to experience a developmental lag despite moderate improvements. This underscores the critical importance of long-term ICT strategic planning. Ultimately, the results suggest that while ICT infrastructure is a fundamental prerequisite for sustainable development in Europe, its uneven distribution may further entrench social and economic disparities.

The empirical findings for the second thematic domain—addressing selected aspects of the quality of life (2017, 2020, 2024)—are summarized in Table 2.

Table 2.
Linear ordering of selected quality-of-life aspects in European countries: 2017, 2021, and 2024

2024	W	2020	W	2017	W
Germany	1	Germany	1	Germany	1
France	0.822	France	0.814	France	0.811
Italy	0.708	Italy	0.717	Italy	0.727
Spain	0.588	Spain	0.572	Spain	0.566
Poland	0.442	Poland	0.455	Poland	0.462
Romania	0.233	Romania	0.236	Romania	0.241
Netherlands	0.221	Netherlands	0.215	Netherlands	0.212
Belgium	0.148	Belgium	0.144	Belgium	0.142
Czechia	0.136	Czechia	0.134	Czechia	0.133
Portugal	0.134	Portugal	0.130	Portugal	0.130
Sweden	0.132	Sweden	0.130	Sweden	0.127
Hungary	0.120	Hungary	0.122	Hungary	0.123
Austria	0.116	Austria	0.113	Austria	0.111
Bulgaria	0.083	Bulgaria	0.084	Bulgaria	0.087
Denmark	0.078	Denmark	0.076	Denmark	0.075
Finland	0.074	Finland	0.072	Finland	0.072
Slovakia	0.071	Slovakia	0.071	Slovakia	0.071
Croatia	0.053	Croatia	0.053	Croatia	0.054
Lithuania	0.041	Lithuania	0.040	Lithuania	0.040
Slovenia	0.032	Slovenia	0.031	Slovenia	0.030
Latvia	0.029	Latvia	0.029	Latvia	0.029
Estonia	0.023	Estonia	0.022	Estonia	0.021

Cont. table 2.

Cyprus	0.018	Cyprus	0.017	Cyprus	0.016
Luxembourg	0.015	Luxembourg	0.014	Luxembourg	0.013
Malta	0.014	Malta	0.012	Malta	0.011

Source: based on own research (https://ec.europa.eu/eurostat).

An analysis of the linear rankings for selected European countries regarding quality of life (2017, 2020, 2024) elucidates the factors determining national positions both preceding and following the COVID-19 pandemic. Indicators such as GDP per capita, self-perceived health status, demographic shifts, and the prevalence of unmet medical needs serve as both metrics of social well-being and integral components of sustainable development strategies.

Prior to the pandemic, economically resilient nations—most notably Germany and France—consistently occupied the top echelons of the ranking. This dominance was predicated on high GDP per capita, robust healthcare systems, and effective preventive care programs. Favorable self-assessments of health and positive demographic trends (e.g., increased life expectancy and lower emigration rates) resulted from long-term investments in health education and social infrastructure. Such outcomes align with the core principles of sustainable development: ensuring a high current quality of life while safeguarding the needs of future generations.

The COVID-19 pandemic induced profound shifts in several quality-of-life dimensions. During the 2020–2021 period, many nations experienced a decline in self-rated health and restricted access to medical services. For Central and Eastern European countries, such as Poland, Romania, and Bulgaria, the crisis exacerbated pre-existing structural challenges, including lower GDP per capita, overburdened healthcare systems, and less favorable demographic indicators. Consequently, the pandemic necessitated urgent investments in preventive healthcare, public education, and service accessibility—all of which are fundamental to achieving the Sustainable Development Goals (SDGs).

Conversely, highly developed countries that exhibited agility by integrating digital solutions into healthcare, education, and public administration either maintained or improved their standing. The efficacy of their crisis management—characterized by the rapid deployment of telemedicine and increased expenditure on preventive lifestyles—positively influenced citizen well-being. This underscores that institutional flexibility and crisis resilience are critical prerequisites for sustainable development.

The final stage of this study incorporates data from the third thematic domain, focusing on investment areas in smart mobility across European countries for the years 2017, 2020, and 2024. The results are presented in Table 3.

Table 3.
Thematic Domain III: Investment areas in smart mobility across European countries (2017, 2020, 2024)

2024	W	2020	W	2017	W
Germany	1	Germany	1	Germany	1
France	0.584	France	0.482	France	0.510
Spain	0.378	Poland	0.330	Poland	0.311
Poland	0.320	Italy	0.253	Italy	0.305
Italy	0.312	Spain	0.243	Spain	0.296
Netherlands	0.260	Sweden	0.240	Netherlands	0.226
Sweden	0.259	Netherlands	0.232	Sweden	0.212
Austria	0.162	Czechia	0.176	Slovakia	0.157
Czechia	0.158	Belgium	0.154	Czechia	0.149
Slovakia	0.152	Slovakia	0.145	Denmark	0.129
Belgium	0.145	Austria	0.122	Austria	0.123
Romania	0.116	Denmark	0.118	Belgium	0.119
Denmark	0.103	Hungary	0.112	Hungary	0.090
Hungary	0.089	Romania	0.083	Romania	0.068
Portugal	0.080	Finland	0.073	Finland	0.066
Finland	0.070	Portugal	0.058	Portugal	0.059
Lithuania	0.052	Latvia	0.039	Lithuania	0.035
Croatia	0.047	Lithuania	0.035	Latvia	0.031
Latvia	0.045	Bulgaria	0.030	Croatia	0.028
Bulgaria	0.043	Croatia	0.029	Bulgaria	0.026
Slovenia	0.031	Slovenia	0.022	Slovenia	0.024
Estonia	0.024	Estonia	0.016	Estonia	0.020
Luxembourg	0.013	Luxembourg	0.016	Luxembourg	0.015
Cyprus	0.011	Cyprus	0.007	Cyprus	0.007
Malta	0.005	Malta	0.004	Malta	0.004

Source: based on own research (https://ec.europa.eu/eurostat).

The ranking of European countries regarding smart mobility investments for the years 2017, 2020, and 2024 is determined by the interplay of four diagnostic variables: the adoption of new zero-emission vehicles, climate-related economic losses, the volume of international trade in ICT goods, and the share of renewable energy in the total energy mix. Prior to the COVID-19 pandemic, the leading positions were occupied by nations characterized by high innovation indices and proactive climate policies, most notably Germany and France. These countries prioritized the development of electric and hybrid vehicle fleets while simultaneously implementing strategies to mitigate greenhouse gas emissions and minimize potential economic losses stemming from adverse climate impacts.

In these leading nations, international trade in ICT-related goods—particularly within the modern transport technology sector—remained substantial. Furthermore, the high proportion of renewable energy in the energy mix, specifically in Scandinavian countries such as Sweden, Denmark, and Finland, provided a robust framework for smart mobility and facilitated further reductions in CO_2 emissions.

The COVID-19 pandemic necessitated a temporary reallocation of fiscal resources to address the immediate health and economic crises, which initially constrained investments in transport infrastructure and renewable energy across many European jurisdictions.

In the post-pandemic era, sustainable development has emerged as a cornerstone of national investment strategies. Countries that demonstrated agility by increasing expenditure on zero-emission vehicles, charging infrastructure, and renewable energy sources have either consolidated or enhanced their ranking positions. Effectively mitigating the economic repercussions of climate change and pursuing a sustainable energy transition have become pivotal elements in fostering socio-economic resilience.

4.2. Identification of homogeneous country clusters based on developmental levels

The initial phase of the analysis utilized Multidimensional Comparative Analysis (MCA) tools to rank European countries across selected dimensions of the smart city concept within the framework of sustainable development, accounting for the impact of the COVID-19 pandemic. The second phase involves identifying clusters of countries characterized by homogeneous development trajectories within the addressed thematic scopes. To identify groups of countries with comparable levels of the investigated phenomenon, the previously established set of diagnostic variables was employed. The classification results for the analyzed countries across selected years are presented below. Domain I: Selected Elements of ICT Infrastructure in European Countries (2017, 2021, 2024).

Cluster analysis of surveyed countries (2024):

Gr 1 = {Bulgaria}
Gr 2 = {Italy}
Gr 3 = {Poland, Latvia}
Gr 4 = {Slovakia, Portugal, Croatia, Lithuania}
Gr 5 = {Sweden}
Gr 6 = {Czechia, Estonia, Slovenia}
Gr 7 = {Denmark, Luxembourg, Netherlands, Austria}
Gr 8 = {Hungary, Malta, Romania, Germany, Spain}
Gr 9 = {Finland}
Gr 10 = {Cyprus, Belgium}
Gr 11 = {France}

Cluster analysis of surveyed countries (2020):

Gr 1 = {Bulgaria}
Gr 2= {France, Poland}
Gr 3 = {Italy}
Gr 4 = {Malta}
Gr 5 = {Latvia}
Gr 6 = {Sweden, Finland}
Gr 7 = {Czechia, Germany, Estonia, Spain, Croatia, Lithuania, Hungary, Austria, Portugal, Romania, Slovenia}
Gr 8 = {Belgium, Denmark, Cyprus, Luxembourg, Netherlands}

Cluster analysis of surveyed countries (2017):

G1 = {Sweden}

G2 = {Finland, Austria}

G3 = {Slovakia, Poland, Lithuania}

G4 = {Romania, Portugal, Italy, Croatia, Bulgaria}

G5 = {Slovenia, Hungary, Spain, Estonia, Czechia, Latvia}

G6 = {France}

G7 = {Belgium, Denmark, Germany, Luxembourg, Netherlands}

G 8 = {Cyprus, Malta}

The cluster compositions identified for the years 2017, 2020, and 2024 reflect the heterogeneous levels of ICT infrastructure development across Europe, as well as the profound impact of external catalysts, such as the COVID-19 pandemic and the strategic shift toward sustainable development. In 2024, the analysis identified several single-element clusters (including Bulgaria, Italy, Sweden, Finland, and France), which signifies idiosyncratic developmental trajectories. These nations may be characterized by unique investment strategies, varying rates of ICT implementation, or distinct levels of resilience to post-pandemic economic shifts. Conversely, the more populous clusters represent countries with comparable developmental levels and similar adaptive responses to recent challenges, such as accelerated digitalization and network infrastructure expansion. In 2020, amidst the peak of the COVID-19 pandemic, a greater number of clusters was observed. This fragmentation may be attributed to divergent national responses to the crisis and fiscal constraints; many nations were compelled to reallocate resources toward healthcare, thereby decelerating digital infrastructure projects. Simultaneously, the emergence of single-element clusters (e.g., Malta, Latvia) highlights individualized survival and adaptation strategies during the crisis. In 2017, preceding the pandemic, the clusters were generally larger and more integrated, suggesting a more synchronized pace of ICT development across Europe. During this period, technological advancement was more evenly distributed among nations. The isolation of specific countries, such as Sweden and France, underscores their preeminent position as digital leaders.

Domain II: Selected aspects of quality of life in European countries (2017, 2021, 2024)

Identified homogeneous clusters in 2024:

G1 = {Belgium, Czechia, Austria, Hungary, Portugal, Sweden}

G2 = {Estonia, Cyprus, Latvia, Lithuania, Luxembourg, Malta, Slovenia}

G2 = {Bulgaria, Denmark, Slovakia, Finland}

G3 = {Germany}

G4 = {Spain}

G5 = {Netherlands}

G6 = {France}

G7 = {Croatia}

G8 = {Poland}

G9 = {Romania}

G10 = {Italy}

Identified homogeneous clusters in 2020:

G1 = {Belgium, Sweden, Portugal, Austria, Hungary, Czechia}

G2 = {Finland, Slovakia, Denmark, Bulgaria}

G3 = {Slovenia, Malta, Luxembourg, Lithuania, Latvia, Cyprus, Estonia}

G4 = {Germany}

G5 = {Spain, Poland}

G6 = {Romania, Netherlands}

G7 = {France, Italy}

G8 = {Croatia}

Identified homogeneous clusters in 2017:

G1 = {Estonia, Cyprus, Latvia, Lithuania, Luxembourg Malta, Slovenia}

G2 = {Sweden, Portugal, Austria, Hungary, Czechia, Belgium}

G3 = {Bulgaria, Denmark Slovakia Finland}

G4 = {Poland

G5 = {Germany}

G6 = {Spain}

G7 = {Romania}

G8 = {Netherlands}

G9 = {Italy}

G10 = {France}

G11 = {Croatia}

In 2024, the analysis reveals a distinct fragmentation into numerous, often single-element clusters. This suggests a divergence in national strategies regarding quality-of-life enhancements and varying degrees of implementation for pro-ecological and digital initiatives. Countries such as Germany, France, Spain, and Italy constitute single-element clusters, indicating idiosyncratic developmental trajectories and individualized responses to the challenges of sustainable development and post-pandemic recovery. Conversely, more populous clusters, such as Cluster 1 (comprising Belgium, the Czech Republic, Austria, Hungary, Portugal, and Sweden), signify a synchronized pace of adaptation and a shared approach to implementing solutions aimed at elevating social well-being.

In 2020, amidst the acute phase of the COVID-19 pandemic, the identified clusters were more numerous and exhibited greater internal consistency regarding their developmental levels. This phenomenon was driven by the urgent necessity for rapid crisis management, which dictated standardized interventions in public health, social security, and public infrastructure investment. Simultaneously, the emergence of single-element clusters (e.g., Germany, Croatia) reflects the adoption of unique national crisis-mitigation strategies.

In 2017, preceding the pandemic, the clusters were characterized by greater size and higher levels of integration, suggesting more equitable developmental progress and narrower disparities in quality of life across the surveyed nations. The isolation of specific countries, such as Germany, France, and Italy, underscores their role as pioneers of innovative solutions for enhancing citizen well-being. The absence of pandemic-induced pressures during this period allowed for a more harmonious developmental trajectory and fostered international cooperation within the framework of sustainable development.

Domain III: Areas of investment in smart mobility in European countries (2017, 2020, 2024)

Identified homogeneous clusters for the year 2024:

G1 = {Germany}

G2 = {Spain}

G3 = {France}

G4 = {Sweden, Netherlands}

G5 = {Lithuania, Latvia, Croatia, Bulgaria}

G6 = {Poland, Italy}

G7 = {Slovakia, Austria, Belgium, Czechia}

G8 = {Finland, Portugal, Hungary}

G9 = {Romania, Denmark}

G10 = {Slovenia, Malta, Luxembourg, Cyprus, Estonia}

Received groups of uniform development for the year 2020:

G1 = {Germany

G2 = {Spain}

G3 = {France}

G4 = {Sweden, Netherlands}

G5 = {Bulgaria, Lithuania, Croatia, Latvia,

G6 = {Italy, Poland,

G7 = {Slovakia, Austria, Czechia, Belgium}

G8 = {Finland, Portugal Hungary

G9 = {Denmark, Romania}

G10 = {Estonia, Slovenia, Malta, Luxembourg, Cyprus}

Received groups of uniform development for the year 2017:

G1 = {Germany}

G2 = {France}

G3 = {Hungary}

G4 = {Malta, Cyprus}

G5 = {Austria, Belgium, Denmark}

G6 = {Finland, Romania, Portugal}

G7 = {Slovakia, Czechia}

G8 = {Bulgaria, Slovenia, Luxembourg, Lithuania, Latvia, Croatia, Estonia}

G9 = {Poland, Italy, Spain}

G10 = {Sweden, Netherlands}

The cluster compositions of nations exhibiting comparable levels of investment in smart mobility across 2017, 2020, and 2024 reflect both long-term developmental trends and the transformative impact of significant external catalysts. In 2017, preceding the COVID-19 pandemic, the analysis revealed a higher number of clusters, suggesting a more balanced rate of development and narrower disparities among the surveyed countries. During this period, the technological gap between nations was less pronounced, allowing for more integrated groupings.

In 2020, however, the clusters exhibited greater internal cohesion. This consolidation was a direct consequence of the pandemic, which necessitated rapid, synchronized responses to the public health crisis. During this phase, nations were compelled to implement standardized solutions in transportation, safety, and critical infrastructure to maintain essential mobility.

By 2024, a distinct fragmentation is observable, characterized by the emergence of smaller, frequently single-element clusters. This shift reflects divergent national strategies regarding smart mobility investments, varying degrees of technological implementation, and individualized paces of adaptation to the stringent requirements of sustainable development. This increasing heterogeneity suggests that while some nations have accelerated their green transition, others are following distinct, often non-linear, developmental trajectories in the post-pandemic landscape.

5. Conclusion

The primary objective of this study was to conduct a taxonomic analysis of smart city implementations in Poland and selected European countries, utilizing a dynamic approach to track evolutionary changes over time, with a specific focus on the pre- and post-COVID-19 pandemic periods. The research employs Multidimensional Comparative Analysis (MCA) tools to, on the one hand, establish a hierarchical ranking of the development levels—enabling a comparative assessment of the entities—and, on the other hand, apply clustering techniques to identify groups of countries characterized by homogeneous development trajectories.

A significant limitation of this research was the availability of statistical data, which dictated the selection of diagnostic variables. Given that smart city concepts and sustainable development encompass a vast array of thematic dimensions, the data scope was narrowed to three primary thematic domains for the years 2017, 2020, and 2024. This focus ensured an emphasis on the most relevant and accessible aspects of the phenomenon while allowing for a robust longitudinal comparison across the pandemic threshold.

The application of taxonomic linear ordering and clustering methods facilitated the identification of countries with similar developmental profiles, distinguishing leaders from laggards in the fields of digitalization, quality of life, and smart mobility investments. The comparative analysis reveals that the COVID-19 pandemic served as a catalyst for digital transformation, yet simultaneously widened the disparities in ICT infrastructure between high-adaptation and low-adaptation nations.

These findings allow for a nuanced analysis of the pace and specificity of technological adaptation within the context of globalization, urbanization, and environmental challenges. The proposed methodology is versatile, offering applicability not only for international comparisons but also for regional and local assessments. The study underscores the necessity of long-term investment strategies in digital infrastructure as a prerequisite for achieving Sustainable Development Goals (SDGs) and mitigating digital exclusion.

From a policy perspective, the results provide decision-makers with a tool to identify areas requiring intervention, design policies to reduce inequalities in service access, and implement solutions that enhance urban resilience to health or climate crises. For practitioners and urban experts, this research offers a framework for evaluating the efficacy of smart city initiatives and monitoring progress toward sustainability.

Despite its limitations, this study provides a significant contribution to both the theoretical and practical discourse on the future of smart cities in Europe. Future research will focus on expanding the temporal and spatial scope, including regional and municipal-level comparative analyses, while incorporating social participation and innovative governance models.

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