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volume XXIX
2026
3

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Editorial

Sustainable Cities

MONOTHEMATIC ISSUE 2026 E & M ECONOMICS AND MANAGEMENT

Sustainable Cities

Cities are increasingly expected to reconcile economic development, environmental responsibility, social inclusion, technological innovation, and resilience to climate change. Although sustainable urban development has become a central objective of international and European policy, translating ambitious strategies into practical and measurable improvements remains a persistent challenge. Rapid urbanisation, changing mobility patterns, climate-related risks, digital transformation, and growing inequalities require cities to move beyond isolated interventions and adopt integrated, evidence-based approaches.

This monothematic issue brings together interdisciplinary research that examines sustainable cities from technological, environmental, economic, institutional, and social perspectives. The contributions demonstrate that urban sustainability cannot be reduced to the deployment of smart infrastructure or the improvement of environmental indicators alone. Sustainable urban transformation also depends on governance capacity, financial institutions, universities, citizen participation, digital literacy, behavioural responses, and the ability of public authorities to translate strategic ambitions into implementation.

Several papers explore the relationship between smart-city technologies, innovation policy, and urban governance. Korzeb, Szpilko, and Di Pietro provide a bibliometric and thematic review of the role of banks in smart cities. Their analysis identifies direct, indirect, and advisory or educational activities through which financial institutions can support urban transformation. The study emphasises that banks are not merely providers of capital but may also act as strategic partners in financing innovation, supporting sustainable investment, and improving the financial literacy necessary for smart-city development.

The contribution by Volosin, Koren, and Kubak evaluates how the European Union's smart-city agenda has been translated into funded urban projects. Based on an analysis of 725 projects implemented under FP7, Horizon 2020, and Horizon Europe, the authors reveal substantial geographical and thematic concentration. Digitalisation, energy, and mobility dominate the portfolio, while governance and social participation receive comparatively less attention. Their findings highlight an important tension between excellence-oriented innovation policy and the objective of territorial cohesion, particularly for medium-sized and peripheral cities.

Urbanik, Horalek, and Otcenaskova examine similar implementation challenges from the perspective of Czech regional development strategies. Their assessment shows that smart-city principles are present across regional strategic documents, but their integration varies considerably in depth, structure, and operational clarity. The identified barriers, including conceptual fragmentation, inconsistent methodologies, limited stakeholder involvement, and gaps between strategic intentions and implementation, demonstrate that technological ambition must be supported by institutional capacity, methodological guidance, and effective coordination.

Sustainable mobility represents another central theme of this issue. Surmikova and Dzupka apply the 15-Minute City concept to university campuses and examine how universities can become active agents of proximity-based urban development. Combining walking and cycling isochrones with spatial analysis of shared micromobility, their study identifies infrastructural and behavioural barriers to sustainable campus mobility. The paper positions universities not only as educational institutions but also as major mobility generators and potential urban living laboratories capable of initiating broader changes in travel behaviour and infrastructure planning.

Perez-Pulido, Mena-Nieto, and Vides investigate bicycle-sharing demand in Seville using self-organising maps and environmental data. Their analysis reveals how precipitation and thermal comfort influence bicycle use and demonstrates the potential of artificial intelligence for operational planning and demand forecasting. By connecting mobility data with climatic conditions, the study provides a practical framework for improving the management and resilience of shared transport systems.

Aguilar-Moreno, Palos-Sanchez, Pozo-Barajas, and Duarte-Atoche focus on the digital dimension of public transport. Using natural language processing, sentiment analysis, and topic modelling, they analyse user reviews of public transport applications in major European cities. Their findings show that users prioritise intermodal integration, accessibility, real-time information, seamless payments, environmental engagement, and overall user experience. The study illustrates how citizen-generated data can support the design of more inclusive and user-oriented mobility services and confirms the growing importance of citizen participation in digital service development.

The attractiveness of sustainable cities to emerging mobile populations is explored by Palos-Sanchez, Lezcano-Calderon, Folgado-Fernandez, and Giraldez-Puig. Using machine-learning models and data from 668 destinations, the authors identify factors that influence the attractiveness of cities to digital nomads. Gender equality, entrepreneurship, safety, accommodation costs, connectivity, and social inclusion emerge as important determinants. The paper broadens the sustainable-city discussion by showing that contemporary urban competitiveness increasingly depends on the ability to combine digital infrastructure and economic opportunity with safety, affordability, and social equity.

Universities and knowledge networks also play a prominent role in sustainable regional development. Stefanikova and Fedak investigate joint study programmes developed within European university alliances and their relationship with regional innovation performance. Their findings suggest that alliances support academic integration, knowledge transfer, and cross-regional collaboration, while also connecting institutions located in regions with different levels of innovation capacity. Joint programmes may therefore serve not only as instruments of internationalisation but also as mechanisms for strengthening human capital, regional competitiveness, and territorial cohesion.

Environmental resilience is addressed by Toth, Sebova, and Saboslajova, who develop a composite index for assessing the vulnerability of Slovak cities to extreme heat. Combining climatic, land-cover, socioeconomic, and governance indicators, the study provides a systematic assessment of heat-related vulnerability across 141 cities. The proposed methodology offers an evidence base for targeted adaptation policies and demonstrates why urban climate resilience requires both environmental data and an understanding of the social and institutional conditions that shape cities' capacity to respond.

Finally, Zanabazar, Mohi Ud Din, and Hong examine the relationship between political awareness, civic engagement, digital literacy, and political participation. Their findings show that political awareness does not automatically translate into participation. Digital literacy strengthens the pathway through which informed citizens become civically engaged and politically active. This contribution underlines a fundamental dimension of sustainable urban governance: smart and sustainable cities require citizens who possess not only access to digital technologies but also the competencies necessary to use them effectively and participate meaningfully in public life.

Several common messages emerge from this collection. First, sustainable cities require integration across sectors and policy domains. Mobility, finance, climate adaptation, digitalisation, education, governance, and civic participation cannot be addressed independently. Second, data analytics, artificial intelligence, spatial modelling, and digital platforms offer powerful instruments for urban decision-making, but their effectiveness depends on institutional capacity and responsiveness to citizens' needs. Third, universities, banks, public authorities, and European networks can function as important intermediaries connecting knowledge, finance, policy, and implementation. Finally, technological advancement must be accompanied by social inclusion, territorial balance, public participation, and resilience.

Rather than presenting a single model of the sustainable city, this monothematic issue offers a multidimensional perspective on the actors, technologies, policies, and behaviours that shape urban transformation. We hope that the contributions will stimulate further interdisciplinary research and support policymakers, urban planners, researchers, financial institutions, universities, and citizens in developing cities that are not only smarter, but also more inclusive, resilient, accessible, and sustainable.

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Banks in smart cities. A bibliometric and thematic review

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Abstract: *This article aims to systematize scientific research on the role of banks in the context of the smart city concept. A bibliometric study of papers obtained from the Scopus and Web of Science databases between 2011 and 2025. Following the application of restricting criteria throughout the search procedure, 110 records were retrieved from Web of Science and 312 from the Scopus database. This study highlights the possible gaps found and provides an appraisal of the current state and future research prospects. It specifies the most referenced publications, the distribution of keywords, and the most productive authors, nations, and journals. In addition, the evolution of the role of banks in the smart city environment over the years is presented. The study identifies 5 clusters – areas of research dedicated to the topic of banking and the role of banks in a smart city. The finding suggests that research topics dedicated to the role of banks in a smart city should be focused on three main areas: direct, indirect, and advisory/educational activities.*

Keywords: *Smart cities, banks, bibliometric analysis.*

JEL Classification: *G21, O31, Q01.*

APA Style Citation: Korzeb, Z., Szpilko, D., & di Pietro, F. (2026). Banks in smart cities. A bibliometric and thematic review. *E&M Economics and Management*, *29*(3), 1–21. https://doi.org/10.15240/tul/001/2026-5-003

Early Access Publication Date: *April 8, 2026.*

Introduction

One solution for improving the quality of life of citizens is the smart city concept, which emerged in the early 1990s and has since gained considerable popularity both in practice and academia (Costales & Zeyen, 2025; Komninos & Mora, 2018). Kumar et al. (2018) define the smart city concept as: "*a city concentrating on the environmental, economic, and social aspects of urban life in a competent, convenient, and clever way for attaining the quality of life with the amalgamation of intelligent and sustainable technologies*." Although there are many different definitions of a smart city (Montes, 2020), there is no doubt that the entire concept aims to implement activities aimed at applying the principles of sustainable development in the social, economic, and environmental spheres through the use of cybersecurity technologies and innovative solutions.

It was not long before citizens recognized the advantages of smart solutions, especially in terms of: digitization of government offices, increased interactivity and efficiency of municipal infra-structure, smart communications, waste management, environmental monitoring, implementation of internet of things (IoT) networks, and the spread of digital technologies that permanently change the way we work, learn, shop, enjoy entertainment, culture and the arts, as well as participate in sports and recreation (Bjørner, 2021; Lim et al., 2024). One of the basic elements of a smart city is to ensure that banking services and products can be used in a secure way and that investment projects in such cities can be financed (Bolourforoush & Jahankhani, 2023).

The aim of this article is to systematize scientific research on the role of banks in the context of the smart city concept. The systematic literature review was based on a bibliometric analysis of articles found in Scopus and Web of Science (WoS) databases. The search was limited to materials published between 2011 and 2025. 312 records from the Scopus database and 110 from WoS were obtained after applying limiting criteria in the search process. The current state of research and possible future directions arising from the identified research gaps are analyzed in this paper. The results of our literature review suggest that future research should focus on key areas such as the role of banks in smart cities, their integration with comprehensive digital platforms, and the security of using products and services. It seems that application solutions that combine scientific research with practical implementations in these matters should overcome the concerns of smart city residents regarding the use of modern banking products and services. Furthermore, the findings suggest that the topic of research on the role of banks in a smart city should be oriented towards three main areas: direct, indirect and advisory/educational activities.

This study aims to fill a research gap in bibliometric analysis related to the lack of analogous publications in this field. The only study conducted so far (Almuraqab & Cruz, 2024) focuses only on analyzing significant existing empirical research, as well as the trends and characteristics of digital banking (e-banking, m-banking, and online/internet banking) adoption research covering the period 2009–2022. This research idea offers several key contributions to the existing literature. First of all, a comprehensive review of the existing literature is necessary due to the growing significance of smart cities as a separate field of study. Second, compared to earlier bibliometric analyses, the research is based on databases that are far more extensive, such as WoS and Scopus. This enables a comprehensive approach as well as the diagnosis and classification of current trends in the field of study. Thirdly, the publication provides reference material for researchers and professionals interested in the subject to consider.

The structure of the paper is organised as follows. Section 1 presents the conceptual background and explains how banks are incorporated into the smart city framework. Section 2 describes the adopted research methodology, including the data collection procedure, selection criteria, and analytical approach. Section 3 outlines the results of the bibliometric and qualitative thematic analyses, while section 4 discusses the main findings in the context of existing studies. The paper concludes with a final section summarising the main contributions, theoretical and practical implications, and directions for future research.

The research methodology applied in this study combines bibliometric and qualitative approaches. Bibliometric analysis was conducted using RStudio (Biblioshiny) and VOSviewer, which enabled the identification of publication dynamics, key thematic clusters, and the evolution of research trends. The qualitative analysis was based on a logical construction approach, allowing for the conceptual interpretation and categorisation of research themes identified through the bibliometric mapping.

1 Theoretical background: Banks within the smart city concept

Bibliometric methods have been used to analyze a variety of topics, including the smart city concept (Bibri & Krogstie, 2017; Gracias et al., 2023; Silva et al., 2018). However, while the topic of banking services is cited quite often in the smart city literature (Khatibi et al., 2022; Makarchenko et al., 2016; Popova & Cernisevs, 2023), the topic has been neglected in bibliometric studies to date. Meanwhile, innovations in financial products and services, such as the rapid development of mobile services, BNPL ("buy now, pay later") deferred payments, online account opening, online lending and credit, and the replacement of traditional channels of interaction with the bank in favor of conversational technologies using artificial intelligence, have radically changed the way customers communicate with banks and use core products and services. The discovered research gap in the form of diagnosing the possibility of using banks' potential in the development of a smart city seems relevant in the context of banks' widespread use of modern solutions based on AI, blockchain, big data, machine learning, cloud computing technology or adapting existing banking applications to the needs of IoT functionalities.

Banks spend more money on IT investments than other sectors (Patenge et al., 2024). Meanwhile, huge scientific, technological, IT or tele-communication advances are accompanied by the emergence of ever newer threats. It is paradoxical that modern financial systems, in spite of up-to-date IT, finance management, management accounting and controlling solutions, are more than ever vulnerable to cyber threats (Maurer & Nelson, 2021). Therefore, the main challenge facing banks in the context of a smart city is to find a rational compromise between ensuring the security of customer authentication and authorization, and the functionality and intuitiveness of the proposed solutions. The implementation of unique solutions in this area may thus become an important determinant of gaining a competitive advantage in the sector.

2 Materials and methods

The research process consisted of two main stages: quantitative and qualitative analyses. At the beginning, three research questions were defined. The first focused on identifying key authors, countries, and journals related to banking within smart cities. The second aimed at determining the thematic scope of the selected publications. The third addressed possible future research directions.

As part of the quantitative research, a bibliometric analysis was employed. Analyses were based on two internationally recognized databases: Scopus and WoS. Subsequently, appropriate keywords were selected. The search was confined to publications containing the terms "bank*" and "smart city" or "smart cities" in the title or keywords, excluding content unrelated to the subject matter. In the next step, inclusion criteria were defined. Publications from the years 2011 to 1 May 2025 were considered, encompassing various document types: articles, proceedings, books/book chapters, reviews, and editorial materials. The year 2011 was selected as the starting point. This year marked the first scholarly publications clearly connecting banking and smart cities. The final date, 1 May 2025, represented the most recent available data during the literature review. Duplicates were removed based on the publication titles and DOI numbers.

Following preliminary processing, an analysis of the results was undertaken. The assessment covered the annual number of publications, as well as the most productive authors, countries, journals, and co-citation patterns. Finally, specific research areas were identified. The most frequently appearing keywords were analysed and presented visually. This allowed for an in-depth thematic evaluation, identifying both established and emerging areas.

The qualitative stage was based on the thematic analysis of the obtained results. The findings from both stages were utilized to formulate conclusions and indicate directions for further research.

The initial search phase involved a general query using the operators "bank*" and "smart cit*" across the full text of publications (Tab. 1). At this stage, 21,032 records were retrieved from the Scopus database and 455 from WoS. Upon reviewing the results, it became clear that a significant portion of the entries were not directly related to the research topic. The use of truncation led to the inclusion of unrelated terms, such as "bankruptcy" or "smart citing". In the second search, the criteria were refined. Only those publications that included the phrases "bank" or "banks" and "smart city" or "smart cities" were considered. There were only 378 records in WoS and 13,750 in Scopus. The search was then restricted to keywords, abstracts, and titles. A more focused search produced 150 records in WoS and 393 records in Scopus. Nevertheless, it was noted that a few of the papers that were retrieved had little to do with the primary study question, specifically waste and energy. A more thorough search approach was used to improve the dataset's relevance (Tab. 1). For Scopus, the query was: *TITLE-ABS*-KEY ((bank*) AND ("smart city" OR "smart cities")) AND NOT TITLE-ABS-KEY (energy OR energies OR "energy bank*" OR "waste bank*"). For the Web of Science database, the query used was: TS = ((bank*) AND ("smart city" OR "smart cities")) NOT TS = (energy OR energies OR "energy bank*" OR "power bank*" OR "waste bank*"). These precise queries ensured thematic consistency by excluding publications unrelated to the research topic. The results' thematic coherence was much enhanced by this adjustment. 110 records were found in the WoS and 322 in the Scopus database as a result of the advanced search.

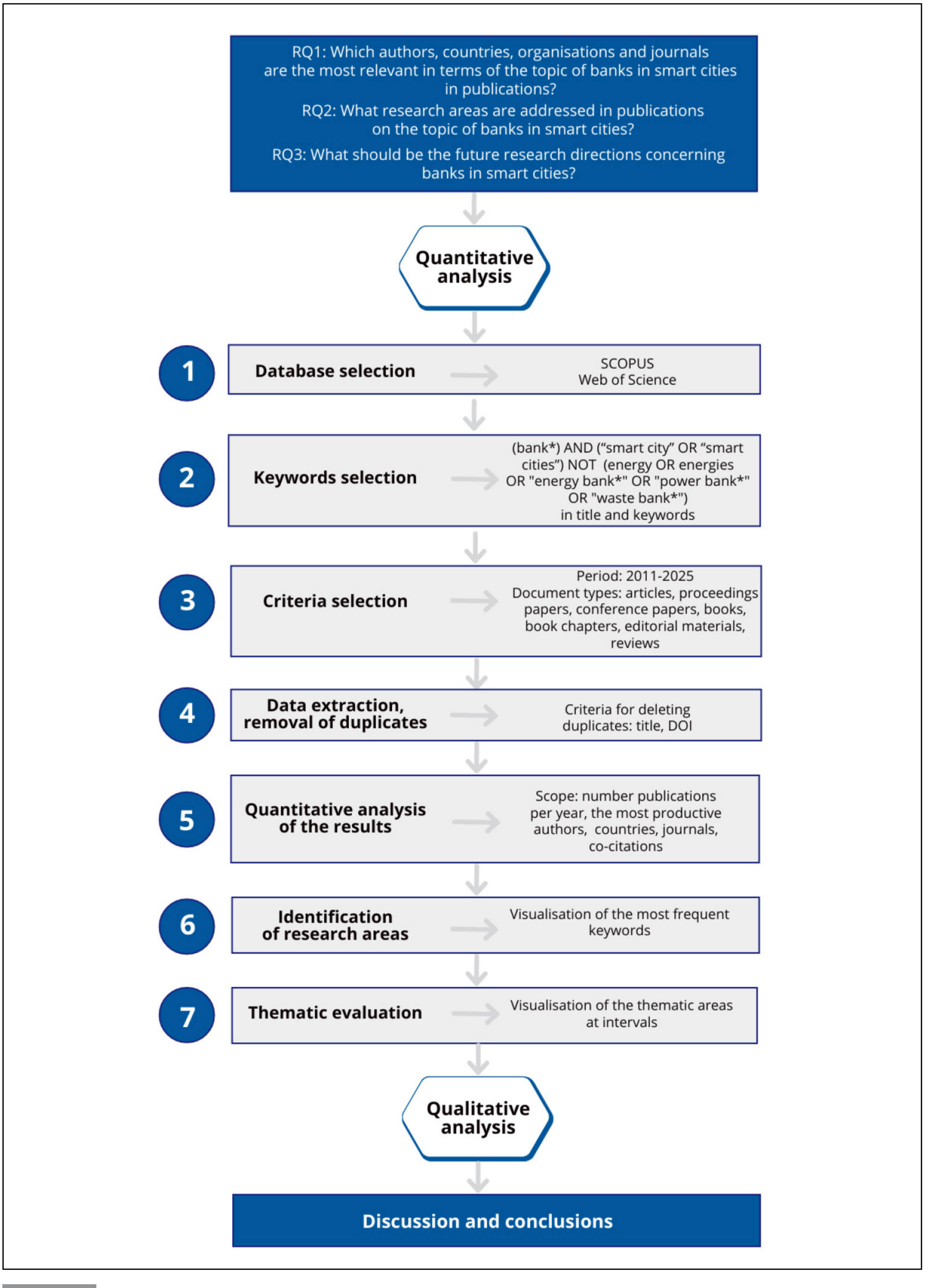

Fig. 1: **Research process**

Source: own based on Szpilko et al. (2024)

Tab. 1: Search results

Specification	Scopus	WoS
Search no. 1		
Research query	ALL (bank* AND smart cit*)	ALL= bank* AND smart cit*
Number of articles before inclusion criteria	21,032	455
Search no. 2		
Research query	ALL ((bank OR banks) AND (“smart city” OR “smart cities”))	ALL= (bank OR banks) AND (“smart city” OR “smart cities”)
Number of articles before inclusion criteria	13,750	378
Search no. 3		
Research query	TITLE-ABS-KEY ((bank*) AND (“smart city” OR “smart cities”))	TS = ((bank*) AND (“smart city” OR “smart cities”))
Number of articles before inclusion criteria	393	150
Search no. 4		
Research query	TITLE-ABS-KEY ((bank*) AND (“smart city” OR “smart cities”)) AND NOT TITLE-ABS-KEY (energy OR energies OR “energy bank*” OR “waste bank*”)	TS = ((bank*) AND (“smart city” OR “smart cities”)) NOT TS = (energy OR energies OR “energy bank*” OR “power bank*” OR “waste bank*”)
The number of publications prior to the inclusion criteria	322	110
Number of articles following inclusion criteria*	312	110
Data extraction		
Removing duplicates based on titles and DOIs	355	

Note: * inclusion criteria – period: 2011–2025; document types – articles, proceedings papers, conference papers, books, book chapters, editorial materials, reviews.

Source: own

In addition, specific inclusion criteria were applied to enhance the quality of the dataset (Tab. 1), including the publication period (2011–2025) and document types such as articles, proceedings papers, conference papers, books, book chapters, editorial materials, and reviews. After applying these criteria, the final dataset consisted of 312 records from Scopus and 110 from WoS. These refined results formed the basis for the subsequent stages of analysis.

Microsoft Office Excel 19 was used to integrate the datasets that were downloaded from the WoS and Scopus databases. Following the merger, duplicates were found and eliminated using the DOI number and title. A final dataset of 335 unique records was created for additional analysis after duplicates were eliminated (Tab. 1). The combined dataset was then subjected to a number of analyses utilizing Biblioshiny’s RStudio version 2024.12.1+563, VOSviewer version 1.6.20, and Microsoft Office Excel 19. The scope and objectives of the analyses are presented in Tab. 2.

After completing the bibliometric analysis, the research proceeded to a qualitative thematic review of the literature. This stage involved the analysis of 335 publications based

Tab. 2: Overview of objectives, methods and software used in the study

Objectives	Methods	Software
Identification of publication dynamics by year	Analysis of data from individual and merged Scopus and WoS databases	MS Office Excel 19 RStudio – version 2024.12.1+563 (Biblioshiny)
Identification of the most influential authors, countries, journals, and articles	Analysis of data from the merged Scopus and WoS databases	MS Office Excel 19 RStudio – version 2024.12.1+563 (Biblioshiny)
Detection of co-citation networks among authors and journals	Co-citation analysis	VOSviewer version 1.6.20
Mapping of international research collaborations	Analysis of bibliographic coupling; analysis of countries' cooperation	VOSviewer version 1.6.20 RStudio – version 2024.12.1+563 (Biblioshiny)
Identification of the conceptual structure based on keywords	Co-occurrence analysis of author keywords	VOSviewer version 1.6.20 RStudio – version 2024.12.1+563 (Biblioshiny)
Identification of thematic clusters	Network analysis of influential keywords	VOSviewer version 1.6.20
Examination of the thematic evolution of the research field	Thematic evolution analysis	RStudio – version 2024.12.1+563 (Biblioshiny)

Source: own based on Korzeb et al. (2024), Raamkhumar and Swamy (2024)

on abstracts and selected full-text articles. The purpose of this analysis was to uncover emerging topics and propose new avenues for future investigation. The selection of articles for in-depth analysis was guided by their thematic relevance.

3 Results

WoS indexed 110 publications and Scopus indexed 312 between 2011 and May 2025. 335 unique papers were left over from both databases after duplicates were eliminated (Fig. 2).

During the initial years (2011–2016), the volume of research remained low. A noticeable increase occurred from 2017 onwards, when the number of unique entries reached 27. From 2018 to 2024, the number of new records consistently exceeded 30 annually. The peak was recorded in 2023, with a total of 50 unique publications. This consistent rise is a reflection of researchers' increasing interest in banking in the context of smart cities.

The analysis of author productivity in the field of banking in smart cities indicates that only a small number of researchers have published more than one article. Among the most active authors are Z. Movahedi and Y. Popova, each with two publications indexed in both Scopus and WoS. Movahedi's works have received an average of 37 citations in Scopus and 6.5 in WoS, while Popova's publications have been cited an average of 19 times in Scopus and 17 times in WoS. Both authors hold an H-index of 2 in both databases.

An analysis of co-citations among authors suggests that the following researchers have the most mutual interest, as evidenced by the highest number of connections: Y. Zhang, Y. Li, J. Zhang, W. Wang, S. Wang, N. Kumar, H. Wang, and X. Zhang. Fig. 3 depicts a map of the 32 most commonly co-cited authors in the subject of banking and smart cities.

Among the journals, Lecture Notes in Networks and Systems is the most productive,

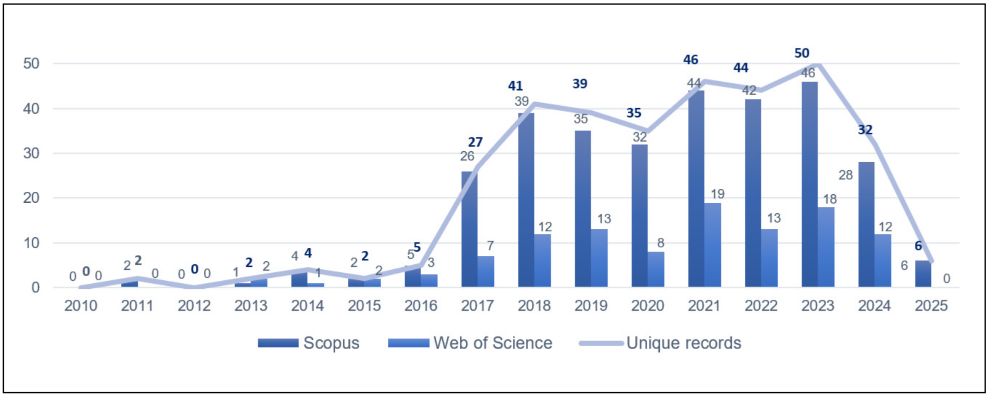

Fig. 2: Number of publications in Scopus and WoS databases

Source: own

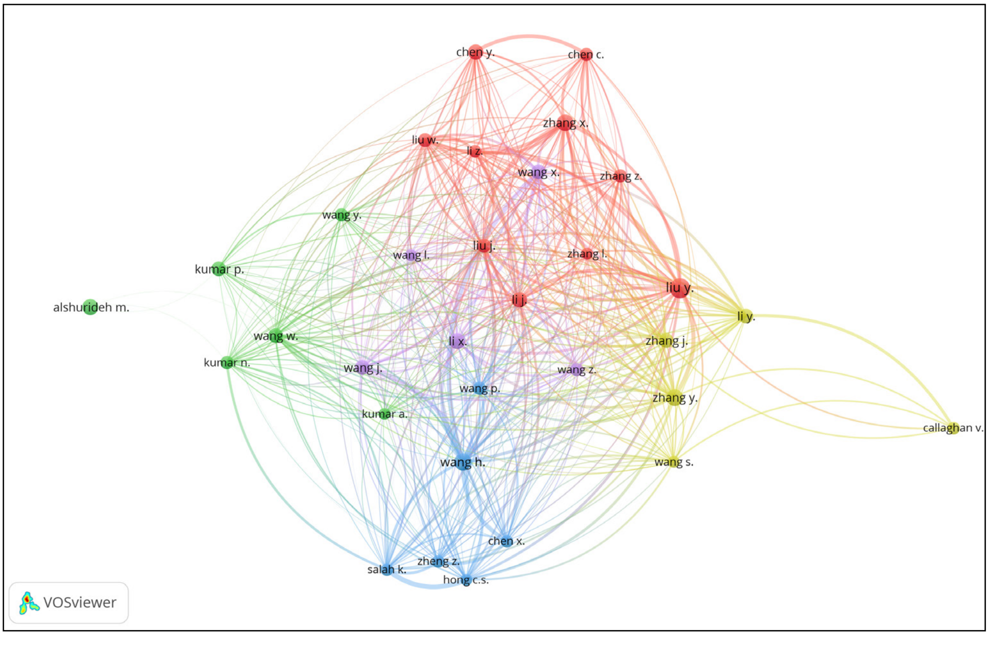

Fig. 3: Co-citation map of authors

Source: own using VOSviewer

contributing 13 publications. However, when considering average citations per article, IEEE Access stands out significantly, with 23.3 citations in Scopus and 15.8 in WoS (Tab. 3).

The journal's co-citation analysis shows that some titles are especially closely connected. The strongest links appear between IEEE Access, Sensors, IEEE Internet of Things Journal,

Tab. 3: Journals publishing the most articles

No.	Item	Number of publication	Percent of total publications (%)*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	Lecture Notes in Networks and Systems	13	3.9	0.3	0.3	1	1
2	ACM International Conference Proceeding Series	10	3.0	2.5	4.0	3	1
3	Communications in Computer and Information Science	10	3.0	1.2	3.0	2	1
4	Advances in Intelligent Systems and Computing	9	2.7	1.8	N/A	2	N/A
5	Studies in Computational Intelligence	6	1.8	6.2	1.0	3	1
6	2018 International Conference on Smart City and Emerging Technology Icscet 2018	5	1.5	16.2	N/A	4	N/A
7	Smart Innovation, Systems and Technologies	4	1.2	1.8	N/A	1	N/A
8	Matec Web of Conferences	4	1.2	3.0	N/A	2	N/A
9	IEEE Access	4	1.2	23.3	15.8	4	4

Note: * percent of total 335 publications.

Source: own

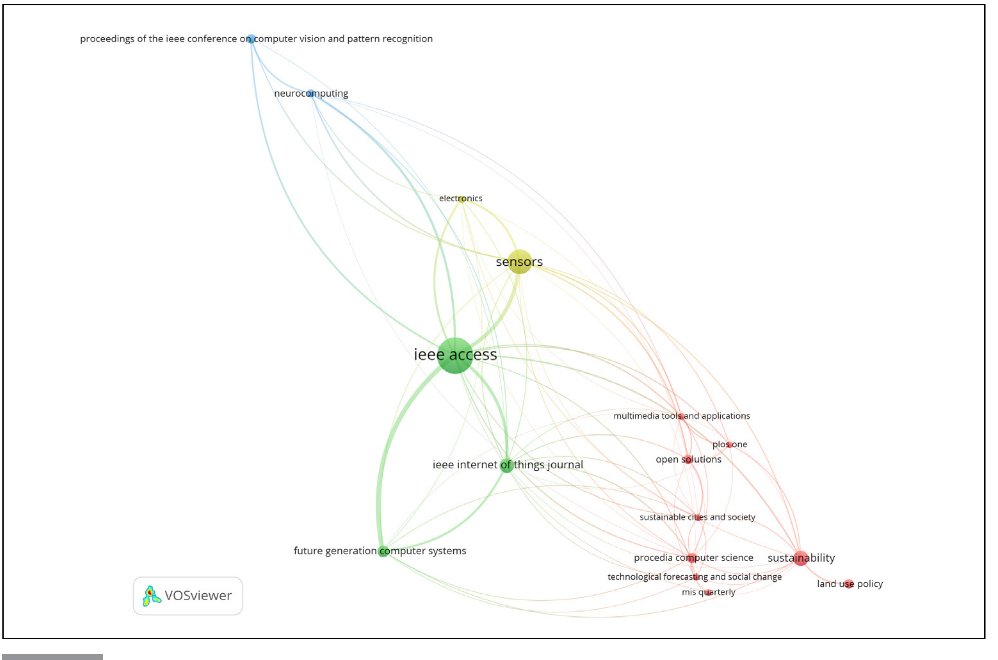

Fig. 4: Co-citation map of journals

Source: own using VOSviewer

Tab. 4: Countries producing the most publications

No.	Country	Number of publications	Percent of total publications (%)*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	India	86	25.7	8.7	14.6	15	8
2	China	46	13.7	6.0	10.4	7	6
3	United States	23	6.9	8.3	10.5	6	4
4	Saudi Arabia	17	5.1	13.9	10.4	8	6
5	United Kingdom	14	4.2	6.3	10.5	4	4
6	Russian Federation	13	3.9	20.8	46.3	4	2
7	Malaysia	10	3.0	6.3	6.2	5	3
8	United Arab Emirates	9	2.7	28.4	24.7	4	4
9	Spain	8	2.4	7.9	9.5	4	3
10	South Korea	7	2.1	51.7	49.5	6	4
11	Pakistan	7	2.1	17.1	6.0	5	3

Note: * percent of total 335 publications.

Source: own

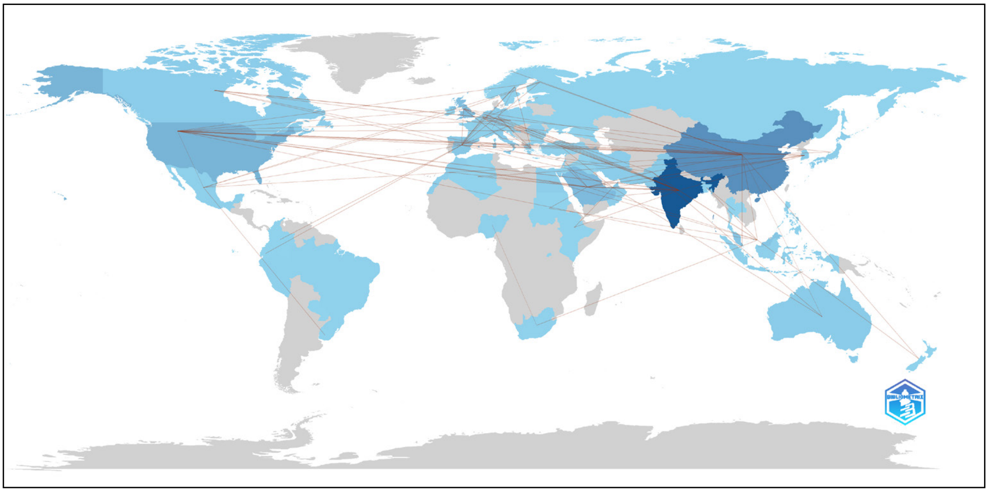

Fig. 5: Countries collaboration map

Source: own using RStudio

and Sustainability. These journals play a key role in shaping research on banks in smart cities. Fig. 4 shows a visualization of 16 most frequently co-cited journals.

Researchers from India have published the highest number of studies on banking in smart cities. Their output includes 86 papers, which accounts for 25.7% of all publications in this area. Although South Korean researchers authored only 7 publications, their work shows the highest average citation rates – 51.7 in Scopus and 49.5 in WoS (Tab. 4).

India, China, the United States, and the United Kingdom show the strongest international cooperation in research on banks in smart cities (Fig. 5).

Among the most frequently cited works in the context of banking and smart cities is the article by Majeed et al. (2021). Most of top-cited studies were published between 2018 and 2022, indicating a growing scholarly interest in the intersection of smart cities, AI, blockchain, and digital financial infrastructures (Tab. 5).

Tab. 5: The most cited articles

No.	Authors	Article title	Journal title	Number of citations	
				Scopus	WoS
1	**Majeed et al. (2021)**	Blockchain for IoT-based smart cities: Recent advances, requirements, and future challenges	Journal of Network and Computer Applications	230	136
2	**Komninos et al. (2019)**	Smart city planning from an evolutionary perspective	Journal of Urban Technology	132	98
3	**Chatterjee (2019)**	Influence of IoT policy on quality of life: From government and citizens' perspectives	International Journal of Electronic Government Research	N/A	53
4	**Li et al. (2022)**	Blockchain-based federated learning methodologies in smart environments	Cluster Computing	53	37
5	**Sedik et al. (2021)**	Deep learning modalities for biometric alteration detection in 5g networks-based secure smart cities	IEEE Access	42	27
6	**Jamil et al. (2021)**	Petroblock: A blockchain-based payment mechanism for fueling smart vehicles	Applied Sciences	41	28

Source: own

The most common keywords were found as part of the bibliometric analysis on banking in smart cities. VOSviewer software was used for the analysis. A specific thesaurus file was made and used in order to improve the dataset. This made sure that the terminology was uniform and consistent. The terms "bank", "banks", "smart city", and "smart cities" were purposefully eliminated. This made it possible to keep the emphasis on increasingly precise and complex terminology. Unrelated words were removed, and terms with comparable meanings were standardised. 56 keywords were left over when the cleaning process was finished (Fig. 6).

To identify the main research themes related to banking in smart cities, a keyword co-occurrence analysis was conducted. The analysis included terms that appeared at least five times in publications. Five major topic clusters were found as a result of the investigation (Tab. 6).

The first sub-area, encompasses research focused on the use of big data analytics to optimize financial services within smart cities (Makarchenko et al., 2016). Scholarly literature identifies advanced analytics, fintech technologies, and electronic commerce as key elements transforming traditional banking and commercial activities (Popova, 2021;

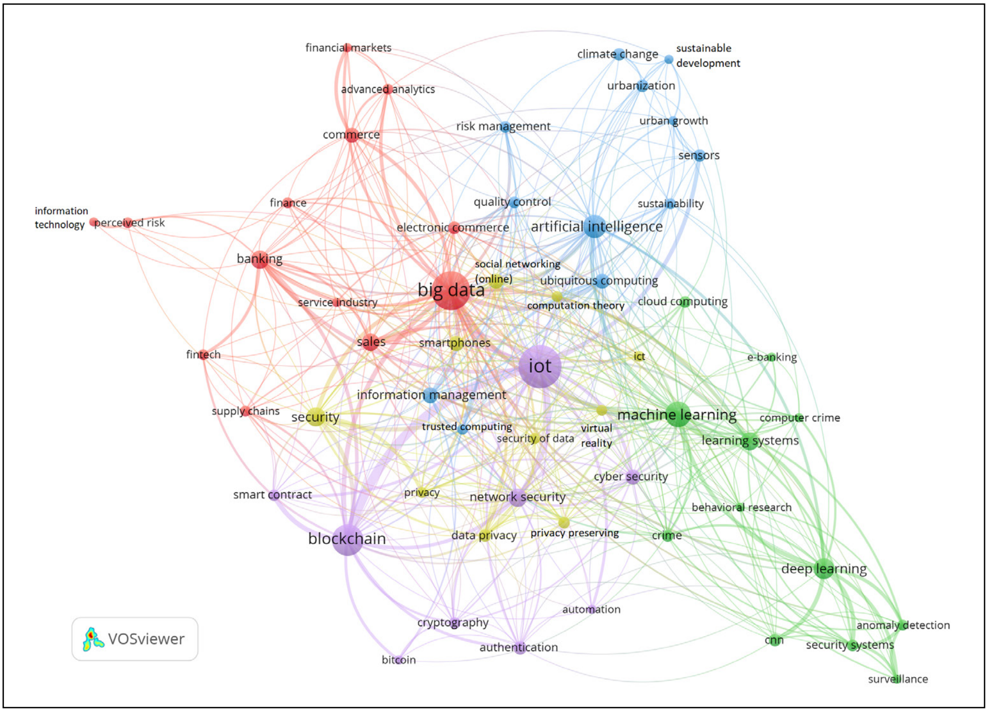

Fig. 6: Co-occurrence map of keywords

Source: own using VOSviewer

Tab. 6: Research sub-areas

No.	Sub-areas	Keywords
1	**Data-driven financial ecosystems (red)**	Big data (50); banking (14); sales (13); commerce (10); electronic commerce (8); advanced analytics (6); finance (6); fintech (6); perceived risk (6); supply chains (6); financial markets (5); information-technology (5); service industry (5)
2	**AI-based risk detection and digital banking security (green)**	Machine learning (26); deep learning (18); learning systems (14); CNN (8); cloud computing (7); crime (7); security systems (7); anomaly detection (6); behavioral research (5); computer crime (5); e-banking (5); surveillance (5)
3	**Smart infrastructure and sustainable financial management (blue)**	Artificial intelligence (22); information management (11); ubiquitous computing (10); climate change (8); sensors (8); urbanization (8); quality control (7); risk management (7); sustainability (6); trusted computing (6); sustainable development (5); urban growth (5)
4	**Privacy and human-centric digital finance security (yellow)**	Security (16); smartphones (10); social networking (online) (10); data privacy (8); privacy preserving (7); computation theory (6); ICT (6); privacy (6); security of data (6); virtual reality (6)
5	**Decentralized technologies and secure transactional frameworks (violet)**	IoT (59); blockchain (35); network security (14); cyber security (10); authentication (9); cryptography (7); smart contract (7); automation (5); bitcoin (5)

Source: own

Sabour & Al-Waeli, 2023). The studies explore perceived risks in financial markets and the strategic integration of supply chains and information technologies aimed at enhancing service efficiency and market adaptability (Popova & Cernisevs, 2023). Particular emphasis is placed on the development of advanced data infrastructures that support more agile financial management and decision-making processes in smart urban environments (Makarchenko et al., 2016; Sabour & Al-Waeli, 2023).

The second sub-area covers the application of machine and deep learning methods to strengthen the security of financial systems in digital environments (Kumar & Kumar, 2024; Sedik et al., 2021). Research investigates convolutional neural networks (CNNs), learning systems, and cloud computing as tools for anomaly detection, crime risk mitigation, and enhanced surveillance in e-banking contexts (Bolourforoush & Jahankhani, 2023; Gupta et al., 2023). These studies contribute to the prediction and prevention of cybercrime and reinforce the security frameworks of banks operating within smart cities (Maurer & Nelson, 2021; Rajendran et al., 2018).

The third thematic sub-area addresses the integration of artificial intelligence and ubiquitous computing technologies to support sustainable financial governance (Bibri & Krogstie, 2017; Kim, 2018). Research focuses on sensor-based urbanization strategies, climate change mitigation efforts, and advanced quality control processes, all of which contribute significantly to financial sustainability and urban development (Bazbauers, 2021). Furthermore, the literature highlights the importance of trusted computing practices and proactive risk management strategies as essential components of sustainable smart city governance (Kim, 2018).

The fourth sub-area explores issues related to privacy protection and security in digital financial services designed around user interaction (Barakat & Dabbous, 2019; Ruan et al., 2019). The research addresses privacy-preserving technologies, computational theory, and secure data management involving smartphones and social media platforms (Alkhammash, 2022; Dhand & Mittal, 2016; Zhang et al., 2022).

The fifth sub-area focuses on how blockchain technology and the IoT function in the

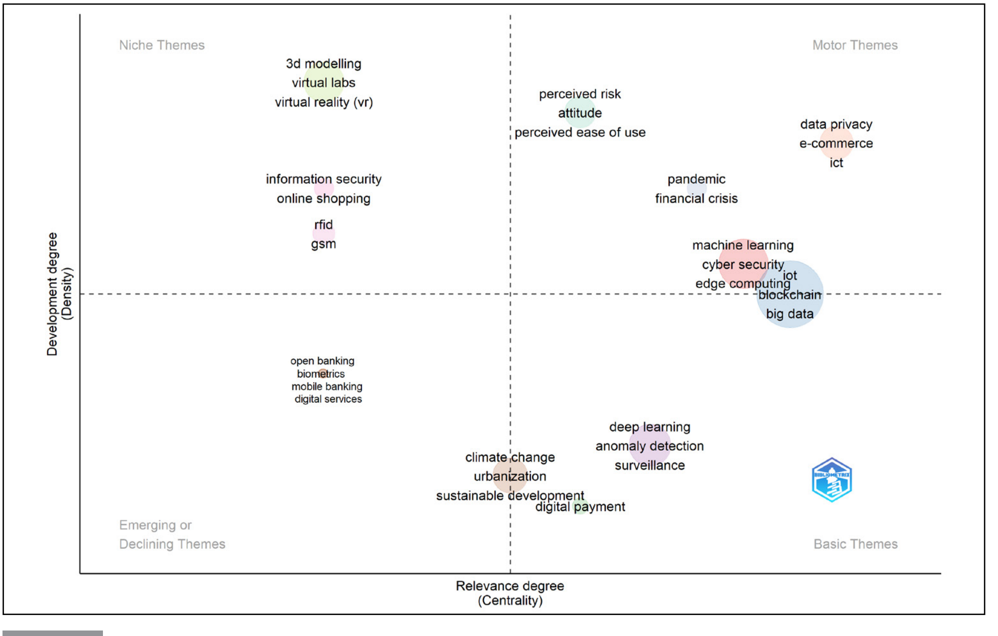

Fig. 7: Thematic map

Source: own using RStudio

framework of decentralised financial operations (Lu et al., 2019; Majeed et al., 2021). Key areas of investigation include cryptography, authentication processes, smart contracts, and network security mechanisms necessary for ensuring transactional integrity (Hertlein et al., 2018; Saini et al., 2021). Studies in this field focus on automation and cybersecurity approaches as fundamental enablers for secure cryptocurrency transactions and financial processes (Majeed et al., 2021).

As part of the conducted study, a thematic map was constructed based on two axes reflecting the degree of importance and the level of development (Fig. 7). Using RStudio software and drawing on an analysis of 335 publications, four thematic categories were identified: basic, motor, emerging or declining, and niche themes.

Emerging or declining themes were found in the lower-left quadrant. These include, among others, open banking, biometrics, mobile banking, and digital services. These topics are characterized by low centrality and density, indicating their early stage of development and currently limited role within the academic discourse. However, their relevance is expected to grow in the future.

The upper-left quadrant includes highly specialized niche themes, which show high internal coherence but relatively low influence on the overall structure of the research domain. These topics include, among others, 3D modelling, virtual labs, and virtual reality (VR). Their application in mainstream research on smart banking remains limited.

The upper-right quadrant contains motor themes. These include machine learning, cybersecurity, blockchain, big data, IoT, and edge computing. These topics are highly relevant to the analyzed domain and, although still at a moderate stage of development, play a key role in driving technological innovation in the banking sector within smart cities. The highest levels of both relevance and development are attributed to themes such as data privacy, e-commerce, and ICT. Their strong centrality and density highlight their pivotal role in current research and their function as engines propelling the evolution of scholarly discourse in the field of banking in smart urban environments.

Additionally, the central area of the map comprises context-specific and systemic themes, including urbanization, climate change, sustainable development, and digital payment. Their moderate centrality and density suggest a mature and stable status in scientific literature.

This thematic evolution in banking-related research in smart cities from 2011 to 2025 is

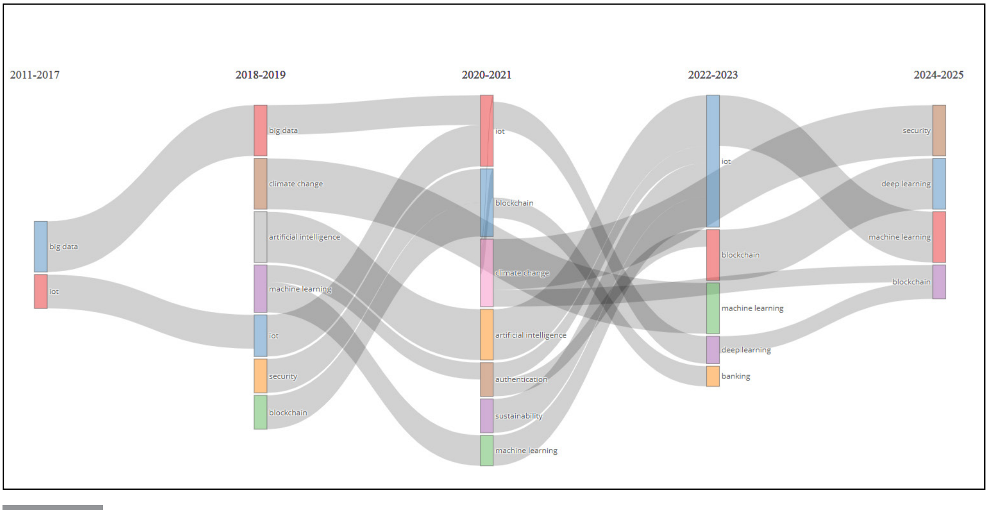

Fig. 8: **Thematic evolution**

Source: own using RStudio

graphically illustrated in the Sankey diagram presented in Fig. 8. In the first analyzed period (2011–2017), research on banking in smart cities primarily focused on "big data" and the IoT. Between 2018 and 2019, the research expanded. New thematic directions emerged, including "artificial intelligence", "climate change", "machine learning", and "security". The topic of "blockchain" was also recorded for the first time during this period, marking the early phase of integrating distributed ledger technologies into banking-related research.

Studies conducted in the years 2020–2021 were strongly oriented towards blockchain, "artificial intelligence", and "sustainability". The relevance of "climate change" and "authentication" also increased. Meanwhile, "IoT" and "machine learning" continued to hold a stable position as core themes within the scientific discourse.

The dominance of "IoT" became particularly evident during the 2022–2023 period. It was closely associated with other key topics such as "blockchain", "machine learning", and "deep learning". In 2024–2025, research efforts continued to concentrate on "machine learning", "deep learning", and "blockchain". At the same time, growing attention was directed towards the topic of "security", which reflects the intensifying challenges and demands related to cybersecurity and data protection in smart cities.

Across the entire period analyzed, a clear continuity and evolution of core themes can be observed. "IoT", "machine learning", and "blockchain" have remained consistently present in the literature. Conversely, "deep learning" and "security" represent emerging areas that respond to the contemporary needs of automation and digital security in the context of smart city banking.

4 Discussion

The conducted bibliometric study confirms the diversity of topics related to the role of banks in the smart city environment. The results of the study allow the identification of 5 clusters – areas of research dedicated to the issue of banking and the role of banks in the context of a smart city (Tab. 7).

The bibliometric analysis has shown that research dedicated to the role of banks in the context of the smart city concept is dominated by researchers representing technical scientific disciplines: computer science, telecommunications, security engineering, etc.

Tab. 7: Framework for the implementation of banking in the smart city concept – Part 1

Specification	Studies
Smart city platform	
Complex platform integrating various smart city systems	Majeed et al. (2021); Lu et al. (2019)
Smart collaborative platform to integrate multiple systems	Dbouk et al. (2014); Kirwan (2011)
Technologies for smart cities to use the banking system	Kabir et al. (2021); Semanjski et al. (2016)
Sharing services	Popova and Cernisevs (2023)
Internet of things (IoT)	Kawale et al. (2023); Nivarthi and Akhilesh (2020)
Providing access to banking products and services	
Communication with customers	Ruan et al. (2019); Dhand and Mittal (2016)
Chatbot	Barakat and Dabbous (2019); Nieto-Chaupis (2018)
Targeted marketing	Vashi et al. (2024)
Optimize the prediction of telemarketing target calls	Tékouabou Koumétio and Toulni (2021)

Tab. 7: Framework for the implementation of banking in the smart city concept – Part 2

Specification	Studies
Banking products and services	
Digital transformation of banks	Chakravaram et al. (2021); Makarchenko et al. (2016)
Smart bank accounts	Sabour and Al-Waeli (2023)
Payments	Widhyastana and Rachmawati (2022); Samouti and Fathy (2020); Rajendran et al. (2018)
Green finance	Bazbauers (2021); Kim (2018)
Exchange rates	Saini et al. (2021)
Operational activities – operation and distribution of bank facilities	
Smart branch	Zhang et al. (2022)
Optimal branch location	Hsieh et al. (2023); Hosseini et al. (2021)
Availability of banking units	Sonea et al. (2019)
Use of geospatial data	Gladilin and Levina (2020); Sharma et al. (2018)
Distribution of ATMs	Nayaz and Haq (2018)
Operational activities – human resources	
Workflow	Lu et al. (2021)
Employee recruitment	Jain et al. (2024)
Motivating employees	Dahake (2018)
Operational activities – other	
Cooperation with fintech	Popova (2021)
Security	
Basic safety rules	Kumar and Kumar (2024); Gupta et al. (2023); Alkhammash (2022)
Identification, authentication, biometrics	Bolourforoush and Jahankhani (2023); Laka et al. (2021); Sedik et al. (2021)
Electronic signature	Behera et al. (2017); Hertlein et al. (2018)
Continuity of power supply	Magesh et al. (2023)

Source: own

The vast majority of research is published at scientific conferences in these disciplines, presenting technical solutions for bank communication with customers, mobile applications or ensuring the security of banking services and products. This technological focus aligns with broader trends in smart city research, where ICT infrastructure and digital security have emerged as fundamental pillars (Bolourforoush & Jahankhani, 2023; Majeed et al., 2021). It is quite surprising that only a few articles deal with the disciplines of finance and management. This observation corroborates Almuraqab and Cruz's (2024) findings regarding the limited interdisciplinary engagement in digital banking research. It seems that this research gap should be explored more thoroughly by the representatives of the disciplines as well, e.g., in performance measurement, shareholder and stakeholder value creation, profitability, risks taken, effectiveness of banking activities in a smart city, etc.

It appears that the topic of the role of banks in the smart city should be focused on three main areas of banking activity. Firstly, on the direct influence of banks in the development of a smart city: access to products and services, ensuring the security of transactions carried out, financing smart city investment needs, etc. The significance of financial institutions in facilitating smart city infrastructure development has been increasingly recognized in recent literature (Bazbauers, 2021; Kim, 2018), particularly in relation to sustainable and climate-resilient urban projects. This is especially true for such infrastructural investments as smart communication systems, smart neighborhoods and buildings, consumption of utilities (electricity, water, heat, natural gas and others), generation of municipal waste and air pollution, creating public security maps and their surveillance, and innovative approaches towards city administration and interaction with citizens. Research by Popova and Cernisevs (2023) demonstrates how banking platforms can integrate with municipal service delivery systems to enhance urban operational efficiency.

Secondly, the role of banks should indirectly stimulate smart city activities: promoting sustainable products and services, using banking products such as mobile apps and payment cards for IoT functionalities and integrating smart city requirements into banking procedures, e.g., assessing the creditworthiness of borrowers. The integration of banking services with IoT ecosystems represents a critical convergence point, as evidenced by studies on blockchain-enabled financial systems in smart environments (Li et al., 2022; Majeed et al., 2021).

Another example is the creation of a system that, by analyzing huge amounts of customer data in real time, uses smart algorithms to make behavioral predictions and NBA (next best action) and NBO (next best offer) recommendations, tailoring product and service offers based on analysis of past customer behavior (marketing automation). Such data-driven approaches reflect the broader trend toward advanced analytics in financial ecosystems, as documented by Makarchenko et al. (2016) and Sabour and Al-Waeli (2023).

Thirdly, and perhaps most importantly, the role of banks should be to advise and educate existing and potential customers and employers. The critical importance of this educational dimension finds support in recent work examining digital service adoption barriers (Barakat & Dabbous, 2019; Chatterjee, 2019). While this is not a mandatory activity, it seems to fit perfectly with efforts to ensure the safety and availability of sustainable banking products and services in the smart city. Indeed, one of the most important barriers to creating a smart city is overcoming residents' fears of change. As Makki and Alqahtani (2024) highlight, the influence of knowledge and skills gaps as well as a lack of awareness are admittedly less important barriers than technical problems, a lack of infrastructure, and high costs, but these aspects still require attention.

Furthermore, research on privacy-preserving technologies and user-centric digital finance (Alkhammash, 2022; Ruan et al., 2019) underscores the necessity of building public trust through transparent communication and educational initiatives, particularly regarding biometric authentication and data security measures (Laka et al., 2021; Sedik et al., 2021).

The findings of this study contribute to the emerging consensus that successful smart city development requires a holistic approach to financial services integration. The identified thematic clusters – ranging from data-driven financial ecosystems to decentralized technologies – reflect the multi-dimensional nature of contemporary urban financial infrastructure (Komninos et al., 2019). The observed evolution from foundational technologies such as big data and IoT toward more sophisticated applications involving machine learning and blockchain technologies (Gupta et al., 2023; Kumar & Kumar, 2024) suggests that the banking sector is progressively adapting to the technological imperatives of smart urbanism. This adaptation, however, must be accompanied by enhanced attention to human-centric considerations, including privacy protection (Dhand & Mittal, 2016; Zhang et al., 2022) and digital literacy, to ensure inclusive and equitable access to financial services within smart city environments.

Conclusions

This bibliometric analysis of 335 publications from 2011 to 2025 reveals the rapid evolution and growing significance of research on banks' role in smart cities. The analysis identified five distinct thematic clusters ranging from "Data-driven financial ecosystems" to "Decentralized technologies and secure transactional frameworks". The thematic evolution demonstrates a clear trajectory from foundational concepts like big data and IoT toward sophisticated applications in machine learning, blockchain, and deep learning technologies, indicating the field's increasing technological sophistication.

Research to date on the role of banks in the context of the smart city concept has been dominated by scientists representing technical disciplines. Meanwhile, ensuring access to bank products and services, guaranteeing security in their use, and creating opportunities for financing infrastructure projects may prove to be critical success factors for smart cities.

For this reason, this study proposes that research on the role of banks in smart cities should focus on three main areas: direct, indirect, and advisory/educational activities. This framework provides a structured agenda for researchers in finance and management to contribute meaningfully to this vital area, while also offering a strategic lens for banking executives to assess their institutional role and identify new value-creation opportunities within the evolving smart city ecosystem. For urban policymakers, this framework can guide the development of more comprehensive strategies that leverage banking sector capabilities beyond traditional financial services. The importance of the advisory and educational function of banks, which is quite often marginalized in the current literature, should not be forgotten. The marginalization of this advisory function in the literature suggests a corresponding research gap concerning the strategic challenges of implementation, such as how bank management can develop effective awareness and communication plans for applying innovative solutions in smart city contexts.

The conducted analysis has some limitations. Most of all, the methodology's dependence on the WoS and Scopus databases. It excludes a number of additional research that would address the topic. More importantly, this study highlights a critical need for research to move beyond purely technical aspects and address the economic, managerial, and societal dimensions of banking in smart cities. The proposed framework of direct, indirect, and advisory activities offers a clear roadmap for these future investigations, particularly in measuring the performance and stakeholder value of these new banking paradigms. Future research should prioritize interdisciplinary approaches that bridge the gap between technical innovation and financial management, explore the effectiveness of banks' advisory roles in smart city development, and investigate the security and trust implications of emerging technologies like blockchain and AI in urban financial ecosystems.

From a scientific perspective, this study contributes to the growing body of literature on the interrelations between smart city development and the financial sector. This has been achieved in particular by identifying the hitherto underexplored role of banking institutions in shaping digital and sustainable urban ecosystems. The results obtained may serve as a basis for further empirical research linking financial innovations with the processes of digital transformation in cities.

From a public policy perspective, the findings emphasise the need for closer collaboration between financial institutions, technology providers and municipal authorities in order to enhance the resilience and inclusiveness of urban financial systems. The evidence suggests that urban policy frameworks should promote the integration of fintech, big data and blockchain technologies, while simultaneously ensuring the accessibility of financial services and the security of data for all city residents.

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A six-dimensional review of the EU's smart city agenda in practice

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Abstract: *European Smart City policy has become a flagship of EU innovation, yet systematic evidence on how these ambitions translate into real urban projects remains scarce. Using project metadata from the European Commission's CORDIS (Community Research and Development Information Service) repository extracted in 2025, we harmonize completed projects across FP7 (2007–2013), Horizon 2020 (2014–2020) and Horizon Europe (2021–2027) to identify 725 Smart City projects with explicit city-level targeting. Each project is coded across six thematic dimensions: digitalisation and technologies, energy and environment, mobility and transport, governance and public services, social and participatory innovation, and explicit Smart City framing; enabling a multi-dimensional view of the EU's Smart City agenda in practice. Results reveal a strong geographic and thematic concentration: a limited number of metropolitan areas (e.g., London, Barcelona, Amsterdam, Milan, and Vienna) capture a disproportionate share of both project counts and total EC funding, while medium-sized and peripheral cities remain marginal participants. The distribution of projects also varies by thematic orientation, digitalisation dominates the portfolio, followed by energy and mobility initiatives, whereas governance and social participation dimensions appear underrepresented. When normalised by funding volume, social and governance projects are notably smaller in scale and shorter in duration, suggesting that socially oriented innovation is less capital-intensive and more fragmented. These imbalances stress persistent tensions between excellence-driven concentration and cohesion-oriented inclusiveness within EU innovation policy. The findings provide an empirical baseline for evaluating how future European funding frameworks can better balance technological leadership with territorial equity in the Smart City domain.*

Keywords: *Smart cities, community research and development information service project portfolio (CORDIS), text mining, urban innovation networks, spatial concentration.*

JEL Classification: *R58, O33, O38, H54, C81.*

APA Style Citation: Volosin, P., Koren, T., & Kubak, M. (2026). A six-dimensional review of the EU's smart city agenda in practice. *E&M Economics and Management, 29*(3), 22–43. https://doi.org/10.15240/tul/001/2026-3-002

Introduction

Urban areas have become the central arenas in which the major economic, environmental, and social challenges of contemporary Europe are played out. Cities concentrate on population, economic activity, and innovation capacity, yet they are simultaneously responsible for a disproportionate share of energy consumption, greenhouse gas emissions, and social inequalities. In response to these pressures, the European Union has increasingly positioned cities at the core of its long-term development strategies, particularly through the parallel advancement of sustainable city policies and the Smart City agenda. Over the past two decades, Smart Cities have evolved from a technologically driven concept into a central policy instrument intended to support climate neutrality, resource efficiency, mobility transformation, and inclusive urban governance.

Despite the prominence of Smart Cities in EU policy discourse, significant analytical gaps remain regarding how these ambitions are translated into practice. While European strategies consistently emphasize the alignment of digitalization with sustainability objectives, empirical evidence suggests that Smart City initiatives often remain fragmented, sector-specific, or overly technology-centric. This disconnect reflects a broader challenge identified in the sustainable cities' literature: the weak integration between technological innovation, long-term environmental goals, social inclusion, and institutional capacity.

Within this context, recent EU Framework Programmes FP7, Horizon 2020, and Horizon Europe have been playing a decisive role. Through large-scale funding of research, development, and innovation projects, they not only shape technological trajectories but also define what "smartness" means in practice. Smart City projects funded under these programmes function as experimental spaces where policy objectives, technological architectures, governance models, and societal expectations intersect. However, existing research has predominantly focused either on conceptual definitions of Smart Cities or on isolated sectoral domains such as energy or mobility. Far less attention has been devoted to systematic portfolio-level analyses that examine how Smart City priorities are operationalized across thousands of EU-funded projects and how these priorities relate to concrete urban contexts.

This paper addresses this gap by providing a five-dimensional review of the EU's Smart City agenda in practice, grounded in empirical analysis of completed projects recorded in the Community Research and Development Information Service (CORDIS, 2025). The study combines policy relevance with analytical rigor, focusing on how Smart City initiatives contribute to sustainable urban development rather than treating technology adoption as an end in itself. The analysis moves beyond rhetorical commitments to sustainability and examines the actual allocation of research and innovation resources, the thematic structure of funded projects, and their spatial embedding in European cities.

The five analytical dimensions reviewed in this paper capture the core pillars through which Smart Cities are expected to support sustainability transitions: (i) technological and digital infrastructures; (ii) energy and environmental systems; (iii) mobility and transport; (iv) governance and participation; and (v) spatial and territorial embeddedness. Particular attention is paid to the distinction between generic Smart City projects and place-based initiatives explicitly targeting specific European cities, such as urban living labs and lighthouse demonstrators. This distinction is critical for understanding whether EU Smart City policy fosters territorially grounded experimentation or primarily supports transferable technological solutions detached from local contexts.

By systematically reviewing Smart City projects across multiple framework programmes and dimensions, the paper contributes to the broader debate on sustainable cities in three ways. First, it provides an evidence-based assessment of how EU Smart City funding aligns with sustainability objectives articulated in European policy frameworks. Second, it advances methodological approaches for evaluating Smart City portfolios using large-scale project data, responding directly to the call for improved analytical and evaluation tools. Third, it offers insights relevant to policymakers, urban authorities, and academic researchers concerned with the design, governance, and long-term impact of Smart City initiatives.

The remainder of the paper is structured as follows. Section 1 reviews the theoretical and policy foundations of Smart Cities and sustainable urban development. Section 2 presents the research methodology and data sources, including the identification of city-targeted Smart City projects. Section 3 discusses the empirical results across the five analytical dimensions. The final section concludes with implications for EU urban policy, research funding, and future Smart City research.

1 Theoretical background

Following lines establish the theoretical foundation of the study by reviewing key strands of the smart city literature and the main conceptual debates in the field. We then trace the conceptual evolution of smart cities from technology-centred interpretations to wider socio-technical and governance-oriented frameworks.

1.1 Conceptual evolution of smart cities

Contemporary scientific literature regarding the smart city phenomenon has undergone a fundamental evolution over the last decade. The current consensus is shifting away from early technocratic optimism, redefining the concept as a complex, multi-layered framework that integrates technological modernization with requirements for long-term sustainability and urban institutional transformation. Early syntheses in this field stressed that urban "smartness" cannot be reduced exclusively to the level of Information and Communication Technologies infrastructure. Instead, the smart city must be understood as a socio-technical urban system in which digital technologies represent only one of the necessary conditions for overall transformation (Batty et al., 2012; Chourabi et al., 2012).

However, a critical current is strengthening within the academic community, warning against the "magical" rhetoric associated with this label. Hollands (2008), in his influential work, argues that the "smart" label often functions as a marketing tool or an entrepreneurial stimulus that can, in reality, obscure deep conflicts of interest, widening social inequality, and the weakening of the democratic accountability of municipal governments. In response to these risks, the tradition of "smart sustainable cities" has come to the fore. This perspective explicitly conditions the deployment of digital solutions on their contribution to environmental goals, inclusive urban planning, and social outcomes, thereby rejecting the perception of technology as an end in itself (Bibri & Krogstie, 2017).

1.2 European trajectories and the discursive production of smartness

The European context is distinctive because smart city trajectories are primarily defined by European Union policy priorities and the specific architecture of programmatic funding. Empirical research is therefore increasingly focusing on the analysis of project portfolios funded by European Union resources and the manner in which these projects communicate their priorities to the public. As Collins et al. (2021) demonstrated through a bibliographic analysis of "public-facing" projects, the framing of priorities evolves over time but remains stably concentrated on themes of integrated energy and decarbonization.

From a critical perspective, Engelbert et al. (2019) demonstrate that "European smartness" is largely produced through discursive and grant-making mechanisms. The "smart" prefix thus becomes a prestigious attribute, an essential ticket to financial resources. This mechanism, however, can indirectly limit the space for authentic civic inclusion if projects are designed more for the needs of grant schemes than for the needs of local communities. Consequently, in the European space, the smart city becomes not only a technological project but also a tool for the strategic management of investments.

1.3 Evidence-based analysis of research, development and innovation investments

The analysis is conducted from the perspective of the Community Research and Development Information Service (CORDIS). For a deeper understanding of the real link between proclaimed policies and factual research activity, portfolio studies mapping investments in research, development, and innovation are crucial. These studies provide a bridge between political narratives and the specific scientific and technical themes actually being addressed in cities.

A significant contribution in this regard is the work of Clerici Maestosi et al. (2019), who conducted a review of European Union-funded research and development projects in the field of smart cities. Their analysis documents clear thematic concentrations and hierarchical structures of project portfolios, allowing for the localization of innovation patterns within the broader EU programmatic environment (such as Horizon 2020 or Horizon Europe). These data suggest that energy and environmental technologies dominate financial allocations, reflecting the European push for a green transition.

In the domain of mobility, Christidis et al. (2024) have moved this research to a higher level. In their study, the authors combine city-level information for 362 European cities with detailed data from the CORDIS (Community Research and Development Information Service) and TRIMIS (Transport Research and Innovation Monitoring and Information System) databases. This unique combination of data allowed the authors to link city profiles with specific activities in transport innovation. The study demonstrated that intensive involvement in transport research and innovation activities is statistically associated with city profiles showing the fastest progress toward achieving climate neutrality. This approach confirms that smart mobility is not merely an isolated layer of urban applications, but an integrated policy where investment portfolios serve as a direct indicator of a city's future capacity to decarbonize its transport system.

1.4 Technological architectures and sectoral pillars of transformation

In the technological dimension, the state-of-the-art documents a fundamental shift from isolated vertical "smart applications" toward urban data platforms. The goal is to create standardized architectures that eliminate fragmentation between individual vendors and vertical systems such as mobility, energy, and security. Hernández et al. (2020) argue that interoperability must be achieved through open specifications and layered platform design to prevent "vendor lock-in".

This trend is corroborated by Jeong et al. (2020), who use the "city data hub" to demonstrate the benefits of a standards-based platform for the interoperability of municipal services. Their findings underscore that meaningful smart city performance does not depend on the number of individual applications, but on the quality of shared data governance and technical interfaces. This "platform turn" is further reinforced by systematic reviews documenting the growing role of artificial intelligence, the internet of things, and cloud-to-edge computing. Sanchez-Gallegos et al. (2025) find that the most convincing results appear where digital infrastructure is explicitly linked to measurable city objectives, such as emissions, service quality, and equity, transforming "smartness" into an infrastructural capability of the city to respond to crises in real-time.

Smart cities are increasingly conceptualized as infrastructure for sustainability transitions (Bibri & Krogstie, 2017). Huovila et al. (2019) highlight the problem of measurement, the choice of indicators is a political act that determines whether an evaluation favours "smart implementation" or wider social impacts. Research on positive energy districts shows that success depends more on data integration and system boundaries than on the choice of technology alone (Brozovsky et al., 2021).

Managing a smart city involves redesigning collaboration and decision-making processes (Meijer & Bolívar, 2016). Bolívar and Meijer (2016) developed models that allow for the comparison of implementation strategies across cities. Tomor et al. (2021) show that identical technological ambitions can lead to different governance regimes depending on local administrative traditions. Regarding users, Wirtz et al. (2021) demonstrate that the success of digital services depends on perceived value and trustworthiness rather than mere technical availability.

The social dimension serves as a counterweight to technocratic readings. Puerari et al. (2018) state that participation in urban living labs is a process of learning and negotiation that determines whether innovations survive the pilot phase. Nevertheless, critical studies (Engelbert et al., 2019; Hollands, 2008) repeatedly warn that participation often remains merely declarative. "Participatory smartness" must therefore be subjected to rigorous empirical scrutiny regarding who is actually included in the decision-making process.

2 Research methodology

This chapter delineates the research design, data sources, and analytical workflow employed to map the EU's Smart City project portfolio. After defining the analytical scope and data provenance, we outline the key stages of data preparation and coding that support the subsequent empirical analysis.

The methodological workflow is structured to address the study's primary objective, analysing the spatial and thematic dimensions of EU-funded Smart City experimentation. This objective is operationalized through three interconnected stages: (i) project identification: delineating the empirical universe of EU-funded urban innovation to establish a precise analytical scope; (ii) territorial extraction: identifying citytargeted initiatives to examine spatial concentration patterns and placebased experimentation; and (iii) thematic classification: providing a systematic basis for assessing the substantive orientation of Smart City investments.

Each methodological step corresponds directly to a specific analytical dimension examined in the results section, ensuring a coherent alignment between the research questions, the empirical strategy, and the resulting insights.

2.1 Scope and data sources

Smart City research within EU Framework Programmes encompasses both generic, scalable urban solutions and place-based experimentation implemented in specific cities. Particularly since Horizon 2020, EU Smart City policy has emphasised urban living labs, lighthouse cities, and large-scale demonstrators as instruments for accelerating innovation diffusion and policy learning (Bibri & Krogstie, 2017; European Commission, 2026). Distinguishing between generic and city-targeted Smart City projects is therefore analytically important. Place-based initiatives enable the study of territorial concentration, urban experimentation, and cumulative advantage mechanisms at the city level, complementing organisation-centric analyses of EU research funding (Lepori et al., 2023).

Our empirical analysis is based on project-level data retrieved 2025 from the Community Research and Development Information Service (CORDIS), the official European Commission repository for EU-funded research and innovation projects. The dataset covers the last three consecutive EU Framework Programmes covering last 18 years: FP7 (2007–2013), Horizon 2020 (2014–2020), Horizon Europe (2021–2027).

To ensure longitudinal consistency and comparability across program cycles, project metadata were harmonized and merged into a unified dataset containing information on project identifiers, titles, objectives, thematic topics, keywords, funding volumes, start and end dates, and program affiliation. Only closed (completed) projects were retained for analysis. Projects were classified as completed if a valid end date was available and the project end date preceded the time of data extraction. This restriction avoids distortions related to incomplete reporting, ongoing activities, or interim thematic descriptions.

2.2 Identification of targeted smart city projects

The first analytical step consisted of funneling the full CORDIS project universe into a subset of Smart City-related projects. Given the multi-dimensional and cross-sectoral nature of Smart Cities, a text-mining-based classification strategy was adopted. Projects were classified as Smart City-related if their title, objective, thematic topics, or keywords contained one or more terms associated with urban digitalization, sustainability, mobility, and energy systems. The keyword dictionary included, inter alia: smart city, smart cities, digital city; urban, cities; urban mobility, smart mobility, urban transport; energy efficiency, smart grid; internet of things (IoT); sustainable city.

This inclusive approach reflects prevailing definitions of Smart Cities in EU policy documents and academic literature, which conceptualise Smart Cities as socio-technical systems integrating digital technologies, energy transition, mobility, and urban governance. Applying this filter to completed FP7, Horizon 2020, and Horizon Europe projects resulted in a dataset of approximately 9,000 closed Smart City projects, which forms the analytical baseline for subsequent steps. While many Smart City projects address generic or transferable urban challenges, a distinct subset explicitly targets specific European cities as pilot locations, living labs, or demonstration sites. To identify these place-based initiatives, a second filtering stage was applied.

A curated dictionary of major European cities, covering Western, Northern, Southern, Central, and Eastern Europe, was constructed based on their recurrent appearance in EU Smart City demonstrators and lighthouse city initiatives. City names were then detected through case-insensitive regular expression matching across the concatenated textual fields: project title, project objective, and thematic topics.

Projects explicitly mentioning one or more cities were classified as city-targeted Smart City projects, and a new variable “Target_Cities” was created to record the identified city or cities (semicolon-separated where multiple locations were involved). This procedure resulted in a final subset of approximately 725 Smart City projects that are explicitly place-based and territorially embedded (Fig. 1).

The merged CORDIS dataset was imported and filtered by programme (FP7, Horizon 2020, Horizon Europe) and project status (completed projects only). Non-informative entries and incomplete records were removed. Textual fields (titles, objectives, topics, keywords) were tokenized. Standard stop-words were removed, and lemmatization was applied to reduce words to their base forms and minimize linguistic

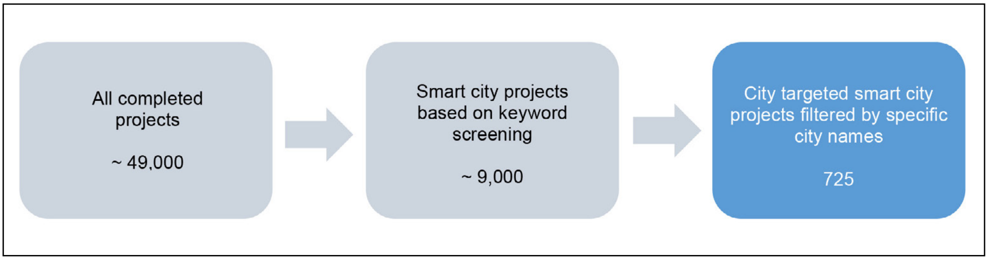

Fig. 1: Selection process for identifying city-targeted smart city projects

Source: own

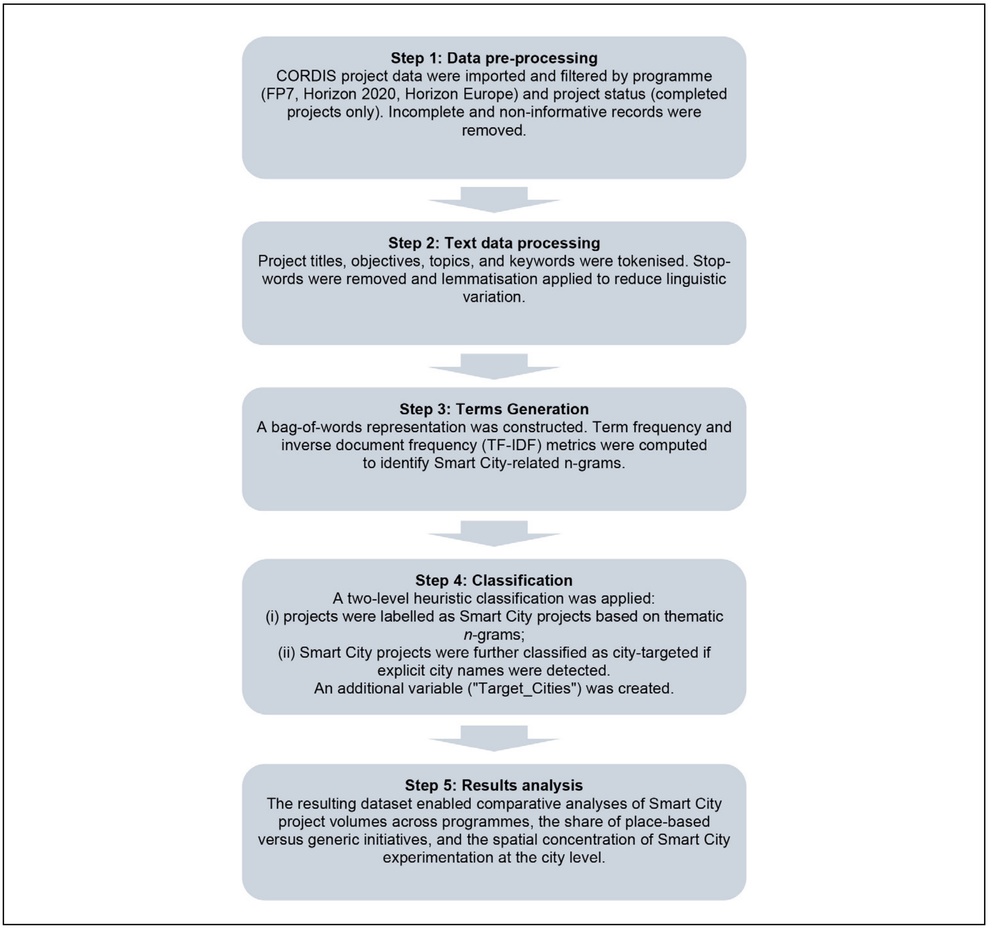

Fig. 2: Workflow for identifying city-targeted smart city projects

Source: own

variation. A bag-of-words representation was implemented. Term frequencies and inverse document frequencies (TF-IDF) were computed to identify salient *n*-grams associated with Smart City themes and urban contexts. A two-level heuristic classification was applied. First, projects were labelled as Smart City projects based on the presence of thematic *n*-grams. Second, Smart City projects were further labelled as city-targeted if explicit city names were detected in the processed text corpus. The output of this step was a structured table of labelled projects with an additional Target_Cities variable. The resulting dataset enabled descriptive and comparative analyses of: Smart City project volumes across programmes; the relative share of place-based versus generic Smart City initiatives; and spatial concentration of Smart City experimentation at the city level.

Fig. 2 illustrates the methodological workflow used to identify city-targeted Smart City projects, following a structured, multi-stage text-mining and classification process.

2.3 Thematic classification of city-targeted smart city projects

Following the identification of city-targeted Smart City projects, the next analytical step consisted of classifying these projects according to their dominant thematic orientation. The selection of the six thematic dimensions used in this classification is grounded in established conceptual frameworks within Smart City research. In particular, Giffinger et al. (2007) propose six core dimensions: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living, which together capture the multi-dimensional and sociotechnical character of Smart Cities. These dimensions have become a widely adopted reference point in both academic literature and policy practice.

This conceptual structure is further elaborated by Caragliu et al. (2011), who explicitly build on the six axes identified by Giffinger et al. (2007) and link them to broader theoretical traditions in urban and regional development. According to their interpretation, the Smart City concept draws on theories of regional competitiveness (smart economy), transport and ICT economics (smart mobility), natural resource management (smart environment), human and social capital (smart people), quality of life research (smart living), and participatory governance (smart governance). Their definition of a Smart City, accentuating investments in human and social capital, communication infrastructures, sustainable economic growth, quality of life, and participatory governance provides a coherent theoretical rationale for treating these six axes as analytically central.

Building on these two foundational frameworks, the present study operationalizes the Smart City concept through six thematic categories used in the dictionary-based text analysis. While the terminology of the categories reflects the language commonly used in EU-funded project documentation, their conceptual scope corresponds to the dimensions proposed by Giffinger et al. (2007) and theoretically grounded by Caragliu et al. (2011). This ensures that the analytical framework is theoretically anchored and systematically linked to the dominant conceptualizations of smart cities.

Six thematic categories were defined using curated keyword dictionaries:

(i) Explicit Smart City, capturing projects that explicitly frame themselves as Smart City initiatives or urban living labs;

(ii) Urban governance and public services, covering institutional, administrative, and policy-related dimensions;

(iii) Mobility and transport, reflecting projects focused on transport systems, logistics, and urban mobility solutions;

(iv) Energy and environment, encompassing energy efficiency, climate mitigation, resource management, and circular economy approaches;

(v) Digitalization, data, and technologies, capturing ICT-driven, data-centric, and platform-based urban solutions;

(vi) Social and participatory dimensions, reflecting citizen engagement, co-creation, inclusion, and community-oriented innovation.

Keyword lists for each category were constructed based on established Smart City frameworks and terminology frequently used in EU-funded project documentation. The dictionaries were refined to ensure conceptual clarity across categories.

For each project, the frequency of category-specific keywords was counted within the composite text field consisting of the project title, objectives, and keywords. This aggregation captures both strategic framing and operational focus, reduces the risk of misclassification associated with single-field analysis, and provides a measure of each project's relative thematic emphasis across the six Smart City dimensions.

To assign each project to a single primary thematic orientation, a dominant category was identified based on the highest keyword frequency across the six thematic dimensions. This category represents the project's principal thematic focus, allowing mutually exclusive classification. A mutually exclusive approach was chosen to ensure analytical clarity, comparability across cases, and unambiguous assignment in subsequent statistical analyses, where multi-label classification would introduce interpretative and methodological complexity. To evaluate the extent of thematic overlap prior to final assignment, we examined how often multiple dimensions shared the highest keyword frequency within a project. A total of 51 out of 725 projects exhibited tied maximum values across categories, indicating that a clear dominant orientation was identifiable in the majority of cases. In cases where multiple categories had equal maximum values, a heuristic tie-breaking rule was applied. This involved a careful review of the project title, keywords, and description to select the category that most accurately reflected the project's thematic focus.

Since many Smart City projects target multiple cities, they were expanded to the city level. Projects targeting more than one city were disaggregated so that each city-project pair constituted a separate observation. This procedure ensures accurate attribution of thematic project activities to individual cities and prevents undercounting cities participating in multi-site initiatives.

In addition, for projects involving multiple target cities, the variable "ecMaxContribution", representing the total financial contribution of the European Union to the project, was proportionally allocated across participating cities. Specifically, the total EU contribution was divided equally among all target cities of a given project, so that each city-project observation received an equal share of the project's funding. This approach enables consistent city-level aggregation of financial resources while avoiding artificial concentration of funding in multi-city projects.

Based on this expanded dataset, city-level summaries were constructed by aggregating city-project observations by the dominant thematic category. For each city, both the number of projects and the associated EU financial contributions were calculated for each Smart City dimension. Project participation was measured by counting city-project pairs per dominant category, while financial intensity was captured by summing the city-level shares of "ecMaxContribution" assigned to projects within each dominant category.

As a result, the resulting city-category matrices capture not only the thematic orientation of Smart City experimentation at the urban level, but also the distribution of EU funding across Smart City dimensions. These matrices form the empirical basis for subsequent spatial analyses.

The final outputs of this step include:
(i) An enriched project-level dataset containing thematic keyword counts, dominant category labels, and disaggregated city-level EU funding allocations;
(ii) A city-level dataset summarizing, for each Smart City dimension, both project participation and allocated EU financial contributions.

2.4 Methodological contribution and limitations

The applied methodology enables a transparent and replicable identification of Smart City projects within large EU Framework Programme datasets, explicitly distinguishing between generic urban innovation and territorially embedded experimentation. However, the analytical framework necessitated several heuristic decisions that influence the interpretation of the results.

First, the keyword-based identification reflects the multi-dimensional and cross-sectoral nature of Smart City discourse. While this approach captures the breadth of the field, it may over-include projects using generic urban terminology that is not strictly aligned with Smart City objectives.

Second, the city-name matching approach ensures high precision in detecting place-based initiatives, yet it presents a dual limitation:
(i) Implicit vs. explicit references: the method relies on explicit textual mentions of cities and may therefore under-represent projects that target urban areas implicitly or focus on urban themes without naming specific locations;
(ii) Geographical bias: the city dictionary prioritizes major European cities, potentially overlooking smaller municipalities involved in niche demonstrators.

Third, to enable comparability across different urban contexts, the dominant-category assignment simplifies multi-dimensional project profiles into a single thematic label. While this stresses dominant thematic orientations for the purpose of the final mapping, the underlying multidimensionality is preserved in the earlier stages of analysis to ensure data depth.

Last but not least, a critical heuristic concerns the proportional allocation of EU financial contributions across multiple target cities. Given the absence of structured city-level budget disaggregation within CORDIS metadata, total EC contribution (ecMaxContribution) was divided equally among participating cities. We acknowledge that in large-scale demonstrators, particularly Lighthouse projects, leading cities frequently receive larger shares of funding compared to follower cities. However, these internal allocations are not systematically available in machine-readable format and manual reconstruction would be non-scalable across 725 projects. The equal-split rule, therefore, represents a transparent and replicable heuristic. Importantly, this assumption likely underestimates rather than exaggerates financial concentration, because leading metropolitan hubs typically coordinate high-budget projects. Consequently, actual funding inequality may be even stronger than reported, and the results should therefore be interpreted as conservative estimates of spatial concentration. Despite these necessary heuristics, the method provides a robust empirical foundation for analysing spatial concentration, urban experimentation, and cumulative advantage dynamics in EU Smart City research and innovation policy.

Finally, all figures were designed using an accessible colour palette to ensure readability and interpretability across diverse audiences.

3 Results and discussion

Results section presents and interprets the empirical results derived from the analysis of city-targeted Smart City projects funded under FP7 and Horizon 2020. The results are structured around the spatial distribution of projects and financial resources, followed by a discussion situating these findings within the broader academic and policy literature on Smart Cities and sustainable urban development.

While Smart City projects are inherently multi-dimensional, a mutually exclusive dominant-category classification was adopted for comparative city-level aggregation. To assess overlap, we conducted a threshold-based robustness check using the six-dimensional keyword-frequency vectors. Defining "high keyword frequency" conservatively as ≥2 occurrences within a dimension, 46.3% of projects (336/725) exhibited high frequencies in more than one dimension. Among these multi-dimensional projects, 58.0% (195/336) showed clear thematic dominance, where the difference between the highest and second-highest category exceeded 20% of total keyword occurrences. As a sensitivity check, when applying an inclusive definition of multidimensionality (≥1 occurrence in ≥2 dimensions), the overlap share increases to 69.4% (503/725) and the dominance share to 69.8% (351/503). These results

Tab. 1: Robustness test of thematic overlap and dominance in city-targeted smart city projects

Definition of multidimensionality	Projects with high frequency in ≥2 dimensions	Share (%)	Projects with dominance margin > 0.20*	Share within multi-dimensional (%)
≥2 keyword occurrences in ≥2 dimensions (conservative threshold)	336	46.3	195	58.0
≥1 keyword occurrence in ≥2 dimensions (inclusive threshold)	503	69.4	351	69.8

Note: * Despite frequent multi-dimensional overlap, most projects classified under the conservative definition retain a dominance margin above 20%, supporting the use of a dominantcategory approach for citylevel aggregation.

Source: own based on CORDIS (2025)

indicate that while cross-dimensional overlap is common, a substantial fraction of projects remains thematically interpretable under a dominant-category approximation, provided the chosen threshold is made explicit.

3.1 Spatial distribution of city-targeted smart city projects

Fig. 3 illustrates the Top 20 European cities by the number of EC-funded Smart City projects. The results reveal a pronounced spatial concentration of Smart City experimentation in a limited group of metropolitan centres. Cities such as London (86 projects), Barcelona (81), Paris (72), Berlin (52), and Madrid (44) dominate in terms of project participation, clearly outperforming smaller and medium-sized cities.

This concentration indicates that Smart City research and innovation activities within EU Framework Programmes are not evenly distributed across the European urban system. Instead, participation clusters around cities that already possess strong innovation ecosystems, administrative capacity, and experience in managing complex EU-funded consortia. At the same time, a secondary group of cities, including Athens, Lisbon, Copenhagen, Vienna, and Helsinki, emerges as significant but clearly subordinate hubs of Smart City activity.

Fig. 4 complements this perspective by ranking cities according to the total EC financial contribution received. While there is substantial overlap with the project-count ranking, notable deviations appear. For example, Barcelona, Paris, London, Helsinki, and Madrid occupy top positions in both rankings, whereas some cities with fewer projects, such as Helsinki or Copenhagen, receive comparatively high

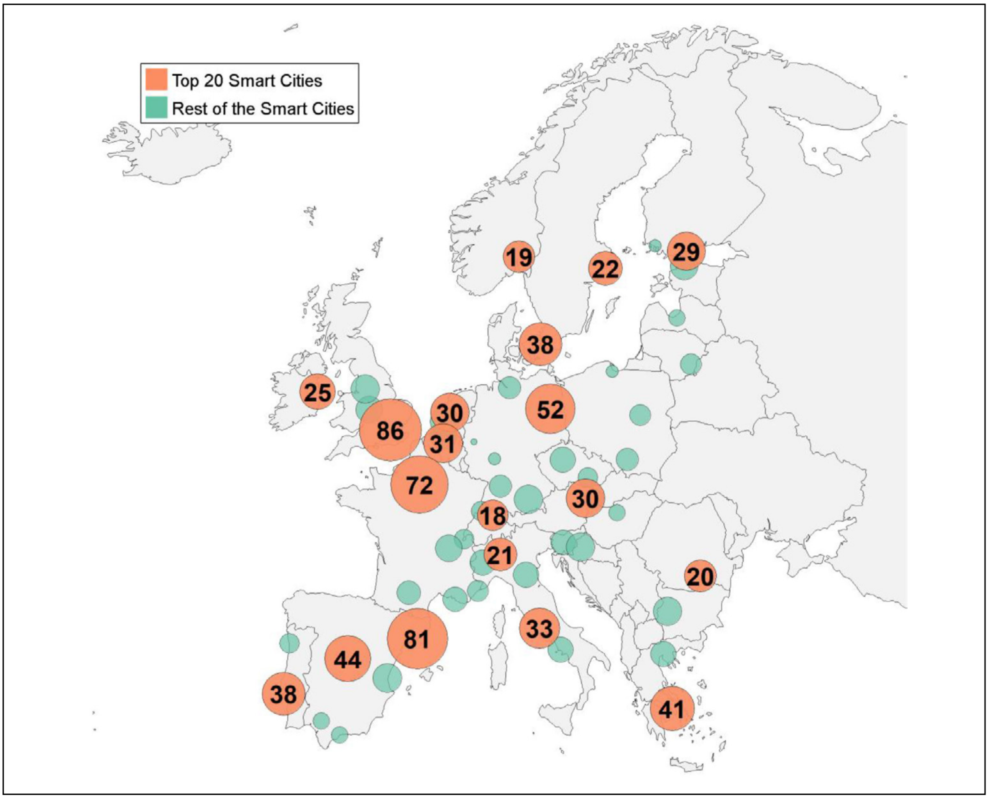

Fig. 3: Top 20 smart cities by the count of EC funded projects

Source: own based on CORDIS (2025)

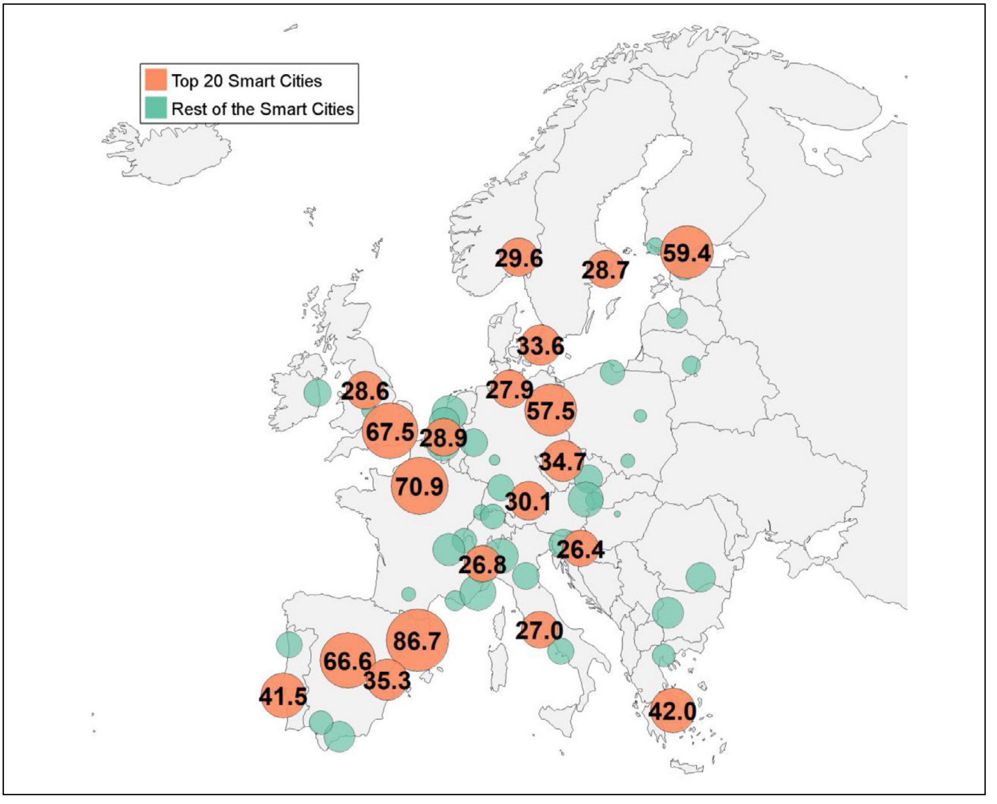

Fig. 4: Top 20 smart cities by the size of EC contribution (million EUR)

Source: own based on CORDIS (2025)

funding volumes. This indicates that project scale and financial intensity vary substantially across cities, and that a higher number of projects does not automatically translate into higher cumulative funding.

Tab. 2 provides a detailed overview of the distribution of project counts and EC contributions across all identified city-targeted Smart City initiatives. Tab. 2 confirms that financial allocations are highly skewed. A small number of cities account for a disproportionate share of total EC funding, while a long tail of cities participates in only a handful of projects with relatively modest financial volumes. For instance, cities such as Barcelona, Paris, and London each attract EC contributions exceeding EUR 65 million, whereas numerous Central and Eastern European cities remain below EUR 10 million despite being formally included in Smart City initiatives.

Altogether, the results demonstrate a dual concentration effect: Smart City experimentation is concentrated both in terms of project participation and financial allocation, reinforcing existing urban hierarchies within the European innovation landscape.

3.2 Thematic orientation of city-targeted smart city projects

Fig. 5 illustrates the thematic orientation of EC-funded Smart City projects in the ten European cities with the highest project participation, using a scatter pie visualisation, which reveals substantial variation in the degree of thematic diversification across cities.

Across the analysed cities, projects related to digitalisation, data, and technologies

Tab. 2: Distribution of city-targeted smart city projects and EC financial contribution by city

City	Projects count	EC contribution (EUR)	City	Projects count	EC contribution (EUR)	City	Projects count	EC contribution (EUR)
Amsterdam	30	25,097,051	**Hamburg**	9	27,884,798	**Riga**	5	7,526,149
Antwerp	13	28,931,043	**Helsinki**	29	59,437,866	**Rome**	33	26,952,006
Athens	41	41,968,239	**Krakow**	9	3,675,803	**Rotterdam**	16	17,361,823
Barcelona	81	86,676,742	**Lisbon**	38	41,498,802	**Seville**	5	10,401,189
Basel	7	4,483,318	**Ljubljana**	11	16,007,761	**Sofia**	15	19,000,805
Berlin	52	57,481,930	**London**	86	67,536,734	**Stockholm**	22	28,733,493
Birmingham	13	4,216,381	**Lyon**	13	19,915,129	**Stuttgart**	9	12,828,654
Bologna	12	13,224,005	**Madrid**	44	66,580,850	**Tallinn**	14	13,408,488
Bratislava	7	5,565,231	**Malaga**	5	17,901,796	**Thessaloniki**	12	9,456,522
Brno	7	14,981,847	**Manchester**	15	28,551,800	**Toulouse**	10	3,734,124
Brussels	31	20,927,084	**Marseille**	11	7,343,953	**Turin**	12	26,845,181
Bucharest	20	16,625,233	**Milan**	21	24,755,626	**Turku**	3	5,369,219
Budapest	5	2,100,922	**Munich**	15	30,122,993	**Valencia**	16	35,343,509
Cologne	2	14,266,606	**Naples**	12	13,039,565	**Vienna**	30	24,416,378
Copenhagen	38	33,593,083	**Nice**	8	25,914,302	**Vilnius**	8	6,057,765
Dublin	25	13,928,845	**Oslo**	19	29,577,343	**Warsaw**	8	3,248,349
Frankfurt	3	2,614,293	**Paris**	72	70,908,547	**Zagreb**	15	26,419,757
Gdansk	3	11,231,223	**Porto**	7	12,535,436	**Zurich**	18	11,175,224
Geneva	7	11,087,787	**Prague**	12	34,695,979			

Source: own based on CORDIS (2025)

constitute the dominant thematic category. However, the relative balance between thematic dimensions differs markedly, suggesting different strategic approaches to smart urbanism.

Cities such as London, Berlin, and Copenhagen exhibit a highly concentrated profile, with digital projects accounting for the majority of their portfolios. Such concentration indicates that cities with established technical infrastructures tend to follow a path-dependent trajectory, reinforcing their lead in data-driven projects rather than diversifying into new themes. In contrast, Madrid, Lisbon, and Brussels show a more diversified allocation, combining digital initiatives with substantial engagement in energy and environmental projects as well as mobility and transport interventions. In these instances, the Smart City concept is treated as a functional enabler to address foundational urban challenges. Paris occupies an intermediate position, with a dominant digital component complemented by a notable share of energy and environmental projects. Across all cities, projects explicitly addressing social or participatory aspects remain scarce. This indicates a persistent technocratic bias in EU funding allocations, where measurable technological outputs are prioritized over harder-to-quantify social innovations.

Beyond differences in population size or GDP, spatial concentration reflects cumulative advantage dynamics. Cities that have previously coordinated EU projects develop administrative expertise, transnational networks, and reputational capital that increase their probability of future funding success. This dynamic resembles the Matthew Effect observed in research funding allocation, but at the urban level.

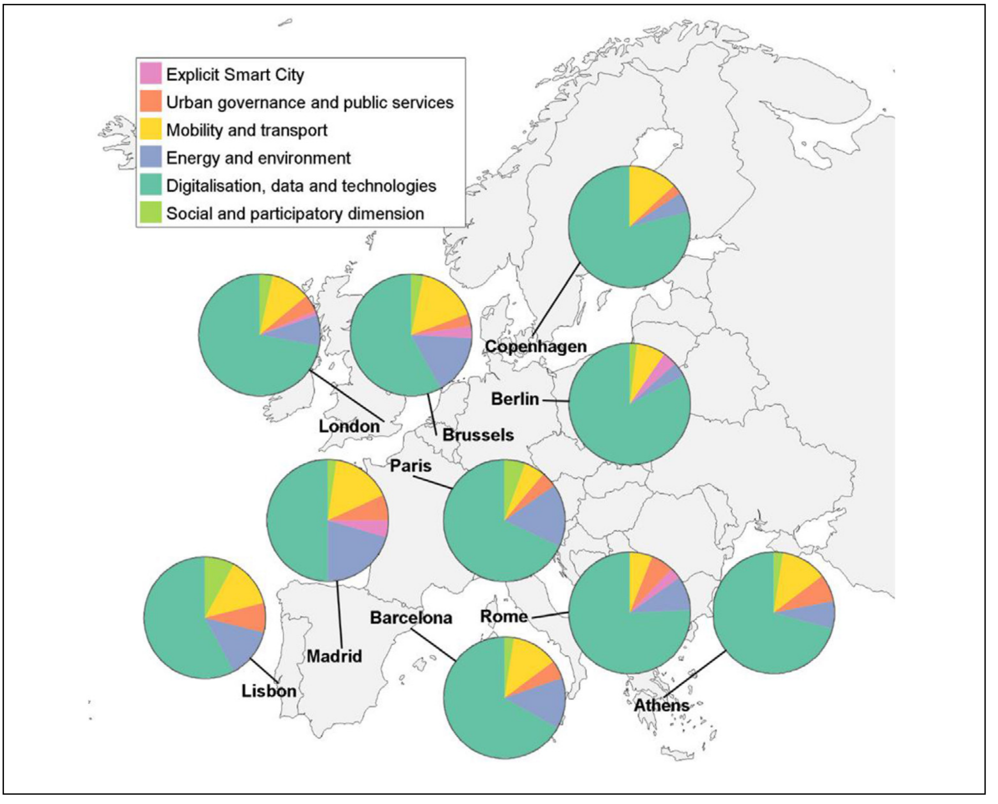

Fig. 5: Thematic orientation of EC-funded smart city projects in the top 10 smart cities by project count

Source: own based on CORDIS (2025)

Participation in Lighthouse initiatives appear particularly consequential: early demonstrator cities such as Barcelona and Amsterdam subsequently exhibit sustained portfolio expansion. Smart City funding therefore functions not merely as a technological instrument but as a mechanism reinforcing urban innovation hierarchies.

The relative scarcity of social and participatory projects cannot be explained solely by technological prioritization. Three structural mechanisms appear plausible:

(i) Evaluation bias toward measurable technological outputs, which favour infrastructure-heavy consortia;

(ii) Grant-design structure, where large-scale demonstrators prioritize hardware integration over institutional experimentation;

(iii) Capacity asymmetries, where cities possess stronger technical engineering departments than participatory governance infrastructures.

The case of Bratislava illustrates this pattern. While active in digital innovation projects, it records no projects in the social dimension. This absence likely reflects limited institutional capacity to design large-scale participatory innovation consortia rather than lack of local need. Consequently, Smart City policy risks reinforcing technocratic modernization without equivalent investment in democratic urban governance.

Tab. 3 provides an overview of thematic engagement in EC-funded Smart City projects for all cities in the sample. Large metropolitan centres such as London, Paris, and Berlin combine high project participation with strong dominance of digital projects. Lisbon, Brussels, Vienna, and Amsterdam, show relatively more balanced engagement

Tab. 3: Thematic distribution of EC-funded smart city projects across EU cities by project count – Part 1

City	Digitalisation, data and technologies	Energy and environment	Urban governance and public services	Mobility and transport	Social and participatory dimension	Explicit Smart City
Amsterdam	19	1	2	3	5	0
Antwerp	10	1	0	1	0	1
Athens	29	3	3	5	1	0
Barcelona	54	11	4	10	2	0
Basel	4	3	0	0	0	0
Berlin	43	2	0	4	1	2
Birmingham	12	1	0	0	0	0
Bologna	9	1	0	2	0	0
Bratislava	4	2	1	0	0	0
Brno	3	0	1	2	1	0
Brussels	18	5	1	5	1	1
Bucharest	17	2	0	0	1	0
Budapest	2	2	0	0	0	1
Cologne	1	1	0	0	0	0
Copenhagen	30	2	1	5	0	0
Dublin	17	3	2	2	1	0
Frankfurt	3	0	0	0	0	0
Gdansk	3	0	0	0	0	0
Geneva	6	0	0	1	0	0
Hamburg	6	2	1	0	0	0
Helsinki	19	2	2	4	0	2
Krakow	6	0	0	2	1	0
Lisbon	22	5	3	5	3	0
Ljubljana	6	1	0	1	3	0
London	62	7	4	9	3	1
Lyon	11	0	0	2	0	0
Madrid	22	9	3	7	1	2
Malaga	1	2	0	2	0	0
Manchester	6	4	4	1	0	0
Marseille	9	0	1	1	0	0
Milan	16	0	0	3	2	0
Munich	6	3	2	4	0	0
Naples	10	1	1	0	0	0
Nice	3	3	0	1	1	0
Oslo	13	1	0	5	0	0

Tab. 3: Thematic distribution of EC-funded smart city projects across EU cities by project count – Part 2

City	Digitalisation, data and technologies	Energy and environment	Urban governance and public services	Mobility and transport	Social and participatory dimension	Explicit Smart City
Paris	49	12	3	4	4	0
Porto	4	2	0	0	1	0
Prague	7	4	1	0	0	0
Riga	2	2	0	1	0	0
Rome	25	3	2	2	0	1
Rotterdam	8	2	1	3	2	0
Seville	3	2	0	0	0	0
Sofia	12	1	0	2	0	0
Stockholm	12	4	2	4	0	0
Stuttgart	5	1	0	3	0	0
Tallinn	12	0	1	0	0	1
Thessaloniki	9	0	0	2	1	0
Toulouse	6	1	2	0	1	0
Turin	4	1	0	5	2	0
Turku	2	0	0	1	0	0
Valencia	10	4	1	1	0	0
Vienna	23	4	1	2	0	0
Vilnius	6	0	1	0	1	0
Warsaw	5	2	0	1	0	0
Zagreb	8	2	1	1	3	0
Zurich	12	3	1	2	0	0

Source: own based on CORDIS (2025)

across digital technologies, mobility and transport, and energy and environmental projects.

At the lower end of the distribution, many cities, particularly in Central, Eastern, and Southern Europe, participate in only a few projects and concentrate on one or two dominant themes, most often digital technologies. Governance, public services, and social or participatory projects remain underrepresented across the sample.

Fig. 6 illustrates the thematic orientation of EC-funded Smart City projects in the ten European cities receiving the highest total EC financial contributions. In contrast to the project-count perspective presented earlier, this funding-based view reveals notable shifts in both the relative prominence of individual cities and the internal thematic composition of their Smart City portfolios.

The digital category remains dominant in almost all cities. In Prague and Berlin, this dominance is particularly pronounced, with digital projects accounting for an overwhelming share of EC funding, reflecting a strongly technology-centred Smart City strategy.

Mobility and transport initiatives attract substantial funding in cities such as London, Helsinki, and Athens. Athens is notable for directing a high proportion of resources to transport despite a relatively small number of projects, reflecting the financial intensity of these interventions. Energy and environmental projects also receive significant funding, particularly in Madrid, Barcelona, Valencia,

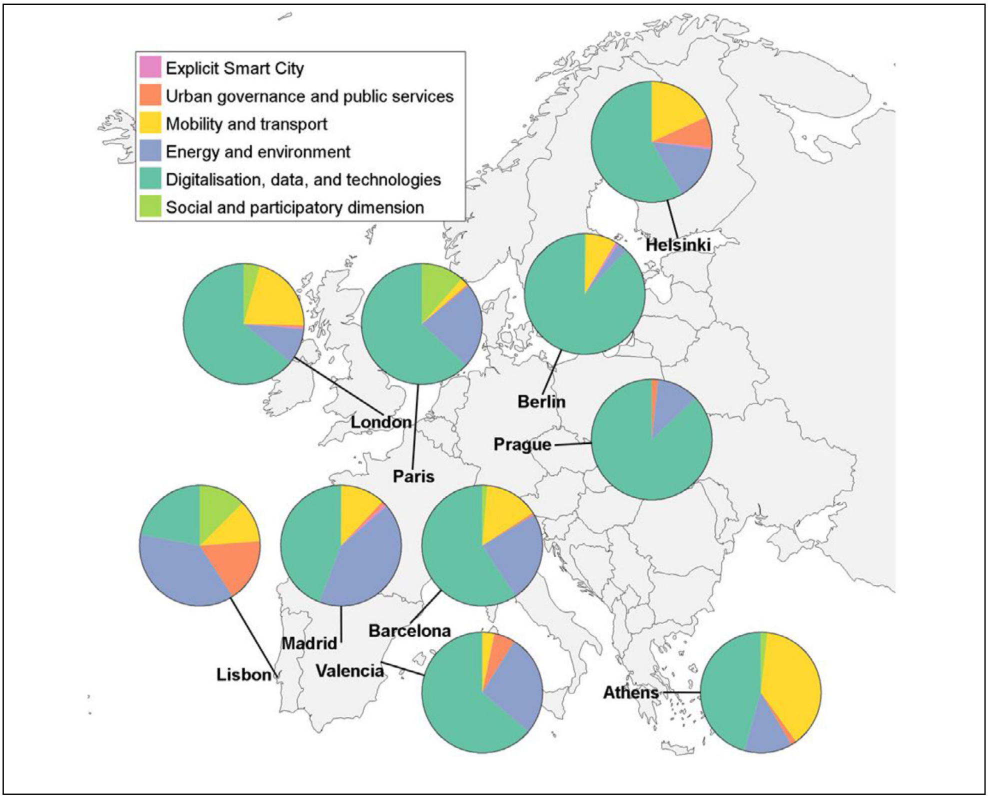

Fig. 6: Thematic orientation of EC-funded smart city projects in the top 10 cities by EC contribution

Source: own based on CORDIS (2025)

Paris, and Lisbon. In several cases, the financial weight of these initiatives exceeds their numerical prevalence, indicating comparatively large-scale investments. This pattern indicates a strategic deployment of resources to address pressing energy or sustainability challenges, rather than spreading funds thinly across many small projects.

Lisbon maintains a relatively balanced allocation across multiple themes, with particular emphasis on energy, environment, and governance projects. This pattern suggests a deliberate diversification of its Smart City project portfolio. Such an allocation may reflect a strategic effort to strengthen institutional capacity, align with broader EU priorities, and enhance the impact of individual initiatives.

Tab. 4 presents EC funding for all cities broken down by thematic category. Across the sample, funding remains concentrated in one or two areas, with digitalisation, data, and technology being the primary recipients. Only a small number of cities show a more balanced distribution of resources across multiple themes reflecting strategic diversification.

In certain cities, non-digital themes receive a substantial share of funding. Mobility and transport projects are the main focus in some cases, while energy and environmental initiatives dominate in others. Funding for governance, public services, and social or participatory projects is generally limited and tends to serve a supporting role within overall city-level Smart City portfolios. This persistent underrepresentation of social and participatory dimensions underscores a structural bias in EU Smart City funding, favouring measurable technological outputs over institutional or community-oriented innovation.

Tab. 4: Thematic distribution of EC-funded smart city projects across EU cities by EC contribution – Part 1

City	Digitalisation, data and technologies (EUR)	Energy and environment (EUR)	Urban governance and public services (EUR)	Mobility and transport (EUR)	Social and participatory dimension (EUR)	Explicit Smart City (EUR)
Amsterdam	14,907,712	264,295	175,866	3,070,833	6,678,345	0
Antwerp	10,532,574	587,320	0	16,376,775	0	1,434,375
Athens	19,142,912	5,389,640	619,542	16,081,497	734,648	0
Barcelona	51,416,885	20,994,404	539,893	12,558,907	1,166,653	0
Basel	1,307,169	3,176,149	0	0	0	0
Berlin	50,514,905	1,596,823	0	4,696,045	246,669	427,488
Birmingham	3,784,779	431,603	0	0	0	0
Bologna	3,246,731	2,024,968	0	7,952,306	0	0
Bratislava	2,155,187	1,410,057	1,999,988	0	0	0
Brno	6,547,339	0	1,049,921	2,924,278	4,460,310	0
Brussels	7,446,679	10,052,360	1,801,111	1,467,034	84,900	75,000
Budapest	567,293	1,144,941	0	0	0	388,688
Bucharest	13,542,125	294,750	0	0	2,788,358	0
Cologne	191,675	14,074,931	0	0	0	0
Copenhagen	19,963,273	3,472,284	142,857	10,014,669	0	0
Dublin	10,771,434	1,500,280	330,723	1,138,542	187,866	0
Frankfurt	2,614,293	0	0	0	0	0
Gdansk	11,231,223	0	0	0	0	0
Geneva	5,887,860	0	0	5,199,927	0	0
Hamburg	21,893,322	3,991,488	1,999,988	0	0	0
Helsinki	34,691,980	8,679,972	4,921,980	10,816,740	0	327,194
Krakow	3,057,394	0	0	528,409	90,000	0
Lisbon	9,158,117	15,377,046	7,079,467	4,698,168	5,186,004	0
Ljubljana	4,688,208	2,193,504	0	652,633	8,473,417	0
London	43,300,160	6,466,521	480,009	14,141,052	2,965,537	183,455
Lyon	10,716,907	0	0	9,198,222	0	0
Madrid	29,383,387	28,130,696	619,542	7,899,278	101,203	446,745
Malaga	2,613,550	11,005,329	0	4,282,917	0	0
Manchester	13,983,147	12,844,618	1,238,125	485,909	0	0
Marseille	6,331,019	0	212,934	800,000	0	0
Milan	18,788,383	0	0	3,468,162	2,499,081	0
Munich	10,324,275	5,942,287	1,361,408	12,495,023	0	0
Naples	12,474,467	499,947	65,152	0	0	0
Nice	1,744,875	20,327,097	0	3,781,696	60,633	0

Tab. 4: Thematic distribution of EC-funded smart city projects across EU cities by EC contribution – Part 2

City	Digitalisation, data and technologies (EUR)	Energy and environment (EUR)	Urban governance and public services (EUR)	Mobility and transport (EUR)	Social and participatory dimension (EUR)	Explicit Smart City (EUR)
Oslo	19,196,373	1,993,647	0	8,387,323	0	0
Paris	44,714,798	16,250,625	308,027	1,480,108	8,154,988	0
Porto	2,223,451	5,851,676	0	0	4,460,310	0
Prague	30,208,188	3,887,791	600,000	0	0	0
Riga	1,292,075	5,748,164	0	485,909	0	0
Rome	23,563,444	2,072,589	540,481	675,492	0	100,000
Rotterdam	9,670,783	539,607	748,785	3,806,244	2,596,405	0
Seville	1,679,322	8,721,867	0	0	0	0
Sofia	17,048,675	1,399,868	0	552,263	0	0
Stockholm	16,263,611	5,247,569	1,361,408	5,860,906	0	0
Stuttgart	3,892,920	2,178,773	0	6,756,961	0	0
Tallinn	12,909,377	0	274,517	0	0	224,594
Thessaloniki	6,917,547	0	0	2,039,155	499,820	0
Toulouse	2,680,802	749,832	242,857	0	60,633	0
Turin	5,852,530	2,030,000	0	17,877,870	1,084,781	0
Turku	1,030,132	0	0	4,339,087	0	0
Valencia	22,557,104	9,635,285	1,999,988	1,151,132	0	0
Vienna	20,970,831	3,123,940	221,606	100,000	0	0
Vilnius	5,482,945	0	75,000	0	499,820	0
Warsaw	2,823,328	382,521	0	42,500	0	0
Zagreb	12,599,477	7,129,753	899,315	471,863	5,319,350	0
Zurich	9,974,557	492,346	75,000	633,321	0	0

Source: own based on CORDIS (2025)

3.3 Discussion

The findings suggest that future EU Smart City calls should incorporate structural balancing instruments, including: (i) dedicated funding windows for participatory and governance innovation; (ii) mandatory inclusion of social impact work packages within technological demonstrators; (iii) capacity-building schemes for medium-sized and peripheral cities; and (iv) graduated co-financing mechanisms favouring first-time city participants.

If Smart City policy is to function not only as an excellence instrument but also as a cohesion mechanism, funding design must explicitly counteract cumulative advantage dynamics.

The observed spatial concentration of Smart City projects aligns closely with prior findings in the Smart City and innovation policy literature. Earlier portfolio-level studies have shown that EU-funded Smart City initiatives tend to gravitate toward cities with strong pre-existing innovation capacities and administrative experience (Clerici Maestosi et al., 2019; Collins et al., 2021). The present results extend this evidence by demonstrating that such concentration persists even when the analysis is restricted to explicitly place-based, city-targeted projects, rather than generic urban initiatives.

These findings advance the literature in several important ways. While earlier studies confirm that Smart City projects concentrate in innovation hubs, this paper extends the evidence by showing that cumulative advantage dynamics persist even at the level of explicitly city-targeted projects and, by linking thematic diversification with financial intensity, demonstrates that cities differ not only in project quantity but also in strategic orientation and resource allocation, reflecting layered roles within the EU Smart City ecosystem.

From a theoretical perspective, the findings support arguments that conceptualize Smart Cities as socio-technical and institutional projects, rather than purely technological deployments (Batty et al., 2012; Bibri & Krogstie, 2017). Cities that perform well in the rankings are typically those capable of integrating digital infrastructures with governance arrangements, stakeholder coordination, and long-term strategic planning. This reinforces the view that Smart City success depends not only on technological solutions, but also on institutional capacity and governance quality (Džatková, 2025; Meijer & Bolívar, 2016).

The discrepancy between project counts and financial volumes observed in Fig. 2–3 further suggests a functional differentiation among Smart Cities. Some cities act as experimental hubs hosting numerous pilot projects of limited scale, while others serve as flagship demonstrators for fewer but financially intensive initiatives. This pattern mirrors findings by Christidis et al. (2024), who show that cities deeply embedded in EU transport and energy research networks tend to attract larger-scale projects aligned with long-term climate and sustainability objectives.

From a policy perspective, the results raise important questions regarding the territorial inclusiveness of the EU's Smart City agenda. While the concentration of projects in leading cities may enhance efficiency and accelerate technological learning, it also risks reinforcing regional disparities. Critical scholars have warned that the Smart City label may function as a mechanism of cumulative advantage, privileging cities already well-positioned within EU research networks (Engelbert et al., 2019; Hollands, 2008). The limited representation of smaller and less affluent cities in Tab. 1 suggests that this risk remains salient.

At the same time, the presence of cities from Central, Eastern, and Southern Europe, albeit with lower project counts and funding, indicates that the Smart City agenda does provide entry points for peripheral urban regions. However, the relatively modest financial scale of their participation raises doubts about the transformative capacity of such involvement. As Huovila et al. (2019) argue, meaningful progress toward smart and sustainable urban development depends not merely on participation, but on the scale, continuity, and integration of funded initiatives.

Overall, the results suggest that the EU's Smart City agenda in practice exhibits a tension between excellence-driven concentration and cohesion-oriented inclusiveness. While leading metropolitan centres function as laboratories for advanced Smart City solutions, the diffusion of these innovations to a broader range of European cities remains uneven. This finding underscores the importance of future policy designs that balance competitive funding mechanisms with instruments explicitly targeting capacity building and long-term learning in less-represented cities.

Building on the observed spatial concentration of Smart City projects, the thematic patterns revealed in the analysis deepen our understanding of the strategic orientations underpinning the EU's Smart City agenda. The predominance of digitalisation, data, and technology across most cities confirms that Smart City initiatives largely remain technology-driven. This reinforces existing critiques that frame Smart Cities primarily as digital experimentation spaces rather than comprehensive urban transformation projects (Kitchin, 2013). The strong focus on digital themes aligns with a technology-centric innovation logic, privileging technical solutions.

Yet, the significant variation in thematic diversification challenges a one-size-fits-all characterization. Some cities exhibit a more specialized, digitally concentrated profile, suggesting strategic prioritization of technological innovation as the core driver of urban development. Others demonstrate a broader portfolio that integrates mobility, energy, and environmental projects alongside digital initiatives. This diversification points to more holistic approaches where digital innovation is embedded within sustainability and urban systems frameworks, reflecting emerging paradigms of Smart City development that emphasize multi-dimensional and integrated strategies (Caragliu et al., 2011).

The divergence between project counts and financial allocations further nuances this picture. Cities targeted by numerous projects with lesser financing may function as experimental hubs, piloting smaller-scale digital initiatives, while those with fewer but larger and resource-intensive projects, particularly in energy and mobility sectors, act as flagship exemplars of capital-heavy urban transformation. This functional differentiation suggests a layered urban innovation ecosystem where resource allocation responds not only to thematic priorities but also to differing strategic roles within the Smart City landscape (Vanolo, 2016).

Importantly, despite some thematic diversification, governance, public services, and especially social and participatory dimensions remain consistently marginal in both project prevalence and funding. The persistent underrepresentation of these areas likely stems from a combination of EU funding structures and local institutional capacity constraints. Many EU Smart City calls prioritize measurable technological outcomes, favouring projects in digitalisation, mobility, and energy, while evaluation criteria give comparatively little weight to participatory or social innovation. Local capacity limitations, including staff expertise and stakeholder networks, further constrain the ability of cities to develop and implement "soft" innovation projects. Together, these factors generate a Matthew effect, where well-resourced cities consolidate technological advantages while socio-institutional dimensions remain marginal. This highlights that institutional transformation and citizen engagement continue to be peripheral in EU-funded Smart City interventions. The limited focus on these dimensions raises critical questions about the extent to which Smart City policies address the socio-political complexities of urban governance and inclusiveness. It indicates a persistent technocratic bias that privileges sectoral innovation over democratic participation and social equity. In summary, the thematic orientation of EC-funded Smart City projects reveals a complex landscape marked by dominant digital innovation, varied degrees of strategic diversification, and persistent gaps in socio-institutional engagement. This landscape both mirrors and shapes the evolving conceptualization and practice of Smart Cities within the EU, highlighting ongoing tensions between technological ambition, sustainability integration, and democratic inclusiveness that must be navigated in future policy development.

Conclusions

This paper maps how the EU's Smart City agenda materialises in practice by systematically tracing city-targeted projects in the CORDIS portfolio and coding them across six thematic dimensions (digitalisation, data and technologies; energy and environment; mobility and transport; urban governance and public services; social and participatory dimension; explicit Smart City framing). The evidence points to a clear dual concentration: a relatively small set of large metropolitan centres dominates participation and EC funding, while many cities appear only marginally, often through isolated, small-scale engagements. At the same time, the ranking of cities by project counts does not fully mirror the ranking by financial intensity, indicating heterogeneous project scale and strategic positioning across the European urban landscape. Thematically, digitalisation-led projects constitute the dominant backbone of the portfolio, typically followed by energy and mobility-oriented initiatives, whereas governance and especially social and participatory dimension components remain comparatively scarce. The persistent underrepresentation of these areas likely stems from a combination of EU funding structures and local institutional capacity constraints. Many calls prioritize measurable technological outcomes, while evaluation criteria give comparatively little weight to participatory or social innovation. Local capacity limitations, including staff expertise and stakeholder networks, further constrain the ability of cities to develop and implement 'soft' innovation projects. Together, these dynamics generate a Matthew effect, where well-resourced cities consolidate technological advantages while socio-institutional dimensions remain peripheral. Overall, the findings suggest that the EU Smart City agenda continues to be dominated by a technology-centric innovation logic and that territorial inclusiveness and democratic participation require more explicit policy attention.

The methodology applied in this study provides a transparent and replicable framework for identifying city-targeted Smart City projects within large EU Framework Programme datasets, distinguishing between generic urban innovation and territorially embedded experimentation. Several heuristic decisions were required, including keyword-based project identification, city-name matching, dominant-category assignment, and the proportional allocation of financial contributions across multiple target cities. These choices were designed to ensure comparability and robustness, while offering a conservative estimate of spatial concentration, thematic orientation, and cumulative advantage dynamics.

At the same time, certain methodological limitations should be acknowledged. The identification of city-targeted projects relies on explicit references to city names in project metadata, which may undercount initiatives that implicitly target urban areas without naming specific municipalities. Moreover, the city-detection dictionary may favour larger or more widely recognised cities, potentially overlooking smaller municipalities engaged in specialised demonstrators. Finally, the equal-split allocation of EU funding across multiple target cities likely underestimates the true degree of financial concentration in leading metropolitan hubs, suggesting that observed inequalities may in fact be more pronounced. Despite these constraints, the approach provides a solid empirical foundation for analysing spatial concentration patterns in EU Smart City research and innovation policy. Future research can address these constraints by combining entity recognition and geocoding with multilingual Natural Language Processing, extending the analysis to project outputs and impacts (deliverables, publications, patents, pilots), and linking portfolios to city-level indicators (e.g., emissions, mobility performance, governance capacity). Network-based analyses of consortia could further clarify whether Smart City funding primarily reinforces cumulative advantage or enables capability-building diffusion across less-represented cities.

Acknowledgments: *This work was supported by the Slovak Research and Development Agency under the Contract No. APVV-22-0090: Application of Behavioural Economics in Mapping Preferences in the Fields of Housing, Employment, and Transport Mobility and by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and Slovak Academy of Sciences within the project 1/0366/23 Value for Money in Public Procurement.*

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Smart cities in Czech regional development strategies: Key challenges and barriers

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Abstract: *The article examines the extent to which the Smart City (SC) concept is integrated into regional development strategies in Czechia, responding to the growing importance of smart approaches and the persistent inconsistencies in their strategic application across regions. The aim of the study is to evaluate how Czech regions incorporate SC principles into their strategic documents and to identify the main barriers that hinder their effective implementation, ultimately offering recommendations for more coherent and results-oriented regional smart development. The analysis is based on a qualitative content assessment of 21 strategic documents, including both general development strategies and dedicated smart strategies, with attention given not only to the presence of SC elements but also to their depth, structure, and thematic orientation. This approach made it possible to uncover substantial differences in the way regions conceptualize and operationalize smart principles. The results show that although all regions address the SC concept to some degree, the level of integration varies considerably, with only half of the regions having a standalone smart strategy and even these differing widely in their structure, priorities, and strategic logic. The study identifies nine key barriers, such as conceptual fragmentation, inconsistent methodological approaches, insufficient stakeholder involvement, and a pronounced implementation gap that limits the translation of strategic intentions into practice. These barriers are mutually reinforcing and closely linked to broader administrative and strategic challenges at the regional level. The findings highlight the need for stronger national coordination, clearer methodological guidance, enhanced regional capacities, and more systematic stakeholder engagement.*

Keywords: *Smart region, urban development, urban strategy, urban planning, strategic planning, application gaps.*

JEL Classification: *O18, O21, R58.*

APA Style Citation: Urbanik, P., Horalek, J., Otcenaskova, T. (2026). Smart cities in Czech regional development strategies: Key challenges and barriers. *E&M Economics and Management, 29*(3), 44–60. https://doi.org/10.15240/tul/001/2026-3-003

Introduction

According to the United Nations (2018), around 55% of the world's population currently lives in cities, a figure expected to rise to nearly 70% by 2050. This accelerating urbanization brings growing challenges in spatial planning, infrastructure capacity, and sustainable resource management (Eremia et al., 2017; Gupta et al., 2019). In response, Smart City (SC) concept has gained prominence as an approach that integrates ICT and innovative management to optimize urban functions, enhance sustainability, and improve quality of life (Dustdar et al., 2017). While often associated with technology, effective SC development also requires strong governance, participatory processes, and alignment with broader societal goals (Jacques et al., 2024).

Global interest in smart and sustainable urban development aligns closely with international frameworks such as Agenda 21 and Agenda 2030, as well as the Sustainable Development Goals (SDGs). In Czechia, these commitments are reflected in national documents, including the Strategic Framework Czech Republic 2030 and the Regional Development Strategy 2021+ (RDS21+) (MoRD, 2020), which emphasize balanced territorial development, digitalization, resilience, and smart solutions. At the European level, initiatives like the European Urban Initiative (EUI) further reinforce the importance of integrated and innovative urban development.

In this context, the concept of SC is increasingly complemented by the notion of the Smart Region, which extends smart principles beyond individual cities to the regional scale. According to Soe (2023), the Smart Region represents an evolution of SC movement, applying technological solutions and innovative governance approaches across broader territorial units that include cities, towns, and rural areas.

Despite this supportive policy environment, the absence of a unified definition of SC concept remains a major challenge, both internationally and within Czechia (Dameri, 2017; Gracias et al., 2023). Local and regional authorities interpret SC differently based on their priorities and capacities, and the concept continues to evolve with technological advances such as IoT, AI, and big data (Dameri, 2017; Hayat, 2016). To guide public administration, the Ministry of Regional Development issued the Smart Cities Methodology (MoRD, 2018) and later the Smart Cities Concept (MoRD, 2021), which outline principles, thematic components, and implementation frameworks for smart and resilient development.

This study analyzes regional development strategies and dedicated smart strategies to assess how SC principles are integrated across Czech regions. Using qualitative content analysis, it identifies key barriers limiting effective implementation and proposes recommendations to support more coherent and coordinated smart development.

1 Theoretical background

SC development is an inherently multidimensional process that relies on the integration of digital technologies, robust governance, effective stakeholder engagement, and sustainable planning. Recent literature identifies a diverse set of persistent and emerging barriers that cities must address to transition toward smart and sustainable urban environments.

Technological barriers and challenges. Cities are frequently confronted with outdated infrastructure and fragmented legacy systems that are not readily compatible with modern digital platforms, such as IoT and AI (Bilal et al., 2021; Makki & Alqahtani, 2024). Studies report that insufficient interoperability, lack of standardized data formats, and technical silos often hinder the seamless exchange of information across municipal departments (Akgün et al., 2024; Paes et al., 2023; Singh et al., 2022). Cybersecurity vulnerabilities remain a persistent concern, especially where multiple vendors' solutions must be integrated (Shah et al., 2024; Wolniak & Stecuła, 2024). Moreover, the complexity of integrating fast-evolving technologies frequently outpaces the technical capacity of public agencies, resulting in skills gaps and an ongoing reliance on outdated systems (Javed et al., 2022; Mansoori, 2021; Moolngearn & Kraiwanit, 2024; Razmjoo et al., 2021).

Governance and institutional complexity. The absence of clear governance frameworks and weak interdepartmental coordination present major obstacles, as highlighted by Akgün et al.(2024), and Mora et al. (2025). Bureaucratic inertia, overlapping mandates, and political instability often result in fragmented or short-term approaches that undermine strategic continuity (Makki & Alqahtani, 2024; Shah et al., 2024). Effective stakeholder governance is also challenged by insufficient collaboration with the private sector and academia (Correia et al., 2022; José & Rodrigues, 2024; Mora et al., 2025), as well as limited citizen participation. The literature consistently stresses the need for adaptive leadership and flexible institutional arrangements (Moolngearn & Kraiwanit, 2024; Schuch De Azambuja, 2021).

Financial limitations. Securing adequate funding for SC initiatives remains a widespread challenge (Akgün et al., 2024; Bilal et al., 2021). Many cities encounter high upfront investment costs, limited access to external funds, and a lack of innovative financial tools tailored to the complexity of smart projects (Javed et al., 2022; Mansoori, 2021; Paes et al., 2023; Razmjoo et al., 2021). Difficulties in demonstrating long-term return on investment can discourage private sector engagement and public-private partnerships (Mashau & Kroeze, 2023; Rosário & Boechat, 2024). These constraints are particularly acute in smaller cities or regions with limited economic resources (Shah et al., 2024; Singh et al., 2022).

Social and cultural barriers. Low digital literacy, mistrust towards authorities, and concerns about data collection and surveillance frequently undermine public acceptance (Javed et al., 2022; Makki & Alqahtani, 2024; Schuch De Azambuja, 2021). Cultural reluctance to change can slow adoption, particularly among older populations or marginalized groups who often lack access to digital services (Paes et al., 2023; Razmjoo et al., 2021). The exclusion of vulnerable communities exacerbates social inequalities and the digital divide (Moolngearn & Kraiwanit, 2024; Rosário & Boechat, 2024). A number of studies emphasize that participatory planning and transparent communication are vital for building trust and ensuring inclusive outcomes (Akgün et al., 2024; Correia et al., 2022; Javed et al., 2022; José & Rodrigues, 2024; Mashau & Kroeze, 2023).

Data management and ethics. As SCs rely on massive volumes of data, issues of security, privacy, and ethics are increasingly prominent. Bilal et al. (2021) and Wolniak and Stecuła (2024) point to frequent challenges with fragmented data governance, insufficient adoption of international standards (such as GDPR), and growing cybersecurity threats. Integrating data from diverse sources can create silos and limit the city's ability to derive actionable insights (Paes et al., 2023; Singh et al., 2022). Studies also highlight concerns about algorithmic bias, surveillance, and user consent, calling for transparent data policies and robust ethical oversight, especially as AI becomes more widespread (Akgün et al., 2024; Correia et al., 2022; Javed et al., 2022; Makki & Alqahtani, 2024; Mansoori, 2021; Mora et al., 2025).

Strategic and planning issues. Many SC projects remain in the pilot phase due to a lack of coherent vision, weak long-term planning, and disconnects between strategic objectives and operational reality (Akgün et al., 2024; Correia et al., 2022; Mora et al., 2025). Planning processes are often top-down, with inadequate engagement of local communities (José & Rodrigues, 2024; Paes et al., 2023; Rosário & Boechat, 2024). Without robust monitoring and evaluation, it is difficult to track progress or replicate successful solutions (Mansoori, 2021; Mashau & Kroeze, 2023; Shah et al., 2024; Singh et al., 2022).

Sustainability and inclusion. Lasting SC transformation depends on both social inclusion and environmental sustainability (Rosário & Boechat, 2024; Schuch De Azambuja, 2021). Digital exclusion remains a significant challenge for vulnerable groups, such as the urban poor or residents of rural areas (Makki & Alqahtani, 2024; Paes et al., 2023). Despite the recognized need, integration of green infrastructure and climate adaptation strategies is often limited in practice (Javed et al., 2022; Mora et al., 2025; Razmjoo et al., 2021; Shah et al., 2024). A number of studies recommend that participatory planning and targeted support for marginalized groups are essential for delivering equitable outcomes (Akgün et al., 2024; Bilal et al., 2021; Mansoori, 2021; Mashau & Kroeze, 2023; Moolngearn & Kraiwanit, 2024; Singh et al., 2022).

While the literature review demonstrates that the barriers to SC development are diverse and interdependent, this article will focus in greater detail on the case of Czechia, with particular emphasis on strategic planning processes and the associated administrative challenges. Specifically, the analysis will examine how strategic and planning issues (highlighted in the review as a key barrier) manifest in the preparation and implementation of SC strategies at the regional level in the Czech context.

2 Research methodology

The aim of this study is to determine to what extent and in what form the SC solutions are integrated into strategic planning in Czechia. This article builds upon the findings of our previous publication and employs the SC domain model introduced in Urbanik and Horalek (2022) as a reference framework, which was derived from a similar analysis of regional strategies, as a reference framework in order to compare current smart strategies and to illustrate their heterogeneity and differences in thematic coverage. The model reflects core SC dimensions commonly identified in the literature, such as governance, mobility, environment, technical infrastructure (e.g., Caragliu & Del Bo, 2019; Giffinger et al., 2007; Singh et al., 2022; Ulya et al., 2024). Given the strong heterogeneity of strategic documents in terms

Tab. 1: List of analysed regional development strategies and smart strategies (details of the sources are provided in Appendix)

Region	Regional development strategies	Approved	Period
PHA	Strategic Plan of the Capital City of Prague (Prague, 2016)	2016	–2030
STČ	Development Strategy of the Central Bohemian Region (Central Bohemian Region, 2019)	2019	2019–2024
JHČ	South Bohemia Region Development Programme (South Bohemia Region, 2021)	2021	2021–2027
PLK	Development Programme of the Pilsen Region (Pilsen Region, 2022)	2023	2022–
KVK	Development Programme of the Karlovy Vary Region (Karlovy Vary Region, 2021)	2021	2021–2027
ULK	Development Strategy of the Ústí nad Labem Region (Ústí nad Labem Region, 2017)	2018	2021–2027
LBK	Development Strategy of the Liberec Region (Liberec Region, 2021)	2020	2021–2027
HKK	Development Strategy of the Hradec Králové Region (Hradec Králové Region, 2021)	2019	2021–2027
PAK	Development Strategy of the Pardubice Region (Pardubice Region, 2021)	2021	2021–2027
VYS	Development Strategy of the Vysočina Region (Vysočina Region, 2020)	2020	2021–2027
JHM	Development Strategy of the South Moravian Region (South Moravian Region, 2020)	2022	2021–
OLK	Development Strategy of the Olomouc Region (Olomouc Region, 2020)	2020	2021–2027
MSK	Development Strategy of the Moravian-Silesian Region (Moravian-Silesian Region, 2019)	2019	2019–2027
ZLK	Development Strategy of the Zlín Region (Zlín Region, 2019)	2019	–2030
	Regional smart strategies		
PHA	Smart Prague concept (Prague, 2024)	2025	–2030
STČ	Smart Countryside for the Central Bohemian Region Development Strategy (Central Bohemian Region, 2020)	2020	2020–2030
JHČ	Strategic Development Plan for the Smart Region of the South Bohemian Region (South Bohemia Region, 2019)	2019	2019–2023
LBK	Concept “Smarter Region” of Liberec Region (Liberec Region, 2019)	2019	2019–2027
HKK	Concept of the Hradec Králové Region Smart Region (Hradec Králové Region, 2019)	2019	2021–2027
MSK	Smart Region Development Strategy of the Moravian-Silesian Region (Moravian-Silesian Region, 2017)	2017	2017–2023
ZLK	Strategy for the Development of the SMART Region Zlín Region (Zlín Region, 2021)	2021	–2030

Source: own

Tab. 2: Smart city reference domains

No.	Reference domains
I.	Systematic science, research, education, and innovation
II.	Transport and accessibility
III.	Technical infrastructure
IV.	Social and healthcare services
V.	Public administration
VI.	Environment, culture, and tourism

Source: Urbanik and Horalek (2022)

of structure, terminology and level of detail, the study applies qualitative content analysis (QCA) as an interpretative and context sensitive approach. The analysis was conducted on the latest (valid on 1 March 2025) regional development strategies of Czech administrative regions. Tab. 1 shows a total of 21 documents from all 14 regions of Czechia were analyzed to determine the extent to which smart concepts are incorporated into regional planning. The primary data source for these documents was the publicly accessible Database of Strategies by MoRD (available at https://www.databaze-strategie.cz/), which contains all relevant international, national, regional, provincial and local strategic documents.

The analysis focused on several key aspects. It examined whether and how regions have incorporated the SC concept into their current development strategies, including how many regions explicitly mention smart concept, the extent to which the topic is addressed, and the strategic level at which the concept appears, distinguishing between priority areas (PAs), strategic objectives, and mere references within broader goals. In regions that have adopted a dedicated smart strategy, the analysis further explored the thematic areas and priorities emphasized, as well as the overall structure and development process of these strategies.

Using QCA, each document was systematically reviewed using a manual and iterative procedure. The primary coding was conducted by the first author. First, all documents were searched for predefined keywords related to the smart concept (e.g., “smart”, “smart city/cities”, “smart region”, “smart solution”, and their Czech equivalents chytrý/chytrá/chytré). In parallel, the analysis included a systematic reading of priority areas and strategic objectives in order to identify thematic elements corresponding to the SC concept, even where the term “smart” was not explicitly used. In several strategies, specific graphical labels or icons were employed to mark measures or objectives as being aligned with the smart concept. Subsequently, all identified passages were examined in their full context in order to assess their strategic relevance. For smart strategies, the analysis further examined how each region perceives the smart concept, and which areas or domains are included in the strategy.

Identified elements were recorded in structured tables in MS Excel and categorized according to thematic patterns. These were subsequently mapped to the individual domains of the SC domain model (see Tab. 2), which serves as a reference framework for comparing current SC strategies and illustrating their heterogeneity and differences in thematic coverage.

Cybersecurity was not included as a separate reference domain because it is only rarely addressed explicitly in regional SC strategies and is generally treated as a mandatory prerequisite rather than a strategic objective. It is understood as a systemic requirement embedded in the broader legal, regulatory, and technical framework governing digital infrastructures and public administration, which further explains why it is not articulated as a distinct strategic priority.

Based on the systematic analysis of regional strategic documents, key barriers and challenges to the implementation of the SC concept in Czechia were identified. These findings then served as the basis for formulating targeted recommendations aimed at mitigating the identified obstacles and enhancing the effective integration of smart principles into regional strategic planning.

Given the large number of strategic documents and their complex hierarchy and interconnections in Czechia, it is not possible to examine all of them comprehensively. Some regions also develop numerous sub-strategies, which may, in some cases, compensate for missing areas. Additionally, the analysis is inherently influenced by subjective interpretation, particularly in the categorization of PAs within smart strategies, meaning that classifications may not always be entirely precise.

The main findings of the analysis, the identified barriers, and the resulting recommendations were consulted with an expert in regional planning from the Centre for Investment, Development and Innovation of the Hradec Králové Region (CIRI HK) in order to validate their practical relevance and interpretation.

3 Results and discussion

3.1 Results

Despite structural differences, most regional strategies follow a similar hierarchical logic, typically consisting of PAs, strategic goals, and specific Measures. Terminology, however, varies across documents, and some regions use these terms inconsistently. The Ústí nad Labem Region represents the greatest deviation from this model, as its strategy is organized into territorial units with independently formulated goals. The number and scope of PAs also differ markedly, ranging from three in Prague to ten in the Central Bohemian Region. While some regions use broad, integrated PAs covering multiple themes, others opt for narrow, sector-specific categories. This heterogeneity complicates the classification of PAs and limits the comparability of strategies.

The analysis shows that all regions incorporate SC concept into their current strategies, yet the extent of integration varies widely and is often vague. Some regions, such as Olomouc, define concrete SC-related goals and measures, whereas others, including Pardubice, Pilsen, Karlovy Vary, and Ústí nad Labem, only mention the concept without further specification. Seven regions have prepared dedicated smart strategies, mostly around 2019, many of which rely on now outdated national guidelines. Interpretations of “smart” also differ. Some emphasize quality of life through innovation, while others reflect earlier methodological influences focused on transport, energy, and ICT. The Central Bohemian Region adopts a particularly distinct approach by combining the SC concept with both the classical S.M.A.R.T. criteria and its own adapted acronym.

As illustrated in Tab. 3 using the domain model by Urbanik and Horalek (2022), there are considerable differences in how regions define PAs and strategic objectives. Tab. 3 maps the priority areas defined in regional SC strategies to the reference domains of the SC domain model (Tab. 2). Each cell lists the specific priority areas that fall within the respective domain for a given region. Where a priority area spans multiple domains, it appears in more than one column. Partial coverage of a domain is indicated in bold. The primary purpose of Tab. 3 is to highlight the heterogeneity of regional SC strategies and the diversity in how PAs are formulated and conceptually framed. It includes only those regions that have adopted a dedicated SC strategy, as these documents provide explicit SC priorities to enable domain-based comparison.

Some PAs span multiple domains due to thematic overlap, while others merge several sub-areas into single categories, resulting in strong heterogeneity. Another key insight from Tab. 3 is the prioritization of certain areas and the omission of others. Although regional differences are expected, major domains such as transport, parking, administration, and healthcare are relevant to all larger cities and should be reflected in strategic documents. Comprehensive coverage would enable more meaningful regional comparisons, clearer evaluation of SC maturity, and better identification of priorities for future development.

The lack of standardization in terminology, structure, and thematic focus further complicates knowledge sharing and practical implementation. Regional practitioners consistently highlight the need for clearer definitions and national-level coordination to streamline processes and support more effective smart development across Czech regions.

3.2 Application gaps

The results revealed significant differences between these strategies, both in terms of their development processes and in how

Tab. 3: Overview of PAs from smart strategies compared to the SC reference model

Region	Reference domains					
	I.	II.	III.	IV.	V.	VI.
PHA	Innovation Management, Innovation culture	**Mobility** and public space	Energy and buildings, Innovation and technology infrastructure			Mobility and **public space,** Environment
STČ	Funding, Education and schools	Transport and mobility	ICT infrastructure, Energy	Social services and healthcare	eGovernance	Water and waste management
JHČ		Mobility	eGovernment and digitalisation, Energy	Healthcare and social services	Efficient territorial governance and innovation	Environment
LBK	**Smart economic development** and tourism, Smart education	Smart transport	Smart technical infrastructure	Smart healthcare, Smart social services	Smart public administration	Smart economic development and **tourism**, Smart environment
HKK	Knowledge economy	Transport	Energy	**eHealth**, eCulture, eTourism	Public administration	Environment, eHealth, **eCulture, eTourism,** Public space and housing
MSK		Transport	ICT infrastructure, De-bureaucratisation, Savings	Healthcare	De-bureaucratisation	Savings
ZLK	Smart People **– education, community development**, culture, **Smart economy, smart business and innovation**, tourism	Smart mobility	Smart energy, **Smart housing**, social services and healthcare	Smart housing, **social services and healthcare**	Smart public administration	Smart economy, smart business, innovation, **tourism**, Smart People – education, community development, **culture**, Smart environment

Note: Partial coverage of a domain is indicated in bold.

Source: own

SC concept is perceived and interpreted. Building on these findings, several key application gaps (AG) were formulated. Gaps that are predominantly administrative in nature and closely linked to the regional systems of strategic management. These gaps contribute not only to inconsistencies in the implementation of SC initiatives across regions but also hinder the exchange of best practices and the establishment of a coherent national approach. The following nine key application gaps have been identified.

AG1) Conceptual and methodological fragmentation

One of the key barriers is the lack of a unified and widely accepted definition of the Smart City/Smart Region concept, both internationally and within Czechia. Although several national methodological documents exist, they provide only general guidance and do not resolve this conceptual ambiguity. The situation is further complicated by regions relying on different methodological versions, most commonly the 2018 methodology, the updated 2021 Smart Cities Concept, and in some cases even the 2015 framework. As a result, interpretations of the SC concept vary widely, ranging from broad and vague understandings to narrowly technocratic, digitalization-focused approaches. These inconsistencies are reflected in the structure of smart strategies, terminology, strategic priorities, and thematic orientation. The resulting fragmentation hinders experience sharing, benchmarking, national-level coordination, and the development of comparable best practices across regions.

AG2) Heterogeneity of development strategies

Significant barrier is the pronounced heterogeneity of development strategies across Czech regions. While the autonomous preparation of strategies at the regional level is both desirable and necessary to address specific local needs, the lack of clear national guidelines regarding the structure and content of these documents leads to substantial discrepancies. The state currently plays only a limited coordinating role and does not sufficiently function as a supervisor or standard-setter in this process. As a result, there is a lack of consistency not only in the level of strategic objectives, but also in the depth and granularity of proposed measures. This fragmentation complicates both the evaluation and comparison of regional strategies and makes it difficult to ensure coherence with national and international goals.

AG3) Outsourcing of strategy development

Another significant limitation is the outsourcing of strategic document preparation to external consultants or agencies, which may lack sufficient knowledge of national and international frameworks and SC concepts. This can result in an inadequate or incomplete reflection of recommendations and trends in SC development, or the omission of key topics altogether. Furthermore, this practice reinforces the heterogeneity of strategies, as the approaches and interpretations applied by various external actors can differ substantially, leading to even greater fragmentation and inconsistency among regional SC strategies.

AG4) Insufficient awareness among regional representatives

Regional representatives often lack sufficient awareness and understanding of relevant national strategic documents, which represents another significant barrier. As a result, regional strategies are often not properly aligned with or explicitly reference key national frameworks. This lack of awareness leads to limited integration of national priorities at the regional level and contributes to inconsistencies, overlaps, and missed opportunities for greater synergy both vertically (between national, regional, and local strategies) and horizontally (among various sectoral documents within regions).

AG5) Absence of dedicated implementation strategies and a clear vision

In many regions, there are no standalone strategies or action plans specifically for the implementation of smart solutions, and often a clear and cohesive vision for SC development is also missing. SC concept is frequently mentioned only marginally within broader priorities (such as digitalization or innovation), without being underpinned by a long-term vision, concrete measures, indicators, or budget frameworks. This results in ambiguity regarding responsibilities, a lack of measurable objectives, and difficulties in evaluating the effectiveness of SC initiatives.

AG6) Fragmentation of strategic documents

At the regional level, strategic documents are often fragmented, hindering coherent planning and implementation. While some regions produce only a few supplementary or sectoral strategies, others create many such documents to compensate for missing thematic areas or to expand specific objectives. However, these partial strategies are frequently poorly connected to the main regional development strategy. The lack of formal integration results in a proliferation of disconnected documents, reducing strategic clarity, complicating implementation, and making it more difficult to assess progress or ensure alignment with broader development goals.

AG7) Insufficient stakeholder and public involvement

Many documents lack emphasis on participatory planning, i.e., the active involvement of key stakeholders (municipalities, citizens, businesses) in the strategy development process. Without their participation, there is a risk of low acceptance and limited progress in implementation.

AG8) Perception of smart city as a "natural development"

Some regions do not perceive the SC as a distinct or innovative concept, but rather as part of the natural evolution of urban planning. Many SC objectives are viewed as already integrated into existing strategies (e.g., fulfilling Agenda 21 and 2030), leading to the absence of dedicated measures and plans. This perspective is also reflected in the official Methodology for the preparation and implementation of the Smart Cities (MoRD, 2018), which states that if a city already implements Místní Agenda 21 (MA21 – a framework for local sustainable development), there is no need to create a parallel structure or a separate SC strategy.

AG9) Insufficient implementation of strategic plans

Despite the existence of strategic documents and action plans, many regions face significant challenges in translating these plans into practical measures and tangible results. This application gap is often due to insufficient stakeholder involvement, lack of clear assignment of responsibilities, limited resources, or inadequate feedback mechanisms. As a result, smart solutions frequently remain at the planning stage, without progressing to real-world application. Bridging this gap requires stronger participatory approaches, ongoing monitoring, and adaptive management to ensure that strategic objectives are realized in practice.

The identified barriers are closely interconnected, with several functioning as direct causes or consequences of others. AG1) Conceptual and methodological fragmentation represents the primary root cause, leading to pronounced AG2) Heterogeneity of development strategies. This is further reinforced by AG3) Outsourcing of strategy development, which introduces additional variability and weakens internal coherence. AG4) Insufficient awareness among regional representatives acts both as a cause and a multiplier, as limited familiarity with national frameworks results in weak integration

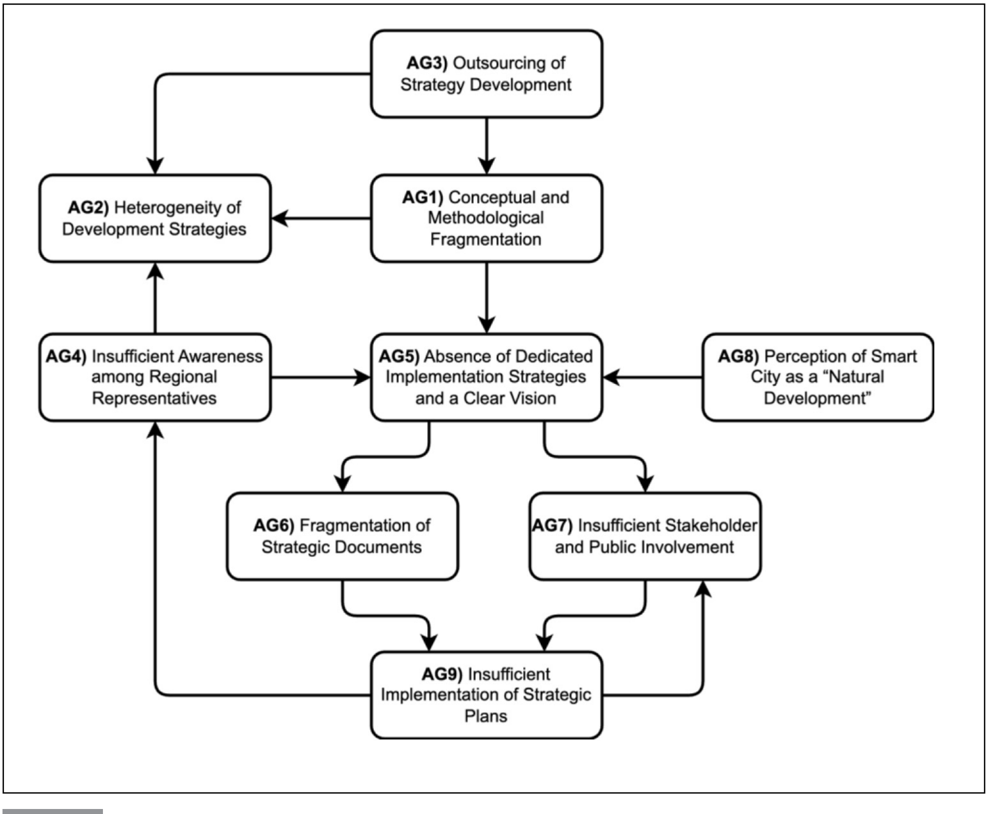

Fig. 1: Interrelationships among key application gaps (AG1–AG9)

Source: own (using Draw.io)

of national priorities into regional strategies. The AG5) Absence of dedicated implementation strategies and a clear vision stems from these conceptual and informational gaps and contributes to further AG6) Fragmentation of strategic documents, as regions attempt to compensate through additional, often uncoordinated materials. AG7) Insufficient stakeholder and public involvement is both a symptom and a driver of weak strategic anchoring, while the AG8) Perception of smart city as a "natural development" reflects the lack of clear definition and leads to the dilution of SC objectives within broader plans. Finally, AG9) Insufficient implementation of strategic plans emerges as both an outcome and a reinforcing mechanism, often resulting from unclear responsibilities, lack of resources, and weak feedback processes. This implementation gap prevents strategies from being translated into practice and perpetuates further fragmentation and disengagement. Overall, these barriers form a mutually reinforcing system in which foundational issues trigger cascading effects that undermine coordination, coherence, and the effective development of SC initiatives in Czechia. Fig. 1 highlights the key causal relationships among the identified application gaps. However, additional interdependencies among these gaps may be present.

Each of the identified application gaps also entails specific economic implications. AG1) Conceptual and methodological fragmentation and AG2) Heterogeneity of development strategies increase transaction costs and weaken economies of scale by preventing coordinated investments and shared solutions across regions. AG3) Outsourcing of strategy development generates direct public expenditures on external consultants, which become sunk costs when strategies are weakly implemented or fail to inform concrete projects. AG4) Insufficient awareness among regional representatives undermines the alignment of strategies with real demand and relevant solutions, thereby distorting ex ante cost-benefit analyses (CBAs) and increasing the risk that SC projects will generate irreversible costs rather than socially valuable returns. AG5) Absence of dedicated implementation strategies and a clear vision, together with AG6) Fragmentation of strategic documents, weakens budgetary planning, leads to duplicated investments, and reduces the cost-effectiveness of public spending. AG7) Insufficient stakeholder and public involvement further amplifies these inefficiencies by increasing the likelihood that projects will be poorly utilized or rejected by intended users. Finally, AG9) Insufficient implementation of strategic plans represents unrealized or misaligned projects result in wasted resources and missed development opportunities, thereby undermining the overall value-for-money performance of SC investments.

3.3 Recommendations

The analysis has identified a set of closely interrelated application gaps that significantly impede the effective implementation of the SC concept in Czechia. These gaps are predominantly administrative in nature and reflect fundamental inconsistencies in strategic management, conceptual understanding, and coordination both within and between regions. Their persistence and mutual reinforcement create a complex and self-perpetuating system of barriers, which not only hinders progress but also undermines the coherence of SC development nationwide. In light of these findings, a set of targeted and systemic recommendations (R) is proposed to address the identified application gaps and support more effective SC implementation at both national and regional levels.

R1) Strengthen national coordination and methodological support

Addresses these application gaps: AG1) Conceptual and methodological fragmentation; AG2) Heterogeneity of development strategies; AG4) Insufficient awareness among regional representatives.

A unified national framework is essential to overcome the conceptual and methodological fragmentation currently observed. The MoRD should intensify its role not only as a provider of methodological materials, but also as a coordinator and supervisor. This process should begin with the updated Smart cities concept from 2021, which should serve as a mandatory reference point for all regional and local strategies. In addition, regular updates and dissemination of the national smart cities methodology are necessary, accompanied by targeted awareness campaigns, training programs, and capacity-building activities for regional and local officials. Furthermore, the establishment of a knowledge-sharing platform would facilitate the exchange of best practices and lessons learned across regions, contributing to greater consistency and efficiency in the development and implementation of SC strategies throughout Czechia.

R2) Foster strategic integration and coherence

Addresses these application gaps: AG2) Heterogeneity of development strategies; AG4) Insufficient awareness among regional representatives; AG6) Fragmentation of strategic documents.

To address the heterogeneity and fragmentation of strategies, it is crucial to promote both vertical and horizontal integration. Vertical integration should ensure that regional and local strategies explicitly reference and align with relevant national and European frameworks, while also encouraging the coordination of sectoral strategies within each region. At the same time, horizontal integration requires the development of clear guidelines for incorporating supplementary or thematic strategies into the primary regional strategic framework, thereby improving overall coherence and clarity. Furthermore, the introduction of a recommended or mandatory structure for SC strategies, including sections on vision, goals, measures, implementation plans, monitoring, and stakeholder engagement, would help standardize the strategic planning process and facilitate comparison and collaboration across regions.

R3) Improve awareness and capacity among regional representatives

Addresses these application gaps: AG1) Conceptual and methodological fragmentation; AG4) Insufficient awareness among regional representatives.

One of the root causes of insufficient strategic linkage is the lack of awareness and understanding of national frameworks among regional representatives. This challenge can be addressed through systematic training of regional and municipal staff on national methodologies and relevant policy documents, supported by interactive workshops and seminars focused on case studies and the practical application of SC principles. Additionally, ongoing support and consultancy provided by national-level experts would help ensure that regional and local actors are equipped with the knowledge and skills needed to effectively align their strategies with national frameworks.

R4) Enhance stakeholder and public involvement

Addresses these application gaps: AG5) Absence of dedicated implementation strategies and a clear vision; AG7) Insufficient stakeholder and public involvement; AG9) Insufficient implementation of strategic plans.

Participatory planning remains an underutilized tool in regional SC strategies. It is essential to actively involve stakeholders, including municipalities, citizens, businesses, and academic institutions, at all stages of strategic planning and implementation. Developing participatory tools and guidelines can help ensure meaningful and systematic engagement, while the incorporation of feedback mechanisms will improve the legitimacy and acceptance of SC initiatives. This approach not only strengthens community ownership and the overall effectiveness and sustainability of smart solutions but also helps to translate proposed measures from strategic plans into practical, real-world implementation.

R5) Promote a clear vision and long-term perspective

Addresses these application gaps: AG5) Absence of dedicated implementation strategies and a clear vision; AG8) Perception of smart city as a “natural development”; AG9) Insufficient implementation of strategic plans.

A key element missing in many regions is a clear, shared vision for SC development. It is important to support regions in the formulation of comprehensive SC visions that are tailored to their specific needs and potential, while still being anchored in national priorities and global trends. Emphasizing the role of strong leadership and long-term planning is essential for driving successful SC transformation. Additionally, it is crucial to monitor and evaluate not only the implementation of specific measures, but also the ongoing relevance and effectiveness of the overarching strategic visions to ensure they remain aligned with evolving challenges and opportunities.

R6) Mitigate the negative impacts of outsourcing

Addresses these application gaps:
AG1) Conceptual and methodological fragmentation; AG3) Outsourcing of strategy development.

While external expertise can provide valuable input, it is important to ensure that outsourced strategies are developed in close collaboration with regional authorities and in accordance with national guidance. External consultants should be required to reference and integrate relevant national and international SC guidelines in their work. Additionally, establishing quality control mechanisms to review and approve strategic documents before their adoption will help maintain consistency, coherence, and alignment with broader policy objectives.

R7) Reduce fragmentation of strategic documents

Addresses these application gaps: AG2) Heterogeneity of development strategies; AG6) Fragmentation of strategic documents.

To address the proliferation of disconnected supplementary and sectoral strategies, it is recommended that regions adopt clear guidelines for integrating these documents within the overarching strategy. Rather than consolidating all content into a single comprehensive document, regions should ensure that whenever a supplementary or thematic strategy is developed, it is explicitly linked to the relevant strategic goals outlined in the primary strategy. This cross-referencing approach increases transparency, facilitates coordination, and enables a more coherent implementation and evaluation of development objectives, while still allowing for the flexibility and depth provided by thematic or sectoral strategies.

Fig. 2 illustrates how the proposed recommendations (R1–R7) address the identified application gaps (AG1–AG9) and reveals the need for integrated policy responses. The chord diagram shows that many recommendations are linked to multiple gaps, indicating that

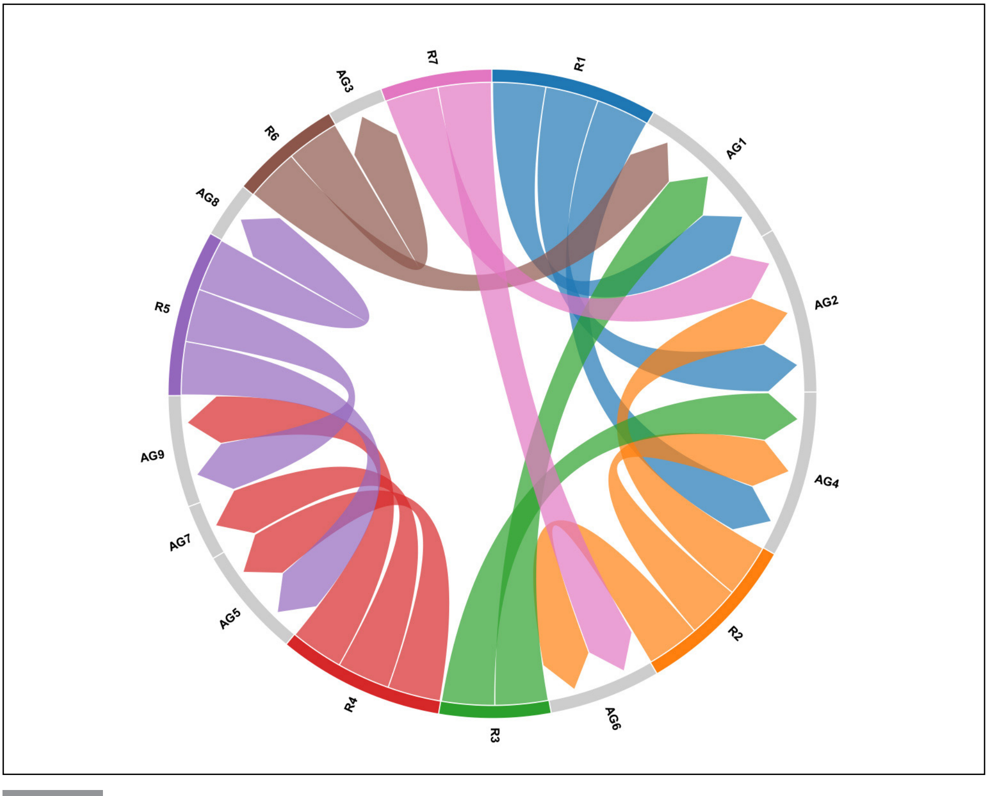

Fig. 2: Mapping of proposed recommendations to identified application gaps

Source: own (using RAWgraphs 2.0)

fragmented or isolated interventions are unlikely to resolve the underlying structural problems.

3.4 Discussion

Implementing the proposed recommendations requires coordinated action across governance levels, as the systemic nature of the identified barriers makes isolated solutions ineffective. A holistic approach combining clearer methodological support, stronger awareness, strategic integration, and participatory planning is essential. This aligns with previous studies, which emphasize that the success of SC initiatives depends on their integration into broader governance frameworks and long-term planning processes (Akgün et al., 2024; Correia et al., 2022; Mora et al., 2025). Addressing fragmentation and incoherence will not only improve Czechia's administrative efficiency and support innovative solutions but also strengthen benchmarking, international cooperation, and access to external funding. Research shows that fragmented governance and limited interdepartmental coordination undermine strategic alignment and lead to duplicated or inconsistent efforts (Makki & Alqahtani, 2024; Shah et al., 2024).

Czechia continues to lag behind many EU countries in the practical implementation of SC concepts. Even when strategies and action plans exist, they often remain unimplemented. An issue also observed internationally (Mashau & Kroeze, 2023; Singh et al., 2022). This implementation gap highlights the need for regional authorities to systematically evaluate past shortcomings and integrate lessons learned into future planning cycles. Enhancing transparency and accountability is equally important. Citizens should be regularly informed about completed projects and their contribution to regional development. Transparent communication and participatory governance are repeatedly identified as key factors for social acceptance and long-term legitimacy in SC transformations (Akgün et al., 2024; Javed et al., 2022; Rosário & Boechat, 2024).

Ultimately, moving from planning to real implementation is essential for credible and effective SC development. Without tangible outcomes, strategic documents risk losing legitimacy and impact, a concern widely noted in the literature (Mansoori, 2021; Shah et al., 2024). Future research should therefore examine the real-world effects of SC initiatives, compare Czechia's performance with other EU countries, and analyze the role of stakeholder involvement and participatory processes. Developing robust evaluation frameworks and exploring themes such as data-driven management, digital inclusion, and resilience would further support adaptive governance (Mora et al., 2025; Schuch De Azambuja, 2021). By addressing systemic barriers and drawing on international experience, Czechia can progress from planning to meaningful smart transformation of its urban and regional environments.

Conclusions

This study examined how the SC concept is incorporated into the strategic planning frameworks of Czech regions and identified the key barriers that hinder its effective implementation. The analysis of 21 regional development and smart strategies revealed substantial variability in the depth, structure, and interpretation of SC principles across regions. While all regions refer to the smart concept in some form, only a minority have developed dedicated strategies, many of which rely on outdated methodological guidance and differ significantly in terminology, thematic focus, and strategic logic. Using SC domain model as a reference, the research demonstrated that PAs are defined inconsistently, with some domains omitted entirely, making meaningful comparison and evaluation challenging.

The study identified nine closely interconnected application gaps, rooted primarily in conceptual and methodological fragmentation, heterogeneous strategic structures, limited awareness of national frameworks, insufficient stakeholder participation, and a persistent implementation gap. These barriers form a mutually reinforcing system that undermines coherence, reduces strategic clarity, and significantly limits the translation of strategic intentions into real-world outcomes.

To address these challenges, the paper formulates seven targeted recommendations focused on strengthening national coordination, improving methodological support, enhancing stakeholder engagement, reducing fragmentation, and promoting clearer strategic visions. Implementing these measures would enable more consistent planning, support knowledge sharing, and improve the integration of smart solutions across Czech regions.

Overall, the findings show that Czechia stands at a critical point in the development of smart regions. By addressing the identified barriers and adopting a more coordinated, participatory, and implementation-oriented approach, the country can move beyond fragmented planning and achieve more effective, sustainable, and citizen-oriented SC development. The study also highlights the need for continued research on implementation practices, evaluation mechanisms, and the long-term impacts of smart initiatives.

Acknowledgments: *This research was supported by the Ministry of the Interior of the Czech Republic under the project "Application of Artificial Intelligence for Ensuring Cyber Security in Smart City" (No. VJ02010016) and by the Faculty of Informatics and Management, University of Hradec Kralove, through the specific research project 2108 "Addressing Current Challenges in the Field of Smart Cities and Cybersecurity".*

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Appendix

Appendix 1: Regional development and smart strategies

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Reimagining campus mobility through the lens of the 15-Minute City

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Abstract: *The 15-Minute City concept envisions urban environments where residents can access essential services within a short walking or cycling distance. Although education is recognized as one of the core functions within this framework, the specific role of universities in promoting proximity-based urban models remains largely unexplored. This study addresses this gap by examining how universities, as significant generators of mobility, can contribute to the realization of the 15-Minute City principles. Using the Technical University of Kosice (TUKE) as a case study, the paper develops a methodological framework to evaluate multimodal accessibility and the use of active mobility within university environments. The research combines spatial analysis of 15-minute isochrones for walking and cycling with Kernel density estimation (KDE) heatmaps to visualize shared micromobility patterns. This analytical approach proves effective in identifying infrastructural barriers and opportunities for promoting more sustainable university-related commuting. The results reveal that universities are often underutilized actors in urban mobility transitions, exposing both infrastructural deficiencies and behavioral patterns that limit sustainable travel to and within campus areas. The discussion highlights that universities have the potential to enhance sustainability and resilience by implementing policy measures aligned with proximity-based planning – focused on integrating active mobility solutions – either independently or through cross-sector collaboration. By positioning universities as pivotal yet often overlooked institutions in urban transformation, this study contributes to the ongoing discourse on the 15-Minute City and introduces a novel methodological approach tailored to higher education contexts. It underscores the potential of academic campuses to act as catalysts for sustainable mobility practices and broader urban change.*

Keywords: *15-Minute City, campus mobility, micromobility, sustainable development, sustainable urban transportation.*

JEL Classification: *R11, R41, R58.*

APA Style Citation: Surmikova, D., & Dzupka, P. (2026). Reimagining campus mobility through the lens of the 15-Minute City. *E&M Economics and Management*, *29*(3), 61–79. https://doi.org/10.15240/tul/001/2026-5-006

Early Access Publication Date: *May 21, 2026.*

Introduction

In 2016, urbanist Carlos Moreno proposed the 15-Minute City concept as an urban revitalization strategy aimed at reducing car dependency, promoting sustainable urban development, and enhancing the overall quality of life for city dwellers (Moreno, 2024). The concept is rooted in the theory of chrono-urbanism, which posits that decreasing the time residents spend traveling within the city contributes to improved quality of life (Rojas-Rueda et al., 2024).

The core principle of the 15-Minute City is that cities should be planned or reshaped so that the core elements of urban life are reachable within a 15-minute walk or bike ride (Moreno, 2024). This concept encompasses six fundamental urban functions: (1) housing; (2) employment; (3) commerce; (4) healthcare; (5) education; and (6) culture and leisure (Moreno, 2024).

According to the 15-Minute City framework, these six functions should be ensured through key dimensions of urban planning: diversity, density, digitalization, and proximity (Moreno, 2024). Fig. 1 illustrates the conceptual framework of the 15-Minute City.

The 15-Minute City emphasizes the spatial proximity of services as a crucial assumption for its successful implementation. Prioritizing proximity in urban planning not only results in environmental improvements but also offers numerous social benefits, such as improved health (Balcetis et al., 2020), enhanced social interactions (Su et al., 2019), and time savings (Khavarian-Garmsir et al., 2023).

A major advantage of service proximity is its potential to foster sustainable mobility. When essential services are located within a short distance of residents' homes, reliance on private cars tends to decrease proportionally (Moreno, 2024). Instead of cars, the 15-Minute City model assumes the use of alternative transportation modes for daily commuting.

Although the 15-Minute City includes education as one of the essential services accessible within the 15-minute timeframe, it lacks a specific focus on the role of universities. Beyond their conventional functions – education and research – universities, with their large communities of students, staff, and visitors, significantly influence urban traffic flows (Mohammed et al., 2022), and therefore play a strategic role in the successful implementation of the 15-Minute City concept.

This study explores university-generated mobility within the context of the 15-Minute City through three key perspectives. First,

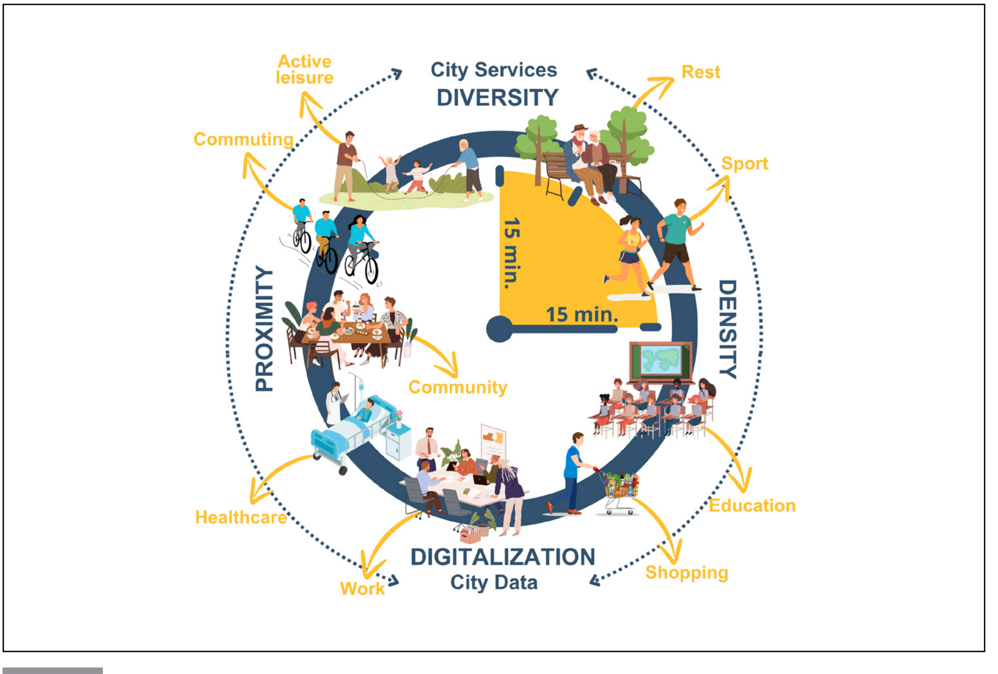

Fig. 1: The 15-Minute City concept

Source: own based on Moreno (2024)

it examines the role of universities within the 15-Minute City framework. Second, it introduces a methodological approach for analyzing multimodal 15-minute travel distances to key university locations, alongside an assessment of current active mobility usage, based on 15-minute isochrones and shared micromobility data, with a particular focus on the travel patterns of students and staff. Third, using Technical University of Košice (TUKE) as a case study, the paper validates the proposed methodology and, based on the analysis results, proposes policy measures designed to support the vision of a sustainable university campus.

Building on the theoretical background, this article addresses the following research questions:

RQ1: How the 15-minute accessibility of strategic university facilities by active modes of transport, together with an analysis of their usage, can be assessed;

RQ2: What policy measures can be adopted independently universities, by cities themselves, or collaboratively by various stakeholders to encourage active mobility among university populations, thereby reducing car dependency and positively influencing overall urban mobility.

The article is structured as follows: section 1 examines the role of universities within the 15-Minute City concept and outlines the theoretical background for university-generated mobility. Section 2 describes the data and methodology used in the study. Section 3 presents the characteristics of TUKE and its current state regarding active mobility, analyzes and discusses the results, and proposes policy recommendations for practical implementation.

1 Theoretical background

1.1 Universities in the 15-Minute City

The increasing volume of scientific literature on the 15-Minute City in recent years underscores the concept's novelty and its growing relevance within the professional community. While research on the 15-Minute City and education has predominantly focused on elementary and high schools and their multifunctional uses (Moreno, 2024), there is a notable gap in understanding the role of universities within this framework.

To address this gap, our study builds on existing framework developed by Büttner et al. (2024), who identify four key areas of action (KA) that are central to the implementation of the 15-Minute City concept: (1) sustainable urban mobility; (2) people-centered urban spaces and planning; (3) smart urban logistics, production, and service sites; and (4) urban governance for mobility transition. We adopt these four key areas and apply them to the university context. In the following sections, we discuss each KA and its relevance for university campuses.

KA1: Sustainable urban mobility

Density and proximity – two dimensions of the 15-Minute City – are directly linked to sustainable transportation over short distances. Thus, sustainable mobility for students and staff within and around the university campus supports the broader city's transportation goals aligned with 15-Minute City principles. University campuses should be designed (or revitalized) to encourage walkability, cycling, and the use of public transportation, aiming to reduce dependence on private vehicles, particularly cars.

KA2: People-centered urban spaces and planning

Another dimension of the 15-Minute City is diversity, which is associated with mixed-use development. KA2 emphasizes that students and staff require a university environment that supports their well-being. In the context of a university campus, mixed-use development that enhances well-being means providing access to essential services within a 15-minute radius not only for students and staff, but also for neighborhood residents.

A crucial step toward establishing campuses that are open to both university members and the local community could involve adopting the idea of blurring campus boundaries (Berman et al., 2022). This would position the university as a collaborative third place and a community-oriented public space.

On the one hand, it is important to objectively assess what the campus can offer to students, staff, and residents. On the other hand, it is equally critical to gather subjective input from these groups regarding their desires and needs for the future campus.

We argue that the essential services within university campuses may differ from those typically found in a 15-Minute City and will likely vary between students, staff, and local residents. For students, services such as dormitories, libraries, canteens, cafés, sport facilities, and relaxation zones may be key. For staff, important services may include co-working spaces, innovation hubs, shops, childcare facilities, and extracurricular activities for children. For neighborhood residents, benefits could come from access to parks, libraries, cultural events, and public workshops.

KA3: Smart urban logistics, production, and service sites

Digitalization – also referred to as ubiquity within the 15-Minute City discourse – is another critical dimension. In the university context, it is closely linked to logistics and technological advancement, enabling the efficient and sustainable management of campus operations. Digital tools can support data collection, analyses, and the creation of more tailored and effective policies. Furthermore, they can optimize campus logistics and services, contributing to greater sustainability in day-to-day university functions.

KA4: Urban governance for mobility transition

To fully align university development with the principles of the 15-Minute City, it is necessary not only to understand the current state of the campus and its surroundings, but also to articulate a vision for its future. However, this vision can only be realized through the formulation and implementation of effective policies. The policy-making process should be inclusive, involving key university and city stakeholders – ideally through structured dialogues such as roundtable discussions and participatory planning sessions.

While the role of universities in the 15-Minute City can be examined through multiple lenses, this study focuses on KA1 – sustainable urban mobility, with particular emphasis on the university's role within transportation systems.

1.2 University-generated mobility in relation to overall urban mobility

Due to their strategic location within urban ecosystems, universities can be regarded as key co-creators of urban mobility (Romanowska et al., 2017). Tens of thousands of students and staff commuting daily generate significant traffic flows, which contribute to urban congestion. As such, universities are important stakeholders in the planning and transformation of urban transport systems (Colleoni et al., 2024).

The term university-generated mobility in this study refers to all forms of movement resulting from the activities of university students and staff, as well as individuals connected to university life in any way (e.g., domestic or international visitors). Within this research, university-generated mobility encompasses not only daily commutes between home or accommodation and the university but also other trips undertaken during the day that originate from or are directed toward the university.

University-generated mobility therefore represents the total set of trips made primarily, though not exclusively, by students and employees during a typical academic working day – from the first journey to the university to the final trip leaving it. For the purposes of this research, university-generated mobility does not merely include direct trips between the university and home or accommodation; it also covers intermediate trips made between different activities throughout the day. Examples include walking from the university canteen to a city center café before returning for an afternoon lecture, or traveling to a gym between separate class sessions. These trips occur as a consequence of the class schedule and the personal needs of individuals.

If classes were not divided into distinct time blocks with long breaks, student and staff mobility would likely differ significantly, as there would be less need to fill gaps between classes with additional activities. When studying university-generated mobility, it is essential to recognize that transport flows generated by universities differ from other mobility patterns: they are determined both by the phase of the academic year and by the structure and timing of students' individual teaching schedules (Ribeiro & Fonseca, 2022).

Students attend classes during the winter and summer semesters for approximately three months each, then visit the university mainly on examination days, with the summer period being a vacation time. These temporal dynamics reduce pressure on urban transport systems, as the flow of people traveling to the university declines markedly during such periods.

University-generated mobility can take many forms and represents a diverse mix of transport modes – from walking and cycling to motorized options such as private cars and public transport (Ribeiro et al., 2020). The choice of transport mode depends on various factors, including season and weather, the availability of public transport, cycling infrastructure, and parking facilities on or near campus (Ek et al., 2021; Ribeiro & Fonseca, 2022). These aspects must be considered when designing and planning university campuses and assessing their impact on citywide mobility.

Among these factors, parking is perhaps the most frequently discussed in the context of sustainability and carbon-neutral campuses. For many universities worldwide, commuting is one of the largest contributors to their environmental footprint (Crotti et al., 2022). As a result, universities are increasingly adopting various parking policies to encourage more sustainable forms of mobility.

Measures that enhance sustainable campus mobility include charging relatively high parking fees to discourage car use, reducing the number of available parking spaces, removing certain parking areas, and even establishing car-free campuses (Rodrigues da Silva et al., 2024). In such cases, campuses effectively become full pedestrian zones, improving accessibility and safety, supporting sustainable transport modes, and ultimately reducing the university's environmental impact.

An environmentally friendly alternative to car travel is micromobility, which has significant potential to become the primary mode of transport for university students and staff while reducing the institution's carbon footprint (Roknaldin et al., 2025). In this context, the present paper explores micromobility as a sustainable alternative for university transportation and examines its potential to reshape commuting patterns among university communities. The term micromobility refers to modes of transport typically limited to speeds of up to 45 km/h (Oeschger et al., 2020). Micromobility is a fundamental component of the 15-Minute City concept (Moreno, 2024); thus, if universities aspire to implement 15-Minute City principles, they must support micromobility through measures such as developing safe and quality pedestrian and cycling infrastructure.

However, a major challenge lies not only in adapting infrastructure but also in motivating students and employees to shift from private car use to more sustainable modes of transport such as walking, cycling, or shared micromobility. Micromobility also plays an important complementary role in public transport systems.

If universities do not provide dedicated public transport routes connecting campuses with key urban areas, public transport networks may become overloaded. The most critical segments are typically those between dormitories and the campus (when the dormitories are not located within the campus) or between the city center and the university area. Overcrowding, irregular service, and delays can discourage students and staff from using public transport, negatively affecting individual well-being and, consequently, overall quality of life (Ruiz-Padillo & de Oña, 2024). Therefore, it is crucial not only to promote sustainable mobility but also to address challenges related to public transport capacity and the availability of alternative transport modes.

This study specifically analyzes the use of shared micromobility services through the case study of TUKE. The main focus is on exploring the transportation patterns of TUKE students and staff, who represent the primary contributors to university-related mobility. The discussion proposes policy measures that can be implemented by the university, the city, shared micromobility service providers, or collaboratively by all stakeholders to encourage the adoption of sustainable modes of transportation among university students, staff, and visitors.

2 Research methodology

First and foremost, it was essential to develop a comprehensive understanding of the 15-Minute City concept, the role universities play within this framework, and university-generated mobility. This was achieved primarily through the literature review on topics such as the "15-Minute City", "active mobility", "campus mobility", "micromobility", "university students and staff travel behavior", and "university transportation flows".

This article primarily focuses on a series of spatial analyses centered on the TUKE Campus. All visualizations in this study were created in RStudio programming environment, with map tiles retrieved from Google Maps via an API key. As a first step, we defined the TUKE Campus and the TUKE Dormitory Complex on Jedlíkova Street, including their strategic buildings and existing micromobility infrastructure. This was done by mapping their boundaries based on coordinates and satellite imagery. The TUKE Campus was delineated using a 7-point polygon, while the Jedlíkova Dormitory Complex was represented by a 15-point polygon encompassing all student and staff accommodation buildings.

Next, we identified the 15-minute accessibility zones around both the TUKE Main Building and the Jedlíkova Dormitory for travel by foot, bicycle, and car. These zones were visualized in QGIS using Valhalla routing plugin. The reference points were based on the precise geographic coordinates (latitude and longitude) of the two locations. Each accessibility zone was modeled as an isochrone with borders corresponding to distances that can be covered within 15 minutes from a certain reference point, based on the selected mode of transport.

Finally, we analyzed the spatial concentration of shared micromobility routes that either originated from or destinated at the TUKE Campus and the Jedlíkova Dormitory. The data were provided by a local shared micromobility provider operating a range of services, including shared bicycles, e-bicycles, e-scooters, and e-mopeds. The unfiltered dataset included 688,258 shared micromobility start and end points, spatially defined by latitude and longitude, covering routes taken by bicycle or e-scooter within the Košice city wards during the period from 2021 to 2023. We chose to merge dataset across these three years to visualize overall transportation patterns and work with a larger sample of routes. After filtering for the areas within the TUKE Campus and Jedlíkova Dormitory polygons, our research sample comprised 9,548 routes, representing 1.39% of the entire dataset.

To reduce potential bias, we further filtered the data by time of the day, focusing on morning and afternoon peak hours. We hypothesize that routes ending at the TUKE Campus between 7 a.m. and 11 a.m. or starting there between 3 p.m. and 7 p.m. were likely taken by university staff or students. Similarly, we assume that routes starting at the Jedlíkova Dormitory between 7 a.m. and 11 a.m. or ending there between 3 p.m. and 7 p.m. were also likely associated with TUKE staff or students. Detailed information on number of routes by time of day and year is provided in the appendix (Tab. A1).

It is also important to note that the start and end points of the analyzed routes may be slightly biased due to zones designated for free parking. In 2023, the local shared micromobility provider introduced fines for improper parking of shared micromobility vehicles. If users park a vehicle in a No Return Zone or No Ride Zone, they will incur an additional fine of EUR 70 through the user application. We assumed that this fine is sufficiently high to ensure that users park e-scooters or bicycles only in designated areas, such as Return Free Zones or Return Paid Zones, which could result in minor data bias. In particular, the location marked in the data as the end of the route may only reflect the place where the vehicle was parked in a Return Free Zone, while the actual end of the journey could be several tens or hundreds of meters away, with the user covering the remaining distance on foot.

To visualize the data, we generated heatmaps that effectively display areas of high and low mobility concentration by representing the geographic density of point data. The heatmaps were created in RStudio applying the two-dimensional KDE method, which estimates route density based on spatial distribution. We utilized the stat_density2d() function with the aesthetics fill = ..level.. and alpha = ..level.., along with the parameters geom = “polygon” and bins = 20. The chosen bin count of 20 provided a balanced level of detail, allowing for accurate visualization of spatial patterns within the data. Each heatmap presented in this study includes an overlaid layer of cycling infrastructure to support the interpretation of observed shared micromobility patterns.

3 Results and discussion

3.1 Micromobility at TUKE: State of the art

TUKE ranks among the leading Slovak higher education institutions and operates one of the country’s most extensive campuses. As of 2024, the university had 12,417 students and employed approximately 1,462 academic and administrative staff members (Technical University of Košice, 2024). According to data from the Statistical Office of the Slovak Republic, this university population of nearly 14,000 exceeds the number of residents in 14 out of Košice’s 22 city wards (Statistical Office of the Slovak Republic, 2024). This highlights TUKE’s strategic role in shaping urban mobility patterns and contributing significantly to traffic flows within the city.

Located in close proximity to Košice’s city center, the TUKE Campus is organized around the Main Building, which houses the rectorate. The campus comprises 7 of the university’s 9 faculties, two smaller student dormitories, the University Library, the University Science Park TECHNICOM, and the TUKE Athletic Stadium (Fig. 2). It also includes various laboratories, production halls, offices for academic staff, as well as a larger parking lot designated for students and another for staff members.

From the perspective of micromobility, the TUKE Campus is equipped with five charging stations with integrated racks operated by a local shared micromobility provider (see yellow squares in Fig. 2). Each station features three universal electric sockets for e-mopeds, three sockets for e-bicycles or e-scooters, and parking racks with capacity for six vehicles. In addition, the provider operates two more charging stations within the campus, each offering three electric sockets exclusively for e-mopeds (see pink squares in Fig. 2). Furthermore, four additional covered racks are located throughout the campus area (see blue squares in Fig. 2), each providing parking for up to ten vehicles. It is also important to note that the availability of the shared micromobility services is seasonally dependent, with vehicles typically accessible from April to November due to weather conditions.

Essential amenities are available to both students and university employees on the TUKE Campus or in its surrounding area. Nevertheless, a significant challenge concerns the TUKE Dormitory Complex, located on Jedlíkova Street (see Fig. 3), approximately 4.5 km from the TUKE Main Building. In terms of micromobility infrastructure, the Jedlíkova Dormitory area lacks adequate equipment, such as charging stations and racks. Currently, there is only one charging station operated by the local shared micromobility provider, which is solely compatible with e-mopeds. The lack of charging infrastructure may serve as a deterrent to using shared micromobility, as users can incur a EUR 30 fine if they park an electric vehicle outside a designated charging station when the e-scooter's battery level falls below 5%. For instance, if a TUKE student or staff member arrives at the Jedlíkova Dormitory on an e-scooter with a battery level below this threshold, they have no means of recharging it and would still be liable for the fine, despite not being at fault.

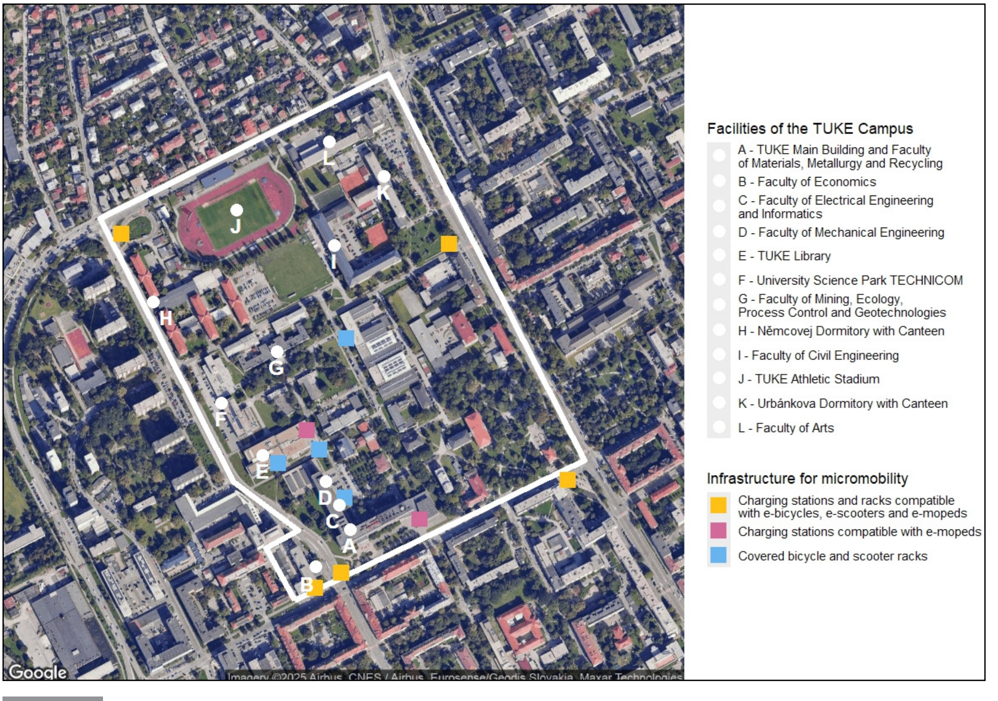

Fig. 2: **The TUKE Campus with its main facilities and micromobility infrastructure**

Source: own

Apart from this constraint, there are no other strict requirements imposed by the shared mobility provider that could discourage usage, such as mandatory insurance or the obligation to wear a personal helmet. The fact that students and staff currently do not use shared micromobility options for commuting to and from the Jedlíkova Dormitory is further supported by our multiple site visits to the dormitory area during weekday afternoons, where we either did not observe any shared bicycles or e-scooters at all, or only noted their presence in numbers not exceeding five.

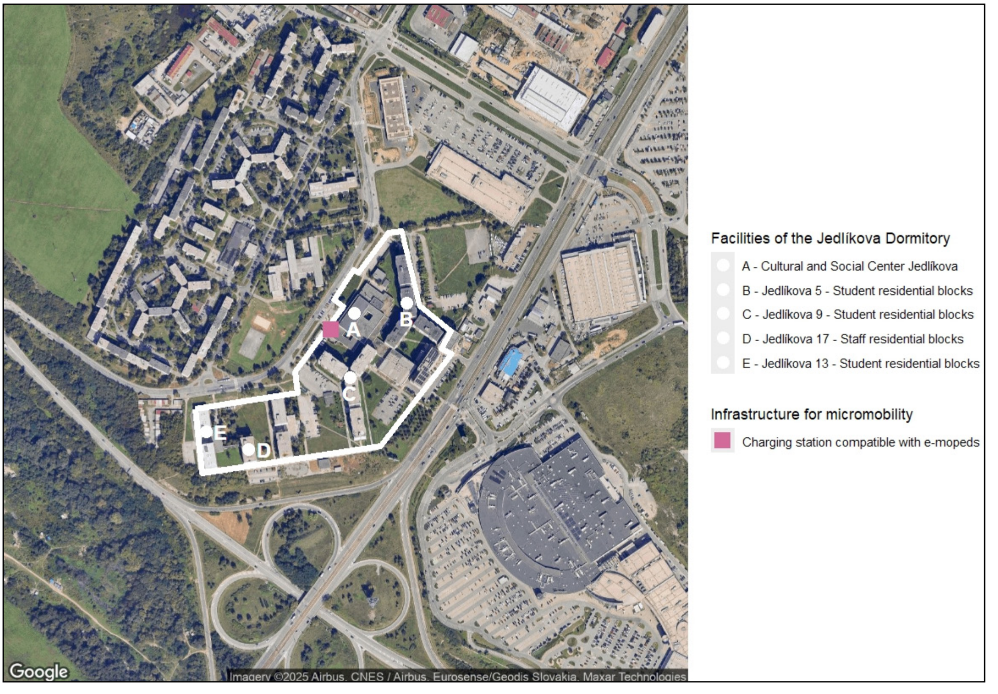

Fig. 3: The TUKE Dormitory Complex on Jedlíkova Street with its main facilities and micromobility infrastructure

Source: own

Fig. 4 illustrates 15-minute isochrones centered around the TUKE Main Building (left) and the Jedlíkova Dormitory (right), based on active transportation modes compared to the car. Reaching the two locations on foot within 15 minutes is not achievable, while commuting by bicycle is possible marginally. A key factor to consider on the route between the TUKE Main Building and the Jedlíkova Dormitory is the difference in elevation. While the route from the dormitories to the TUKE Main Building is likely manageable within 15 minutes, the reverse route may take longer due to the elevation increase, which is approximately 3.5 times higher from the TUKE Campus to the dormitories. The two locations are reachable by a 15-minute car ride.

We also assess the 15-minute commuting range between a key gateway into Košice – the Railway and Bus Station – and the TUKE Main Building. This analysis is essential, as we assume that daily commuters from nearby towns and villages significantly contribute to university-generated mobility.

As shown in Fig. 4, the TUKE Campus can be reached within 15 minutes from the Railway and Bus Station when using bicycle, underscoring the opportunity for further development of micromobility on campus.

However, challenges arise when examining the route between the Railway and Bus Station and the Jedlíkova Dormitory, as from an active mobility perspective, this route is not

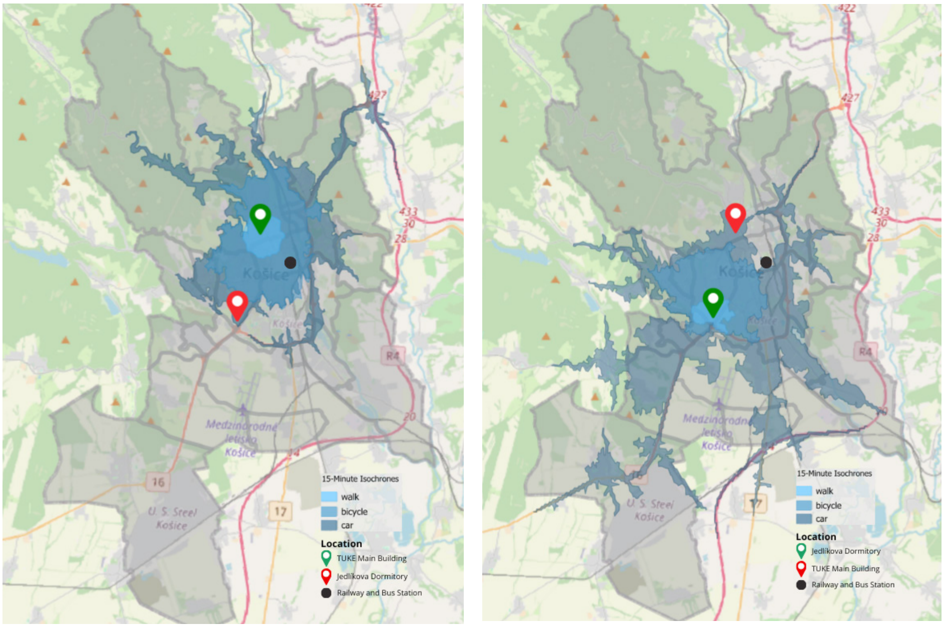

Fig. 4: Multimodal 15-minute accessibility of the TUKE main building (left map) and the Jedlíkova Dormitory (right map)

Source: own

feasible. Additionally, students typically travel to the dormitories at the end of the weekend while carrying luggage, which makes the use of shared micromobility vehicles impractical. The same issue applies to their reverse routes from the dormitories to the Railway and Bus Station at the end of the workweek.

Another challenge regarding the dormitories is that the connection between the TUKE Campus and the Jedlíkova Dormitory remains insufficiently supported by current micromobility infrastructure. Students and staff generally cannot complete this journey within 15 minutes – whether on foot, by e-scooter, or, in most cases, by bicycle.

At present, about 70% of the route features a mostly continuous and safe cycleway. However, the remaining 30% lacks dedicated infrastructure. While the initial segment – though not officially designated as a cycling path – is relatively smooth and provides access to the formal cycleway, the final section reveals serious limitations. This last part, extending from the end of the designated path to the dormitory complex, is not well-suited for micromobility. It consists primarily of a narrow, poorly maintained pedestrian walkway that restricts safe travel by bicycle or e-scooter. The official cycleway ends at the turnoff toward the dormitories, leaving the remaining route disconnected from the broader network.

This section provides key background for a further, more detailed analysis of the travel behavior of TUKE students and staff in terms of shared micromobility usage.

3.2 Routes originating from or destinating at the TUKE Campus

Our analysis of routes ending or starting at the TUKE Campus (see Fig. 5) reveals that the highest density of shared micromobility usage is observed in its immediate vicinity. Students and staff appear to use shared bicycles and e-scooters to access nearby public transport stops such as the Amphitheater or District Office, which provide key connections to other parts of the city. Other areas with high density of shared micromobility usage were found along Hlavná and Moyzesova Streets, both of which have cycleways.

Another area of high shared micromobility usage is observed around Osloboditeľov Square, suggesting it may serve as other strategic transfer point between shared micromobility vehicles and public transport (buses or trams). Similarly, significant shared micromobility activity is noted in the Mier neighborhood, likely due to the presence of the local shared micromobility provider's headquarters. This location is strategically advantageous for users, as it reliably offers shared vehicles and includes a designated area for free parking.

When considering the theoretical 15-minute travel distances (see Fig. 4), bicycles and e-bicycles could potentially cover greater distances than what is reflected in the data.

Fig. 5 also reveals that the Railway and Bus Station is another area with high shared micromobility usage. Many TUKE students and staff commute daily from nearby towns and villages, using the station as a key entry point into the city.

Further analysis of the dataset revealed a distinct commuting pattern, which is visually supported by the maps in Fig. 5: morning routes (left) typically end at the TUKE Campus, while afternoon routes (right) generally originate from it. These routes show significant spatial overlap, indicating that students and staff follow regular and predictable commuting habits. The similarity between morning and afternoon flows reflects recurring mobility behavior, as also demonstrated by the route volumes in the appendix (Tab. A1).

The data did not reveal a significant number of routes between the TUKE Campus and the Jedlíkova Dormitory, either originating from or destinating at these locations. While such routes likely exist, their frequency is too low relative to the entire dataset for inclusion

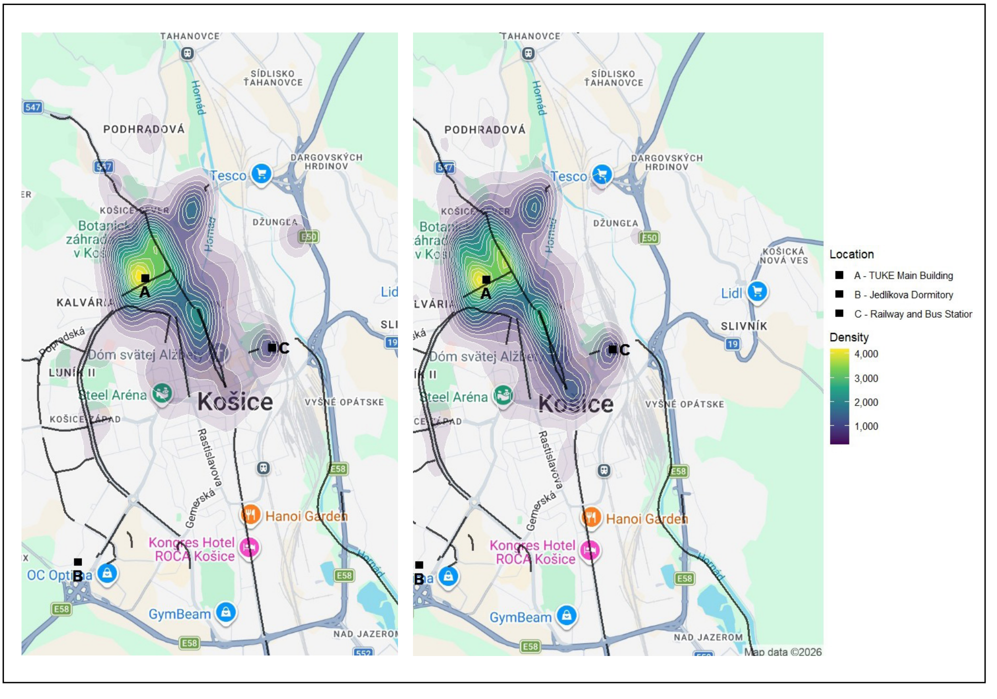

Fig. 5: Origins of routes destinating at the TUKE Campus between 7 a.m. and 11 a.m. (left map) and destinations of routes originating from the TUKE Campus between 3 p.m. and 7 p.m. (right map)

Source: own

in the density estimation. The absence of routes to and from the Jedlíkova Dormitory may indicate a preference for alternative transportation modes or low utility of shared micromobility services among university students and staff.

3.3 Routes originating from or destinating at the Jedlíkova Dormitory

The comparison between the TUKE and Jedlíkova datasets reveals a significant difference in the volume of routes. Far fewer routes originate from or destinate at the Jedlíkova Dormitory compared to the TUKE Campus (381 vs. 9,167 routes, see appendix – Tab. A1). This disparity is also evident in the visual comparison of the maps. While the distinctions between routes originating from and destinating at the TUKE Campus are minimal, the maps of routes related to the Jedlíkova Dormitory indicate noticeable differences upon initial examination. This is likely due to the smaller number of routes associated with Jedlíkova compared to the TUKE Campus, making the KDE more sensitive to variations in the smaller dataset. In practice, when KDE is calculated from a limited number of observations, even a few routes can appear as dense areas on the map. For instance, Fig. 6 shows a significant number of routes originating from the Jedlíkova Dormitory and destinating at the TUKE Campus in the morning hours. Consequently, this area may be highlighted as a zone of dense shared micromobility, relative to other routes displayed. However, Fig. 5 does not show these routes from Jedlíkova to TUKE, as their overall count is negligible compared to the total dataset.

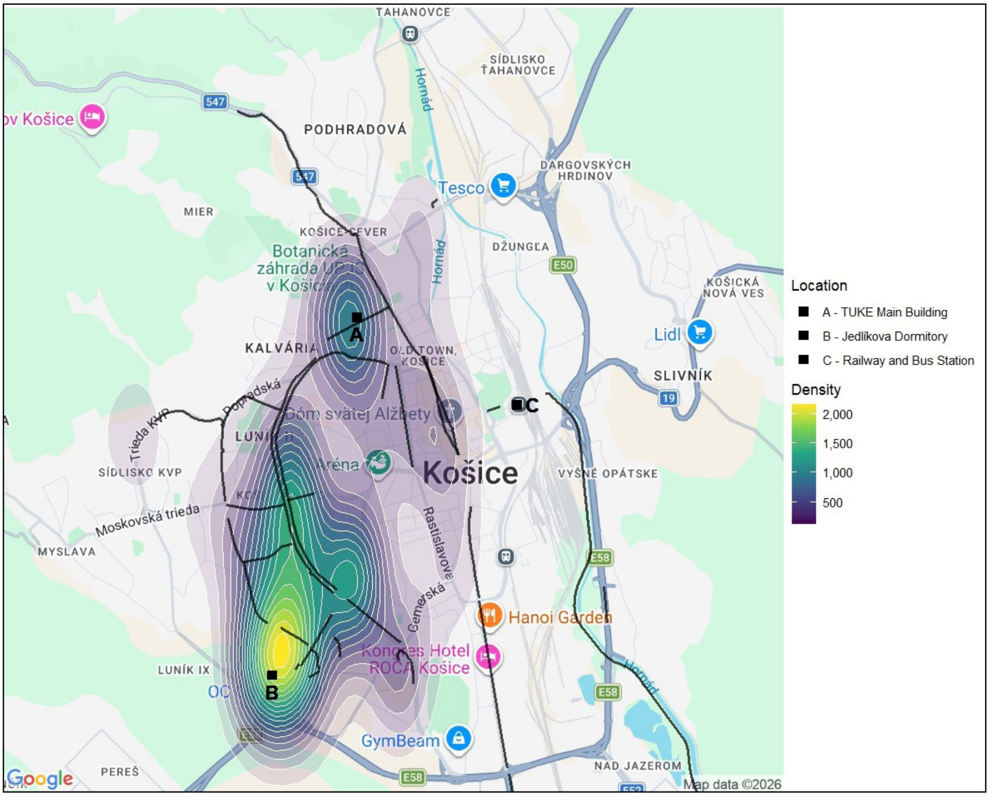

Fig. 6: **Destinations of routes originating from the Jedlíkova Dormitory between 7 a.m. and 11 a.m.**

Source: own

Fig. 6 also reveals a more dispersed distribution of destination points compared to the origin points shown in Fig. 7, suggesting that routes originating from Jedlíkova are relatively longer than those destinating there. Nonetheless, the highest route density remains concentrated in the immediate or slightly broader vicinity of the Jedlíkova Dormitory. This observation supports the findings from the TUKE dataset, which suggest that students and staff generally do not use shared micromobility services for travel to distant locations.

Moreover, most of the routes around Jedlíkova Dormitory fall within the theoretical 15-minute walking or e-scooter radius, with the exception of routes between Jedlíkova and the TUKE Campus. This distance can only be covered within the 15-minute timeframe by bicycle or e-bicycle. Similar to the TUKE maps, we assume that students and staff use shared micromobility vehicles for shorter trips to bus or tram stops, continuing their journey to the TUKE Campus via public transport, or vice versa. This is supported by the fact that areas with higher route densities often coincide with public transport stops.

3.4 Discussion of the results

The findings reveal clear spatial and behavioral patterns in the use of shared micromobility among TUKE students and staff. A recurring observation is that shared micromobility is predominantly used for short, localized movements – primarily to reach nearby public transport stops or amenities – while longer-distance commutes remain rare.

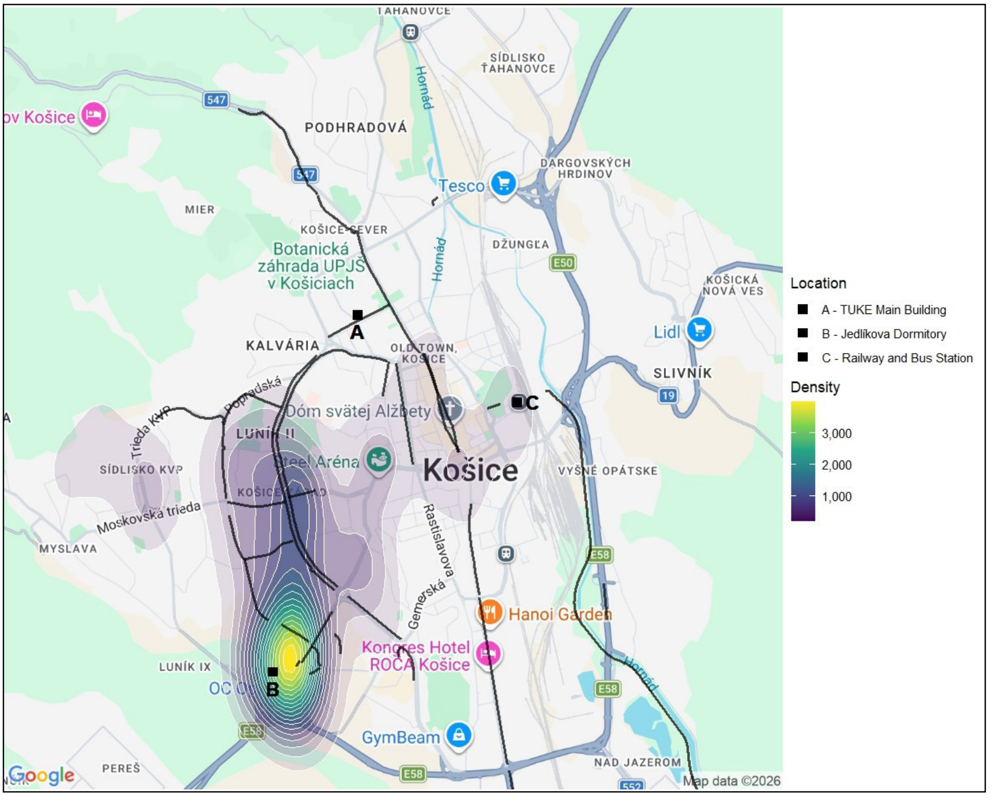

Fig. 7: **Origins of routes destinating at the Jedlíkova Dormitory between 3 p.m. and 7 p.m.**

Source: own

At the TUKE Campus, the highest route densities occur in its immediate surroundings and along several central cycling corridors. The presence of short, clustered routes suggests that users primarily employ shared micromobility for first- and last-mile travel, as well as for non-commuting activities such as social visits or errands. This aligns with established research describing complex trip-chaining behavior in urban environments (Hu & Li, 2021; Schneider et al., 2021).

Although bicycles and e-bicycles could theoretically cover significantly greater distances within 15 minutes, the actual patterns reveal a much more constrained spatial reach. Existing literature indicates that this discrepancy between the potential range of micromobility options and their actual usage can be attributed to practical barriers such as fragmented cycling infrastructure, safety concerns, and the absence of direct, continuous connections (Maas et al., 2020). In Košice, cycleways tend to be recreational rather than commuter-oriented, reducing their usefulness for daily travel between key destinations. Supporting longer micromobility commutes would therefore require the development of continuous cycling infrastructure, with the city taking the lead in close cooperation with TUKE.

The Railway and Bus Station emerges as a significant mobility node, reinforcing the importance of shared micromobility as a complementary mode for students and staff commuting from surrounding towns. Although the entire route between the station and the TUKE Campus is not covered by an official cycleway, certain sections – such as those passing through the City Park – can be safely cycled. Enhancing wayfinding along this corridor could further strengthen multimodal commuting. In addition, newly enrolled TUKE students should be encouraged to use shared micromobility services when travelling from key entry point to the campus, for example, through informational leaflets or introductory discounts. Previous studies have shown that individuals' environmental awareness positively influences the uptake of sustainable transport modes (Hamidi & Zhao, 2020).

International examples demonstrate how targeted programs can shift university mobility cultures. The University of Kentucky, for instance, has implemented incentive schemes such as Bike Voucher and Cash Out programs to promote car-free commuting. The Bike Voucher program provides students and staff with up to USD 500 for purchasing a bicycle or related accessories, while the Cash Out program offers staff USD 200 annually (distributed across paychecks) in exchange for giving up their parking permits (Cleveland, 2025).

Similarly, the University of Brighton's Move for Change initiative rewards sustainable commuting by allowing students to collect points for walking, cycling, or using public transport. These points can be redeemed for vouchers at local businesses or donated to charity (University of Brighton, 2025).

These initiatives show how higher-education institutions can incentivize behavioral change through soft policy measures. However, hard measures – such as stricter on-campus car-parking regulations, reduced parking availability, or the introduction of parking fees for students and staff – should also be considered as part of TUKE's long-term strategy to reduce car dependence and advance the vision of a more sustainable campus environment.

One of the most significant findings is the minimal use of shared micromobility between the TUKE Campus and the Jedlíkova Dormitory, despite the high number of students residing there. Structural factors – including distance, elevation, and insufficient micromobility infrastructure – likely deter longer micromobility trips. The fragmented final section of the route, ending in a narrow pedestrian walkway in poor condition, presents a specific infrastructural bottleneck. As a consequence, students rely heavily on public transport for this connection.

However, public transport capacity on this route appears insufficient, particularly during morning peak hours. At present, the Jedlíkova-TUKE corridor is served by four direct tram lines operating at three-minute intervals between 6:58 a.m. and 7:07 a.m., intended to align with the 7:30 a.m. start of lectures. For classes beginning at 9:10 a.m., two direct trams depart at 8:30 a.m. and 8:40 a.m., and for classes starting at 10:50 a.m., only one tram departs at 10:20 a.m. Overcrowding frequently results in delays, with students reporting that trams bypass stops due to capacity constraints. As a result, even students who arrive at the tramp stop on time often miss the start of classes by 5 to 15 minutes.

Although students have requested that Košice's public transport operator (DPMK) increase tram frequency during these periods, such measures have not been implemented, likely due to high financial costs. Expanding micromobility options could therefore offer a more flexible and cost-effective means of relieving pressure on public transport.

This issue requires urgent attention, particularly as rising enrolment at TUKE increases the number of students residing in the dormitories. A potential solution could involve collaboration between TUKE and DPMK to introduce a dedicated university line serving only two stops: one near the Jedlíkova Dormitory and one near the TUKE Main Building. Buses could also be deployed alongside trams to alleviate overcrowding. While the current commute takes approximately 25 minutes, a dedicated university line could potentially reduce this to around 15 minutes.

A good example to follow is the University of Catania in Italy, where a dedicated Bus Rapid Transit line has served the campus since 2013 and has become the most popular bus line among students (European Commission, 2019). The university also provides students with unlimited free access to the city's public transport network, which could serve as inspiration for similar initiatives at TUKE. If providing free public transport for all TUKE students and staff is financially unfeasible, discounted public transport passes or a dedicated fee-free university bus or tram line could be effective in reducing car dependence. Adjusting class schedules to ease pressure on urban transport during morning peaks could also be considered, as it represents a low-cost measure within the university's control.

Additionally, our observations suggest that the Jedlíkova Dormitory area lacks adequate shared micromobility infrastructure, which may partly explain the low uptake of shared bicycles and e-scooters. We recommend that TUKE collaborate with shared micromobility providers to promote affordable and sustainable transport options. This could include offering discounted user fees for TUKE students and staff, expanding micromobility infrastructure within the dormitory area, and increasing vehicle availability near both the TUKE Campus and the dormitories.

An inspiring example is the collaboration between the UK shared micromobility provider Beryl and several local universities, which expanded micromobility infrastructure and introduced student discount schemes. As a result, approximately 2,100 students at Bournemouth University and 1,550 students at the University of East Anglia began using Beryl's services, collectively saving around three tons of carbon emissions (Lee, 2024).

We also see considerable potential in integrating multiple transportation modes along a single route. Mobility as a Service (MaaS), which is gaining global popularity, could streamline the user experience by allowing individuals to plan and pay for an entire multimodal journey through a single mobile platform. In the case of travel between the TUKE Campus and the Jedlíkova Dormitory, a MaaS approach could enable the first leg of the trip via shared micromobility to a public transport stop, followed by a seamless transfer to the campus.

Finally, the results highlight a broader challenge in aligning TUKE's mobility ecosystem with the principles of the 15-Minute City. While essential services around the campus meet this standard, student housing on Jedlíkova does not. The spatial separation between living and learning environments limits the potential for low-carbon, time-efficient travel. Achieving a more integrated 15-minute mobility environment will require close collaboration among key urban stakeholders, including the university, the city, the public transport operator, and shared mobility providers.

3.5 Study limitations and future research

Despite the contributions of this study, several limitations need to be acknowledged.

First, the micromobility analysis is based exclusively on anonymized operational data provided by a local shared micromobility operator. Due to GDPR regulations, the provider does not collect or share personal user data. Consequently, although a multi-step temporal and spatial filtering procedure was applied, it is not possible to conclusively verify whether all trips included in the density estimations were undertaken by students or staff members of TUKE. The attribution of trips to university-related users is therefore based on reasonable assumptions derived from time-of-day patterns and spatial proximity rather than direct identification.

Second, the dataset captures only shared micromobility vehicles equipped with sensors and does not include privately owned bicycles or e-scooters. As a result, the study does not reflect the full spectrum of micromobility usage in the examined area. The relatively low intensity of shared micromobility trips between the TUKE Campus and Jedlíkova Dormitory, as well as within the campus area, compared to the overall dataset, cannot be interpreted as evidence of low micromobility use among university members in general. It is possible that students and staff rely substantially on private micromobility vehicles, which remain unobserved in this dataset.

Third, although the existing cycling network was overlaid with trip density in Fig. 5–7 to enhance spatial interpretation, the study does not statistically test the relationship between micromobility usage and cycling infrastructure. The visual co-occurrence of higher trip densities along certain cycling corridors may suggest a spatial association; however, no causal relationship between infrastructure provision and micromobility adoption is empirically verified in this paper. Future research could employ inferential statistical methods to examine the strength and direction of this relationship more rigorously.

In addition, the cycling infrastructure displayed in Fig. 5–7 includes only officially designated cycle paths defined by the city of Košice. In practice, cyclists may also use sidewalks or other non-designated routes. However, as such behavior does not represent formal cycling infrastructure and may raise safety concerns for both cyclists and pedestrians, these unofficial routes were not included in the visualization. Consequently, the maps reflect planned infrastructure rather than the full complexity of actual cycling practices within the city.

Fourth, the study is primarily quantitative and descriptive in nature. It does not include primary survey data that would capture subjective mobility preferences, motivations, or barriers to micromobility use. Therefore, behavioral interpretations – such as assumptions regarding morning commuting patterns – should be treated as indicative rather than causally validated. Future research should complement sensor-based mobility data with questionnaire surveys or interviews to better understand decision-making processes and to validate inferred mobility patterns.

Finally, the results and corresponding policy implications are inherently shaped by the specific spatial, infrastructural, and institutional characteristics of TUKE. The intention of this study was not to derive universally applicable conclusions, but to present an analytical approach for exploring shared micromobility patterns within a university setting. Applying a similar framework in different academic environments with varying urban structures and transport systems would allow for a broader understanding of how contextual factors influence campus mobility dynamics. Such extensions could further refine the applicability of the proposed approach in diverse settings.

Conclusions

This study explored university-generated mobility within the 15-Minute City framework through three complementary lenses.

First, it highlighted the untapped potential of universities as strategic actors in advancing the 15-Minute City concept. Despite the model's inclusion of education as a core urban function, the specific mobility patterns and infrastructural needs of university communities are often overlooked in urban planning discourse. Yet, universities generate substantial and recurrent mobility flows due to their large populations of students and staff. As such, they need to be systematically integrated into urban transportation planning and decision-making processes.

Second, the study proposed a methodological approach to assess multimodal 15-minute travel distances and analyze active mobility usage in relation to key university locations. TUKE served as a case study to validate this methodology through spatial analyses, demonstrating how the current mobility environment can be evaluated within the 15-Minute City paradigm. This easily replicable approach can be applied to universities worldwide to identify accessibility barriers and infrastructural gaps in university-centered mobility systems. Moreover, utilizing shared micromobility data proves useful in generating valuable insights for mobility-related policy development even within the university environment. The analysis results revealed that shared micromobility among TUKE students and staff remains largely underused, thus representing significant potential for shifting commuting patterns toward more sustainable modes of transportation.

Third, the research outlined policy recommendations aimed at fostering more sustainable university environments while simultaneously supporting cities in their transition toward the 15-Minute City model. These include soft measures such as behavioral incentives, hard infrastructure improvements, and institutional partnerships with public and private mobility providers – all intended to reduce car dependency and promote sustainable commuting behaviors.

Ultimately, the findings underscore the unique yet underutilized potential of universities – with their stable populations and specific spatial layouts – to serve as catalysts for urban transformation. Bridging the gap between the theoretical accessibility of micromobility and its actual use requires a coordinated combination of adequate financing, behavioral change, and institutional-level collaboration. Various initiatives can be implemented by universities themselves, by cities, by local shared micromobility providers, or through cooperation among all stakeholders.

Policy measures that universities can implement independently include various financial incentives to encourage sustainable commutes (e.g., voucher or cash-out programs for sports gear in exchange for giving up parking permits, or reward schemes with vouchers redeemable at local businesses), intra-campus parking regulations (e.g., introducing parking fees or reducing parking spaces), and adjustments to class schedules during morning peak hours.

Measures requiring collaboration among multiple stakeholders include the development of high-quality, safe, and continuous micromobility infrastructure with proper signage; discount schemes promoting the use of shared micromobility within the city; the introduction of a dedicated public transport line between dormitories and the main campuses; and the creation of integrated MaaS platforms at the city level.

By integrating micromobility and multimodal strategies into university mobility planning, institutions not only improve campus accessibility but also contribute to broader goals of urban sustainability. As living laboratories of innovation, universities are well-positioned to lead mobility reforms and foster behavioral change among their students and staff. When aligned with the 15-Minute City principles of proximity, diversity, and accessibility, they can serve as pivotal nodes in shaping more livable, inclusive, and resilient urban environments. Therefore, universities need to be recognized as essential stakeholders in the implementation of 15-Minute City strategies across diverse urban contexts.

Acknowledgments: *Supported by Project APVV No. APVV-19-0263.*

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Appendix

Tab. A1: Number of shared micromobility routes around the TUKE Campus and the Jedlíkova Dormitory by time of day and year

Year	Location	Point type	Time of day						Point type	Time of day					
			7:00	8:00	9:00	10:00	11:00	7:00–11:00		15:00	16:00	17:00	18:00	19:00	15:00–19:00
2021	TUKE Campus	End	296	273	227	230	301	1,327	Start	301	328	316	324	253	1,522
	Jedlíkova Dormitory	Start	9	3	6	12	5	35	End	14	16	11	16	6	63
2022	TUKE Campus	End	367	307	274	306	318	1,572	Start	370	400	332	320	299	1,721
	Jedlíkova Dormitory	Start	16	15	12	14	9	66	End	9	24	20	23	16	92
2023	TUKE Campus	End	325	315	247	277	266	1,430	Start	354	380	343	300	218	1,595
	Jedlíkova Dormitory	Start	6	11	10	11	15	53	End	11	18	18	16	9	72
2021–2023	TUKE Campus	End	988	895	748	813	885	4,329	Start	1,025	1,108	991	944	770	4,838
	Jedlíkova Dormitory	Start	31	29	28	37	29	154	End	34	58	49	53	31	227

Source: own

Application of self-organising maps to analysed bike-sharing usage in large cities: A case study of Seville

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Abstract: *This study provides a quantitative analysis of the relationship between Seville's public bicycle-sharing system usage and the city's environmental conditions, employing an unsupervised artificial intelligence method. The dataset spans from 2018 to 2023 and combines operational service data (daily rentals, turnover) with weather data (temperature, precipitation, humidity), including the heat index as a measure of thermal comfort. The method is based on self-organising maps (SOM), implemented through a neural network with a 12 × 12 hexagonal grid. After 100 iterations of unsupervised training, hierarchical clustering was applied to the neuron weight vectors, resulting in 8 clusters representing distinct patterns of usage and environmental conditions. The results indicate that segmentation is strongly influenced by weather variables, showing a negative relationship between service demand and precipitation and a nonlinear relationship with thermal sensation, which discourages system use at extreme levels. The proposed model provides a practical tool for operational planning and demand forecasting, enabling system management optimisation based on weather forecasts. Additionally, its application could benefit other cities with similar mobility systems.*

Keywords: *Self-organising maps, bicycle sharing, sustainable urban mobility, urban climatology, thermal sensation, irradiance.*

JEL Classification: *R41, Q54, C45.*

APA Style Citation: Perez-Pulido, L., Mena-Nieto, A., & Vides, J. C. (2026). Application of self-organising maps to analysed bike-sharing usage in large cities: A case study of Seville. *E&M Economics and Management*, *29*(3), 80–101. https://doi.org/10.15240/tul/001/2026-3-005

Introduction

Bike-sharing systems (BSS) have emerged as an effective and sustainable transport alternative for short-distance urban travel. By reducing reliance on private vehicles, they contribute to lower carbon emissions, alleviate congestion, and enhance last-mile connectivity to public transport (Li et al., 2023). As a result, understanding the factors that shape their usage has become a key issue in urban mobility research.

Despite the growing body of literature on BSS, existing studies have predominantly focused on demand forecasting using linear models or a limited set of meteorological variables, such as temperature or precipitation (Butt et al., 2023; El-Assi et al., 2017). More recent contributions have incorporated advanced machine learning techniques, including deep learning architectures such as convolutional neural networks (CNN) and recurrent neural networks (RNN), to improve predictive performance

(Du et al., 2019; Ren et al., 2020; Sathishkumar et al., 2020). However, even these approaches remain primarily oriented towards prediction tasks and typically treat weather variables in isolation, overlooking the identification of latent behavioural patterns and the nonlinear interactions between environmental stressors.

In particular, previous studies have not examined how combined climatic conditions, such as the interaction between temperature and humidity captured by the heat index, outline usage patterns in contexts characterised by extreme thermal conditions. This limitation is especially relevant in Mediterranean cities, where high temperatures and humidity may generate threshold effects and behavioural adaptations that are not adequately captured by conventional approaches. Thus, this study addresses this gap by analysing how complex environmental conditions give rise to distinct, nonlinear usage patterns in bike-sharing systems.

Accordingly, the main objective of this study is to identify and characterise nonlinear usage patterns in bike-sharing systems by integrating multi-year operational data with advanced climatic indicators, with a particular focus on the role of the heat index in a Mediterranean urban context. In this sense, Seville provides an appropriate case study due to its extensive cycling infrastructure and extreme summer temperatures, making it particularly suitable for analysing thermal stress effects on cycling behaviour.

To address this objective, this paper is guided by the following research questions (*RQs*):

RQ1: How do extreme heat conditions, as measured by the heat index, shape bike-sharing usage patterns?

RQ2: Can unsupervised learning techniques, such as self-organising maps (SOM), uncover latent structures in usage behaviour that are not detected by traditional approaches?

RQ3: To what extent do interactions between temperature and humidity explain variations in demand compared to other meteorological factors such as precipitation?

Given the exploratory and unsupervised nature of the methodology, the following hypotheses are interpreted as expected patterns emerging from the data rather than formally tested causal relationships:

H1: Thermal threshold pattern: distinct clusters associated with high heat index levels are expected to emerge, characterised by lower bike-sharing activity beyond critical thermal thresholds.

H2: Temporal adaptation pattern: clusters reflecting temporal reallocation of cycling activity towards cooler periods of the day (early morning and late evening) are expected under extreme heat conditions.

H3: Precipitation sensitivity pattern: clusters associated with precipitation events are expected to display sharper reductions in usage intensity compared to those characterised by high temperature conditions.

H4: Trip stability pattern: distinct usage profiles are expected between utilitarian trips (e.g., commuting) and leisure-related trips, with the former exhibiting greater stability under adverse environmental conditions.

This study makes three main contributions. First, from a theoretical perspective, it advances the understanding of thermal resilience in active mobility by incorporating perceived temperature measures into the analysis of cycling behaviour. Second, from a methodological standpoint, it demonstrates the convenience of self-organising maps (SOM) for identifying nonlinear and high-dimensional patterns in urban mobility data. Third, from a practical perspective, it offers evidence-based insights for urban planners to design adaptive strategies for bike-sharing systems under extreme weather conditions.

The remainder of the paper is organised as follows. The following section 1 develops the theoretical background. Section 2 presents the study area and its mobility context. Section 3 describes the data and methodological approach. Section 4 discusses the empirical results. Section 5 concludes and outlines key implications.

1 Theoretical background

1.1 Individual and socio-demographic determinants

The decision to use a bicycle as a mode of transport is made by a complex and multifactorial set of determinants. The literature generally distinguishes between individual characteristics, environmental factors, and policy interventions as the main drivers of cycling behaviour.

At the individual level, socio-demographic characteristics play a key role. Factors such as age, gender, income, and place of residence have been found to significantly influence the likelihood of cycling (e.g., Rietveld & Daniel, 2004; Wuerzer & Mason, 2015). In addition, daily routines and activity patterns, including shuttle needs or domestic responsibilities, affect transport choices and modal preferences (Van Eenoo & Boussauw, 2023).

Beyond observable characteristics, subjective and psychosocial factors are also relevant. Personal standpoint towards cycling, environmental awareness, and perceived safety (particularly in car-dominated urban environments) have been identified as essential determinants of bicycle use (Nankervis, 1999). The encouragement of a cycling culture and familiarity with bicycle use further strengthens these behavioural patterns (Pisoni et al., 2022).

Overall, individual-level factors determine the baseline conditions for cycling adoption, although their outcomes are often mediated by contextual and environmental conditions.

1.2 Built environment and infrastructure

The physical environment plays a central role in shaping cycling behaviour. Urban form and spatial structure, such as city size, density, and land-use patterns, have been widely recognised as key determinants of bicycle use (e.g., Hansen & Nielsen, 2014; Martens, 2004; Pucher & Buehler, 2006).

More specifically, the availability and quality of cycling infrastructure are essential factors. The existence of dedicated bike lanes, network connectivity, and safety conditions along routes significantly increase the attractiveness of cycling as a mode of transport (Pritchard, 2018; Scott et al., 2021). Other elements, such as pedestrian-friendly environments, topography, and urban green spaces, also contribute to shaping cycling behaviour by influencing comfort and the perception of safety (Sang et al., 2025; Timperio et al., 2006).

These structural factors not only facilitate the use of bicycles, but also interact with individual characteristics, which can influence the adoption of the bicycle as a regular means of transport or limit it.

1.3 Weather conditions and thermal comfort

Climatic and meteorological conditions constitute an important dimension of the environment that influences cycling behaviour. Variables such as temperature, precipitation, wind, and daylight hours have been systematically identified as important determinants of bicycle use (El-Assi et al., 2017; Gebhart & Noland, 2014; Spencer et al., 2013).

Previous research demonstrates that the impact of climate on cycling behaviour is inherently multidimensional, with combined effects of temperature, precipitation, and other environmental factors influencing travel decisions (Böcker & Thorsson, 2014; Saneinejad et al., 2012). In this context, adverse weather conditions are often associated with a reduction in cycling activity, although the magnitude and direction of these effects can vary depending on local conditions and user characteristics.

Among these factors, thermal comfort has received increasing attention in recent years. Beyond objective temperature measurements, perceived heat stress has been shown to better explain behavioural responses to environmental conditions (Maras et al., 2016). In particular, the interaction between temperature and humidity plays a key role in determining the perception of heat exposure, especially in contexts characterised by extreme weather conditions. Recent studies have further underlined the role of extreme heat in shaping bike-sharing patterns, showing that high heat stress can significantly alter travel behaviour and induce adaptive responses in urban mobility patterns (Wang et al., 2024).

However, most existing studies analyze climatic variables separately, overlooking their combined effects and the resulting nonlinear dynamics. Consequently, threshold responses and behavioural adaptations, such as temporal changes in cycling activity, remain insufficiently explored. This limitation underscores the need for approaches capable of capturing complex environmental interactions when analyzing usage patterns in bike-sharing systems.

1.4 Policy frameworks and bike-sharing systems

At the institutional level, public policies play an essential role in encouraging cycling and shaping urban mobility patterns. Policy interventions incorporate investments in infrastructure, regulatory frameworks, awareness campaigns, and the implementation of bike-sharing systems.

Bicycle-sharing systems have become a key policy tool for promoting cycling by reducing barriers to access and offering flexible mobility options (Pucher & Buehler, 2006).

These systems facilitate short-distance travel and improve intermodality within urban transport networks. However, their effectiveness depends on multiple factors, including system design, station density, pricing schemes, and integration with other modes of transport.

Previous research has also shown that policy measures aimed at promoting cycling culture and improving infrastructure can significantly increase bicycle use, even in contexts with initially low adoption rates (Pucher et al., 2010). At the same time, the interaction between policy frameworks and environmental conditions remains largely unexplored, particularly in relation to extreme weather events.

In this sense, while socio-demographic and infrastructure factors establish the basic conditions for cycling, adverse environmental factors, especially thermal conditions, can constitute significant limitations to its use. Therefore, understanding how these factors interact is essential to explaining the observed patterns in the demand for shared bicycles.

Based on a review of the literature, this study focuses on a set of environmental and operational determinants particularly relevant to the use of bike-sharing systems. Specifically, we analyze thermal comfort (measured using the heat index), as well as rainfall and temporal usage patterns. While socio-demographic and infrastructure factors provide the basic conditions for cycling, this study highlights the role of environmental stressors, particularly extreme heat, as key drivers of nonlinear behavioural responses in bike-sharing systems.

2 Study area and mobility context

2.1 City profile and climate

The municipality of Seville, located in southern Spain, covers an area of approximately 140.8 km² and has a population of around 700,000 inhabitants (INE, 2024), resulting in a high population density. The city is characterised by a Mediterranean climate, with extremely hot and dry summers and mild winters. Rainfall is highly seasonal and concentrated in the winter months, while summer periods are typically characterised by very little rain. These climatic conditions make Seville an ideal case study for analysing the impact of heat stress on cycling behaviour, especially due to the frequent occurrence of extreme heat waves during the summer months.

2.2 Mobility infrastructure and the Sevici system

Seville has developed an extensive cycling infrastructure over the last two decades, positioning itself as one of the leading cycling cities in Spain. The network includes a dense system of segregated bike lanes that ensures connectivity in most urban areas.

The Sevici public bike-sharing system, operated by JCDecaux, has approximately 2,600 bicycles distributed across some 260 stations. The system is characterised by a high density of stations, with an average distance of about 300 m between them, facilitating access and short-distance travel. According to the Sustainable Urban Mobility Plan (SUMP), the average duration of a bike trip is approximately 20 min.

Fig. 1 plots the evolution of the number of Sevici subscribers over time. After an initial period of expansion, the number of users shows a downward trend, followed by a gradual recovery in recent years. This evolution reflects changes in urban mobility patterns and external factors that affect the use of the system.

2.3 Descriptive analysis of bike-sharing usage

Next, Fig. 2 shows the monthly evolution of the use of the bike-sharing from 2007 to 2025. A clear seasonal pattern can be observed, with higher levels of use during spring and autumn, and a notable decrease during summer, especially in August. This behaviour has remained constant over the years, except in 2020, which shows an anomalous pattern associated with mobility restrictions imposed during the COVID-19 pandemic. The observed seasonality suggests a strong relationship between weather conditions and bicycle use. In particular, periods of extreme heat appear to coincide with lower levels of demand, supporting the importance of incorporating climate indicators into the analysis.

2.4 Personal mobility vehicles and regulatory framework

In recent years, urban mobility in Seville has undergone significant changes with the emergence of personal mobility vehicles (PMVs), particularly electric scooters. Their adoption has increased rapidly, offering an alternative mode of transport for short journeys and contributing to the diversification of mobility options.

In Spain, PMVs are regulated by Royal Decree 970/2020, which establishes the general

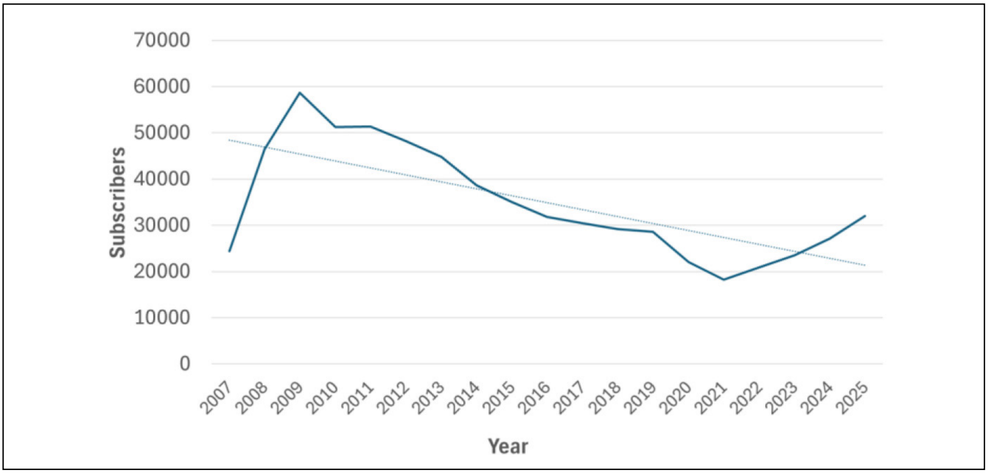

Fig. 1: **Evolution of the number of Sevici users**

Source: own

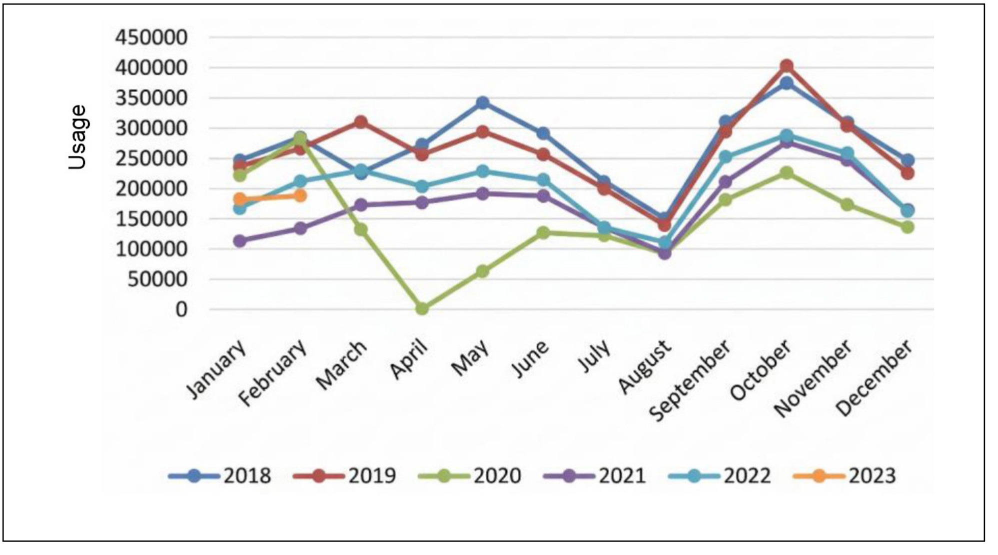

Fig. 2: **Monthly evolution of usage from 2018 to February 2023**

Source: own

operating conditions. At the local level, the Seville City Council has implemented specific regulations through its Municipal Mobility Ordinance. This ordinance permits the use of PMVs in bike lanes, residential streets, and low-speed zones (up to 30 km/h), restricting their use on sidewalks and pedestrian areas. The coexistence of bicycles, bike-sharing systems, and personal mobility vehicles introduces new dynamics into urban mobility, which can influence demand patterns and modal competition within the city.

In short, the combination of climatic conditions, availability of infrastructure and constantly evolving mobility alternatives makes Seville a particularly suitable environment to analyze the interaction between environmental factors and the use of the shared bicycle system.

3 Research methodology

3.1 Study design

This study adopts an exploratory quantitative design aimed at identifying latent patterns linking climatic conditions and bicycle-sharing usage in Seville. Given the multidimensional nature of the dataset (combining environmental indicators and mobility variables) an unsupervised learning approach was selected. Specifically, a self-organising map (SOM) was employed to detect nonlinear structures and classify daily weather-mobility regimes without imposing predefined group labels.

The SOM approach is particularly suitable for analysing complex urban systems where interactions between variables may not follow linear patterns and where dimensionality reduction is required to facilitate interpretation.

3.2 Data sources

The empirical analysis combines meteorological and mobility data at a daily frequency.

Meteorological data were obtained from the Spanish State Meteorological Agency (AEMET), specifically from the Seville San Pablo Airport station. Variables include temperature, precipitation, humidity, and wind speed.

Bicycle-sharing usage data were obtained from the Sevici system, including daily rentals, rotation rates, bikes in service, and bikes in maintenance.

The final dataset spans multiple years and consists of 1,885 daily observations after data cleaning. In addition to these variables, irradiance, which measures solar radiation, was considered a relevant parameter due to Seville's specific latitude and longitude. This variable can be a factor closely related to Sevici usage at different times of the year; however, it was not possible to obtain daily measurements. The available data consisted of theoretical monthly hourly estimates (Fig. 3), which are influenced by various conditions such as cloudy days and pollution.

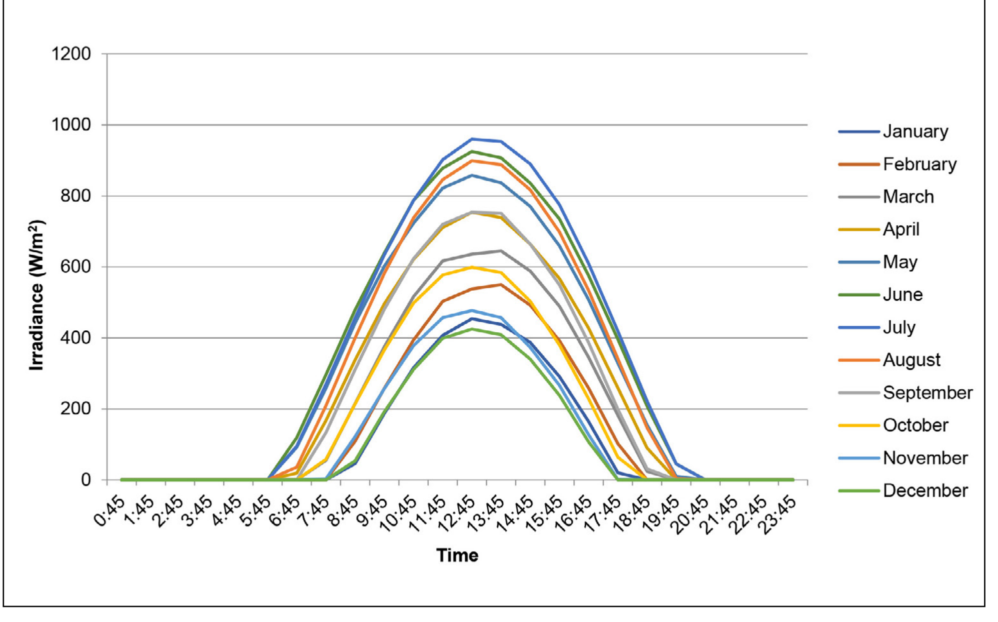

Fig. 3: **Monthly comparison of solar irradiance reproduced from the PVGIS-5 geo-temporal irradiation database**

Source: European Commission, Joint Research Centre

Atmospheric pollution can affect the quantity and quality of solar radiation that reaches the Earth's surface. Suspended particles, such as dust and smoke, can block solar radiation and reduce the amount of light reaching the surface. Solar radiation can therefore affect bicycle use through the following factors:
i) Increased radiation (irradiance) can cause an unpleasant thermal sensation for cyclists;
ii) Strong solar radiation can impair drivers' vision and therefore increase the risk of accidents;
iii) Solar radiation can influence the time of day chosen for cycling, meaning that journeys may require a combination of transport modes for the outward or return leg;
iv) Solar radiation influences the type of clothing and accessories used for cycling.

On the other hand, whilst temperature and humidity can influence usage, it is also true that for a given temperature, the thermal sensation can differ depending on the humidity or wind speed. This thermal sensation can be considered to have a very direct relationship with bicycle use, as it can create conditions of discomfort that encourage the use of other transport modes.

To determine this thermal sensation, various indices exist, such as the heat index (HI) or the index for assessing heat stress, Wet Bulb Globe Temperature (WBGT), outlined in the technical prevention note NTP 322 from the National Institute for Health and Safety at Work (INSST), among others. However, these indices are defined for very specific measurements that require particular instruments and conditions, which are not met by the environmental data from a standard AEMET meteorological station. In contrast, the calculation of thermal sensation due to cold (wind chill) and heat (heat index) can be performed using values for ambient temperature, relative humidity, and wind speed, without such specific measurement conditions being required.

Wind chill is the perceived temperature felt on the skin when it is both windy and cold. This sensation occurs because the wind accelerates the evaporation of moisture from the skin, causing it to feel colder than the actual air temperature. Furthermore, in very cold conditions, the body also attempts to conserve core temperature by reducing blood flow to the skin, which makes the skin feel colder.

Conversely, the thermal sensation of heat is the subjective perception of temperature felt on the skin when it is both hot and humid. This sensation occurs because increased air humidity hinders the evaporation of sweat from the skin, causing it to feel hotter than the actual temperature. Additionally, in very hot conditions, the body also attempts to regulate

Tab. 1: Variables used in the analysis

Variable	Description	Unit
Daily rentals	The total number of bicycle hire transactions recorded over a 24-hour period	Number of trips
Rotation index	A measure of fleet efficiency, calculated as the average number of trips per available bike per day	Trips per bike
Precipitation	The total volume of rainfall measured in millimetres (mm) during the observation period	mm
Maximum temperature	The highest ambient air temperature recorded daily, measured in degrees Celsius (°C)	ºC
Thermal sensation	The perceived outdoor temperature (heat index or apparent temperature) based on combined meteorological factors	ºC
Bikes in service	The total count of bicycles actively available for public hire within the docking system	Number of bikes
Bikes in maintenance	The number of units temporarily withdrawn from the fleet for mechanical repairs or safety inspections	Number of bikes

Source: own

its temperature through perspiration, leading to the loss of essential fluids and electrolytes.

Considering Seville's climate, particular attention must be paid to the thermal sensation of heat (heat index), as it can lead to heatstroke or exhaustion, especially during certain months of the year. The wind chill effect, however, is not significant in this context.

3.3 Variables

The analysis incorporates a set of environmental and operational variables, summarised in Tab. 1.

These variables capture both environmental exposure and operational system conditions, allowing identification of distinct weather-mobility regimes.

3.4 Thermal indices calculation

The thermal comfort analysis was conducted using the heat index (HI), a metric rooted in the theoretical framework developed by Steadman (1979). This index defines the 'sensation of heat' by integrating air temperature and relative humidity to determine the apparent temperature perceived by the human body. To operationalise this concept, the multiple regression model proposed by Rothfusz (1990) was employed (Equation (1)). This model represents a refinement of Steadman's work, consisting of a polynomial equation that calculates the index based on temperature (T) in degrees Fahrenheit and relative humidity (RH). Furthermore, a specific adjustment factor was applied to enhance the precision of the original Rothfusz calculation under certain atmospheric conditions (Equation (2)). This correction is particularly relevant for scenarios involving low humidity (below 13%) at high temperatures, or high humidity combined with moderate temperatures. For the purposes of this study, the adaptation provided by the State Meteorological Agency (AEMET, 2014) was followed, which applies these algorithms to the Celsius scale.

For the calculation of the heat index from ambient temperature in degrees Celsius and relative humidity as a percentage, the following Equation (1) is used:

$$\begin{aligned}T_{HI} &= -8.78469475556 + 1.61139411 * T + \\ &+ 2.33854883889 * H_r - 0.14611605\mathrm{T} * H_r - \\ &- 0.012308094 * T^2 - 0.0164248277778 * \\ &* H_r^2 + 0.002211732T^2 * H_r + 0.00072546 * \\ &* T * H_r^2 - 0.000003582 * T^2 * H_r^2\end{aligned} \tag{1}$$

where: T_{HI} – heat index (°C); T – actual air temperature (°C); H_r – relative humidity (%).

When using this method, the risk assessment is carried out according to the following scale:

i) Caution: 27 °C to 32 °C. Fatigue is possible with prolonged exposure or physical activity;

ii) Extreme caution: 33 °C to 40 °C. Sunstroke, heatstroke, and cramps are possible with prolonged exposure or physical activity;

iii) Danger: 41 °C to 53 °C. Sunstroke, heatstroke, and cramps are highly likely with prolonged exposure or physical activity;

iv) Extreme danger: 54 °C or higher. Heatstroke or sunstroke is imminent.

Equation (1): Calculation of the thermal sensation of heat

Where the thermal sensation is due to cold, the following analogous formula is used:

$$\begin{aligned}T_{WC} &= 13.1267 + 0.6215T - \\ &- 11.37 * V^{0.16} + 0.3965 * T * V^{0.16}\end{aligned} \tag{2}$$

where: T_{WC} – wind chill temperature (°C); T – actual air temperature (°C); V – wind speed (km/h).

In this case, the risk assessment is carried out according to the following scale:

i) Low risk: −10°C to −27 °C. Risk of hypothermia with prolonged exposure to the elements;

ii) Moderate risk: −28 °C to −39 °C. Risk of frostbite with prolonged exposure (10 to 30 min);

iii) High risk: −40°C to −54 °C. Risk of frostbite within 10 min;

iv) Very high risk: −55 °C or lower. Risk of frostbite in under 2 min.

Equation (2): Calculation of the thermal sensation of cold

To provide a comprehensive assessment of thermal conditions, the heat index (HI) was calculated using both daily mean and maximum temperatures. The calculation based on mean temperature allows for an evaluation of the sustained thermal load throughout the day, while the use of maximum temperature identifies the peak heat stress periods, which are critical for understanding shifts in bike-sharing usage. Both indices were processed following the operational guidelines of the State Meteorological Agency (AEMET, 2014).

However, in Seville, the calculation of thermal sensation due to cold is scarcely applicable, given the year-round temperatures.

The study by Garcia and Arco Díaz (2023) highlights the microclimate created in the city as a consequence of the lack of vegetation and the covering of natural ground with asphalt and other materials that retain and reflect heat. These factors contribute to a sensation of heat in these locations, which they term "urban heat islands (UHI)". The UHI phenomenon, by locally raising temperatures, has a very direct impact on the physical and mental well-being of urban inhabitants. Furthermore, it is essential to consider that environmental data from meteorological stations are typically recorded in settings surrounded by vegetation and landscaped areas. This contrasts with the locations of many cycle lanes, which often lack buildings or trees to provide shade from the solar radiation that heats building walls and urban surfaces. This causes these areas to become heat reservoirs, which affects the thermal comfort of cyclists using these routes. This effect is exacerbated in cities like Seville, where, due to its geographical location, solar radiation levels are high for much of the year.

There are current initiatives to minimize the climatic impact in the city through the use of bioclimatic technology, such as water vaporization or the creation of artificial shade. This would have a very positive impact on bicycle use in the areas where such systems are implemented (although limitations mean they may only be applicable at certain times of the year), leading to an increase in cycling.

The study by Brey et al. (2017) analyses various cost-benefit factors, but it could be complemented with information on how to address the costs and benefits of implementing cyclist-specific infrastructure that promotes thermal comfort and safety, such as shaded cycle lanes, drinking water stations, and public showers. Additionally, the cost-benefit ratio of policies promoting cycling in extreme weather conditions could be evaluated. For example, if investment in specific infrastructure for cyclists that enhances thermal comfort and safety can significantly increase the number of people choosing the bicycle as a mode of transport, then the benefits of this investment could far outweigh the costs.

In conclusion, the study on cycling promotion in Seville could be useful for evaluating the effectiveness of such policies in conditions of high temperature and humidity. By assessing the costs and benefits of specific policies that promote thermal comfort and safety, it would be possible to determine how to make cycling a more attractive and accessible transport option for people living in hot and humid climates, with these results being extrapolated to other cities.

3.5 Data analysis and procedures

Using the historical data on environmental conditions cited previously, once collated and organised, along with the daily usage data from the Sevici bicycle-sharing system, an analysis was conducted using self-organising maps (SOM). This was implemented by applying the Kohonen algorithm, a technique based on unsupervised artificial neural networks used for classifying information and reducing the dimensionality of a specific analysis. This method allows for visualizing data from numerous variables, which would otherwise be very complex to display, on two-dimensional maps.

The training of this type of network is classified as unsupervised because the training patterns are formed solely from the input variables of the classification process. Consequently, it is not necessary to include output variables, such as the group to which each pattern belongs. This aspect represents a significant advantage over other information classification methods. To train the neural network, the weights of a predefined number of neurons are modified through an iterative process. During this training phase, the learning rate decreased linearly from 0.05 to 0.01. The initial neighbourhood size included two-thirds of all distances between the map units, and it also decreased linearly during the first third of the iterations. After each iteration, the neuron weights are updated based on these parameters, and once the initial phase is complete, only the winning unit is adapted (Fig. 4).

As previously indicated, the thermal sensation of heat was calculated using temperature, humidity, and wind speed data provided by the AEMET network's meteorological station at Seville Airport (San Pablo) from 2018 to the present. When the risk assessment intervals for this variable are applied to the results, it is found that the thermal sensation is above 27 °C on 47% of the days of the year. This proportion drops to 30% for days when the thermal sensation rises to 33 °C (the start of the extreme caution range), and to 13% for days reaching 40 °C. A thermal sensation

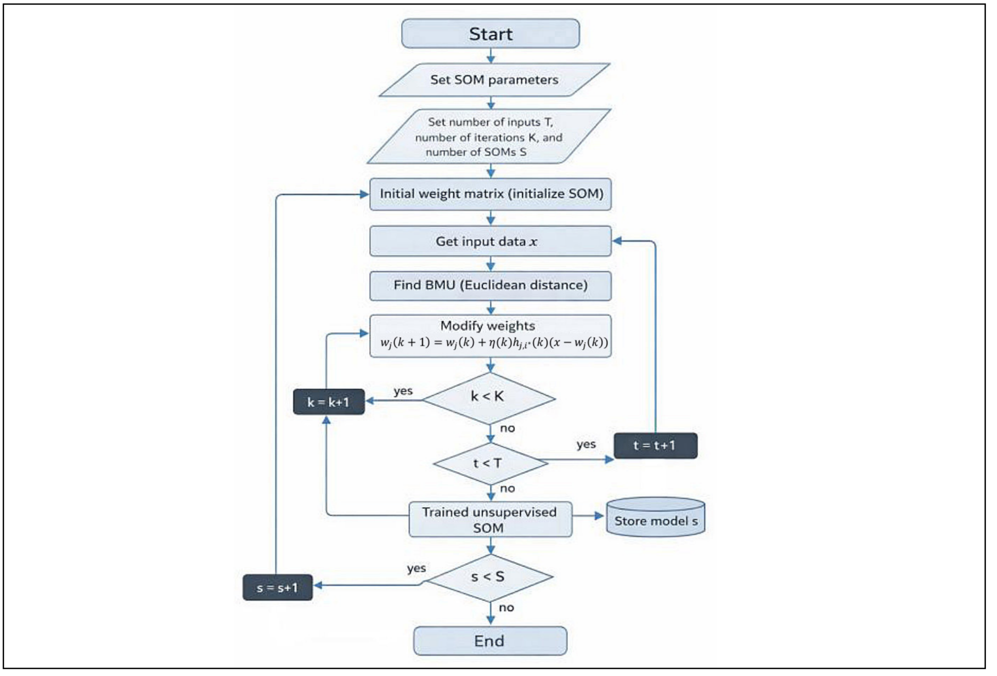

Fig. 4: Flowchart for the unsupervised SOM algorithm

Source: Seifert et al. (2023)

of 53 °C is exceeded on only 0.3% of days, falling to 0.2% for days surpassing 54 °C.

Due to Seville's climatic characteristics, risk conditions related to cold are not met. This has a very positive impact on promoting bicycle use for much of the year, when the temperature is pleasant, and encourages cycling. This, combined with the scarcity of rain and its concentration in specific months, considerably fosters usage.

On the other hand, it must be taken into account that throughout the year there are days with diurnal temperature ranges of up to 20 °C. This means that although the thermal sensation might be acceptable at certain times of the day, it could be uncomfortable at others. Depending on the journey. and travel times, this can lead to reduced use of Sevici bicycles, with users opting instead for public transport, other electric personal mobility devices that avoid physical exertion and are thus less affected by thermal sensation, or private vehicles.

According to the PMUS diagnostic document (Fig. 6), journeys in Seville exhibit two clearly distinct peak periods. The first occurs between 8 a.m. and 9 a.m., with a volume that accounts for 7.4% of daily journeys, and the second is in the 14:00–15:00 interval, representing 8% of daily journeys. As has been previously highlighted, there can be a significant difference in thermal sensation between these two periods.

The initial data was prepared by removing erroneous or missing values. To ensure data integrity and prevent variables with larger ranges from dominating the calculation, the data was then normalized and standardised by scaling based on the mean and standard deviation of each variable.

A 12 × 12 hexagonal grid of nodes was constructed as it is shown in Fig. 7. This hexagonal structure is commonly used in SOMs due to its efficiency in representing proximity relationships between nodes. The SOM was trained with the scaled data using an iterative algorithm. During training, the grid's nodes are adjusted to resemble the patterns present in the input data. The training phase consisted

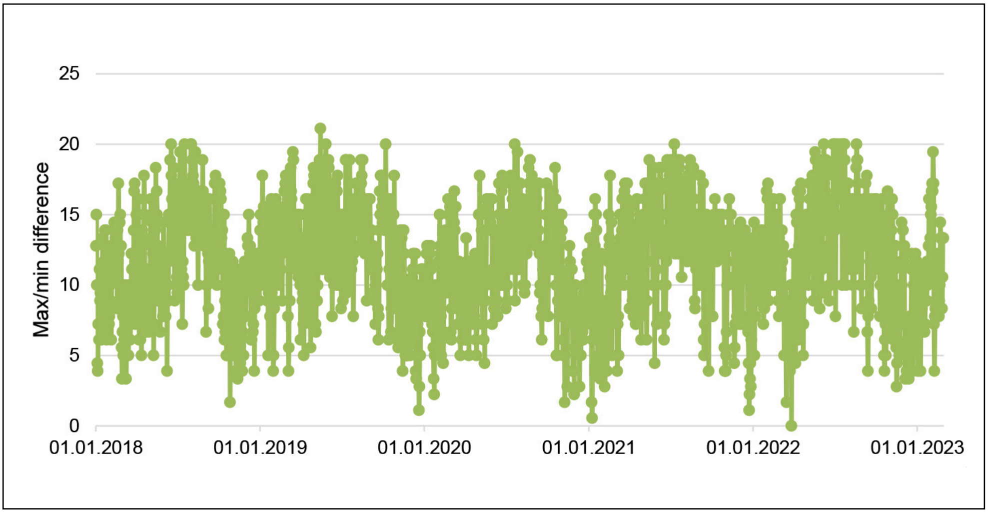

Fig. 5: **Maximum and minimum temperature differences**

Source: Aemet

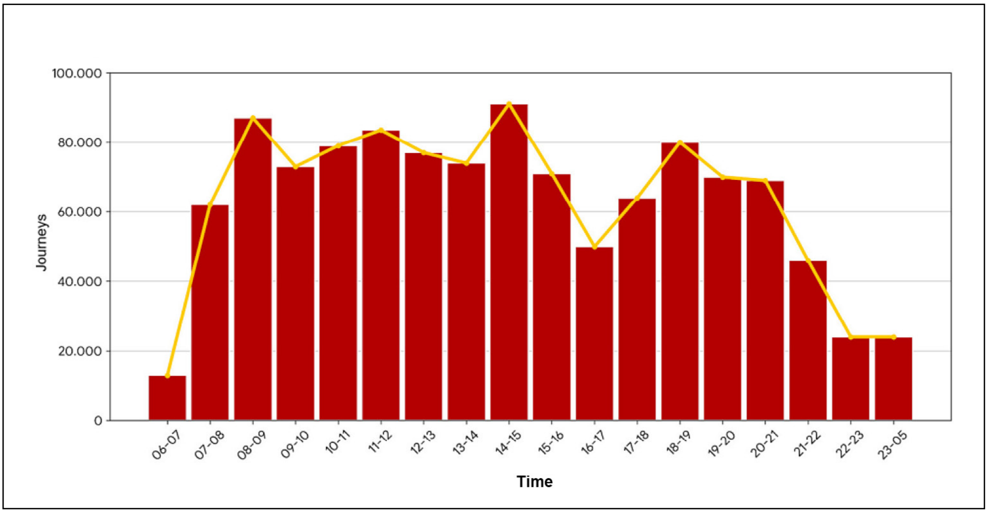

Fig. 6: **Distribution of journeys by start time**

Source: Seville Office of the Bicycle 2024

of 100 iterations, with a learning rate that decreased linearly from 0.05 to 0.01.

Once the SOM was trained, various visualizations were generated to understand its structure. To simplify interpretation and obtain groups of days with similar characteristics, hierarchical clustering was applied to the SOM nodes. The root mean square error (RMSE) was calculated for each variable, and the results were displayed in a bar chart. A low RMSE for a variable suggests that the SOM has effectively captured its variation pattern, whereas a high RMSE could indicate that the variable is more difficult to model with the current SOM configuration.

In this case, 8 clusters ($k = 8$) were defined, meaning the SOM is divided into 8 main regions, each representing a distinct type of day. For each cluster, metrics such as the number of days it represents, the assigned observations, and the mean value were calculated.

Each node of the SOM represents a characteristic type of day according to the analysed variables. The resulting chart shows, for each node, the mean profile of the six variables (hires, rotation, precipitation, maximum temperature, thermal sensation, bikes in service, and bikes in maintenance).

Within each cell of the map, a radar-type chart is drawn, where: i) each radius represents a variable; and ii) the length of each radius indicates whether that variable has a high or low value in that node.

The charts act as "fingerprints" of daily behaviour, making it possible to see if a node represents rainy days, days with high demand, or days with few available bikes, for example. By comparing the shapes of the nodes, gradual transitions or sharp breaks between types of days can be detected. For instance, a node with peaks in hires, temperature, and rotation represents a typical spring day with high demand, whereas another with peaks in rain and few bikes in service might represent a rainy winter day.

This map is useful for understanding what defines each zone of the SOM and how the variables are interrelated.

3.6 Data preprocessing

Prior to model estimation, a structured data preprocessing procedure was applied. Raw daily

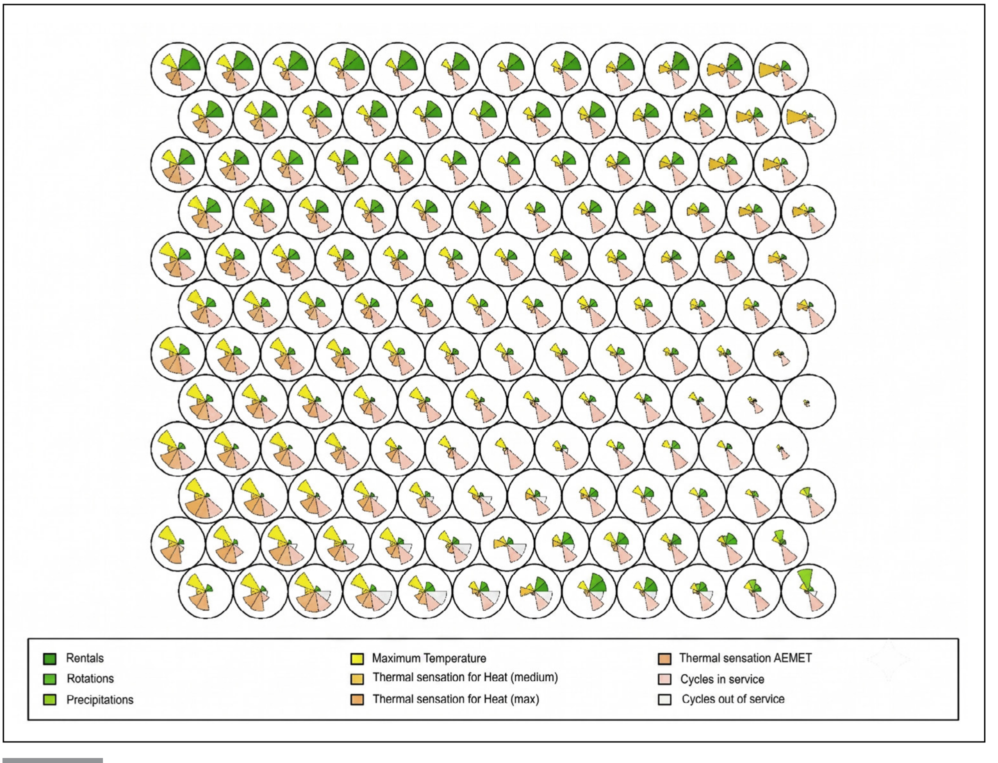

Fig. 7: Prototypes per node (12 × 12 node matrix)

Source: own

observations were screened to identify incomplete or inconsistent entries; records containing missing or erroneous values were removed, resulting in a final dataset of 1,885 complete observations. All selected variables were then converted to numeric format to ensure computational consistency. Finally, to prevent scale dominance in Euclidean distance calculations, variables were standardised using *z*-score normalisation (mean zero and unit variance). This standardisation was essential given the heterogeneous magnitudes of the climatic and mobility indicators included in the analysis.

3.7 SOM model specification validation and clustering

The self-organising map (SOM), originally proposed by Kohonen (2001), was implemented in *R* using the kohonen package. The dataset consisted of 1,885 daily observations combining climatic and bicycle-sharing variables. All variables were converted to numeric format and standardised using *z*-score normalisation (mean zero and unit variance) to prevent scale dominance in Euclidean distance computations.

A two-dimensional hexagonal lattice composed of 12 × 12 units (144 neurons) was defined. The hexagonal topology was selected because it provides smoother neighbourhood transitions and improved adjacency structure relative to rectangular grids.

The grid size was chosen following common SOM heuristics suggesting that the number of map units should be proportional to five times the square root of the number of observations (Vesanto & Alhoniemi, 2000). Given n = 1,885, this rule yields approximately 217 units as an upper reference. The selected 144-unit configuration provides sufficient resolution while preserving interpretability. During training, each observation vector x was assigned to its best matching unit (BMU), defined in Equation (3) as the neuron whose prototype vector w minimises Euclidean distance:

$$c(j) = \arg \min_{\mathrm{i}} \{\|x_j - w_i\|\} \tag{3}$$

where: x_j – the j^{th} input vector; w_i – the prototype vector associated with neuron i.

The norm corresponds to the Euclidean distance between the observation and the neuron's weight vector. The resulting value was QE = 0.519, indicating satisfactory representation accuracy in the standardised input space.

Codebook vectors were iteratively updated using a Gaussian neighbourhood function centered on the winning unit. The training length was set to 100 using the batch algorithm, which inherently avoids the need for a specific learning rate schedule by computing the update based on the weighted average of data points in the neighbourhood.

Model quality assessment

Model performance was evaluated using two standard SOM diagnostics (Kiviluoto, 1996). On the one hand, we use the quantization error (QE), which is defined as the average Euclidean distance between each observation and its BMU, as shown in Equation (4):

$$QE = \frac{1}{n} \sum \|x_j - w_{c(j)}\| \tag{4}$$

where: $w_{c(j)}$ – the prototype vector of the winning unit for observation j.

On the other hand, the topographic error (TE), stated as the proportion of observations for which the first and second BMUs are not adjacent on the lattice, was TE = 0.299. This reflects moderate preservation of neighbourhood relationships, consistent with the structural heterogeneity of daily weather-mobility interactions.

Cluster extraction

After training, clustering was performed on the 144 SOM codebook vectors using the k-means algorithm, following the approach suggested by Vesanto and Alhoniemi (2000). Applying clustering to the prototype vectors exploits the topology-preserving and noise-reducing properties of the SOM representation.

Alternative k values were evaluated, and the selection of k = 8 was supported by inspection of within-cluster dispersion and cluster interpretability. The eight-cluster configuration provided the most meaningful segmentation of daily climatic mobility regimes without excessive fragmentation. Each observation inherits the cluster label of its corresponding BMU, enabling classification of days into eight distinct profiles.

4 Results and discussion

4.1 Results

This section reports the main findings derived from the self-organising maps, highlighting how distinct combinations of weather conditions translate into different levels of bicycle demand. The results allow for a clear identification of daily usage profiles and the climatic drivers behind them.

Tab. 2 summarizes the central tendencies and dispersion for the main variables within each of the eight clusters**.** Tab. 2 confirms the visual patterns from the component planes: i) clusters with high maximum temperature and negligible precipitation present peak rentals and rotation; ii) clusters with light-to-heavy precipitation show systematically lower demand; and iii) clusters with very high thermal sensation (heat stress) also register reduced usage, even in the absence of rain. In addition, Tab. 2 reveals intermediate regimes, such as temperate, dry or warm-humid that sustain medium demand levels, consistent with the gradients seen on the map.

Tab. 2: Cluster characteristics

Cluster	Number of days	Rentals	Rotation	Precipitation	Maximum temperature	Thermal sensation
1	31	4,859	2	0	36.9	42.5
2	347	4,539	2	0	35.5	40.4
3	130	6,495	3	0	23.5	23.8
4	524	11,255	5	0	25.3	27.0
5	68	4,713	2	13	17.3	17.7
6	11	4,258	2	32	17.2	17.1
7	739	5,853	2	1	21.3	21.7
8	35	98	0	0	0.7	21.4

Source: own

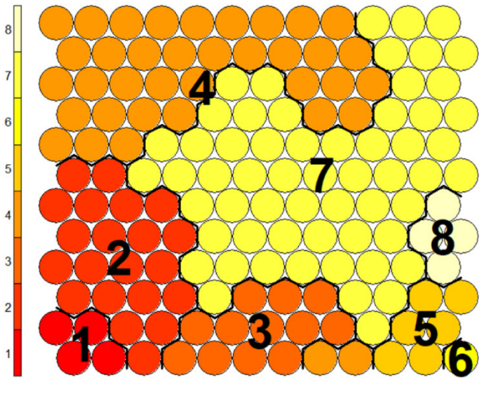

Fig. 8: SOM cluster results

Source: own

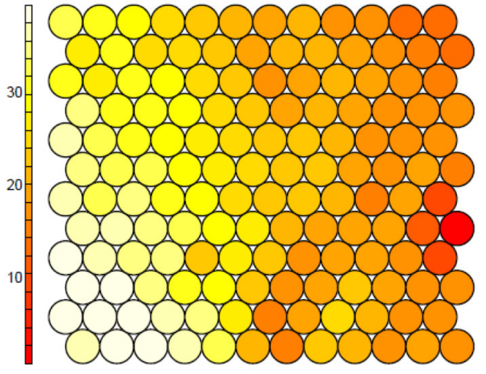

Fig. 9: Clusters for maximum temperature

Source: own

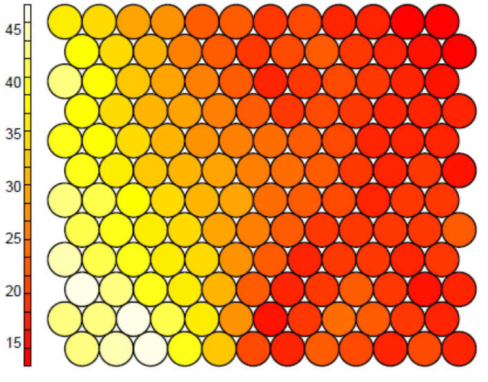

Fig. 10: Clusters for thermal sensation

Source: own

As we can see, Fig. 8 presents the SOM cluster map (U-matrix) with the eight-node partition used in the analysis. The map displays well-defined boundaries and internally homogeneous nodes, indicating that the topology captures stable daily profiles. In addition, Fig. 9–10 show the component planes for maximum temperature and thermal sensation, respectively. Warmer colours (higher values) concentrate along contiguous areas of the grid, suggesting a clear thermal gradient across nodes.

For its part, Fig. 11 displays the precipitation component plane. Rainfall concentrates on a set of nodes that are largely disjoint from the warm-dry areas observable in Fig. 9–10. This separation anticipates a negative association between precipitation and the demand metrics. Thus, Fig. 12–13 report the demand outcomes: bicycle rentals and rotation (rentals

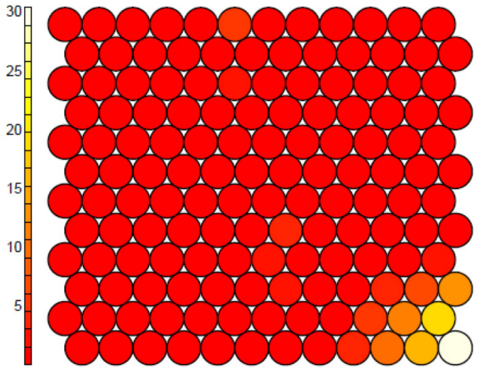

Fig. 11: **Cluster for precipitation reading**

Source: own

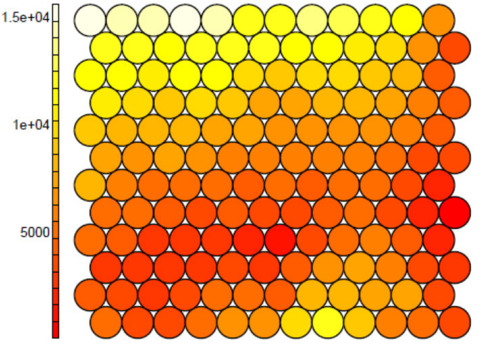

Fig. 12: **Cluster results for rentals value**

Source: own

per bike per day). The highest demand intensities appear in nodes characterised by warm and dry conditions in the climate planes (Fig. 9–10), while the lowest values cluster in rainy nodes, regardless of temperature. This pattern points to a strong meteorological segmentation of bicycle use.

Attending to the training of our model, Fig. 14 tracks the training evolution of the SOM, indicating stable convergence after successive iterations, while Fig. 15 reports the variable-level squared error, highlighting precipitation and temperature/thermal sensation as the features with the strongest structuring effect on the map.

The eight-cluster configuration reveals a set of clear and behaviourally consistent patterns linking weather conditions to shared bicycle demand. The eight-cluster configuration reveals consistent patterns linking weather to demand. Cluster 4 represents the peak

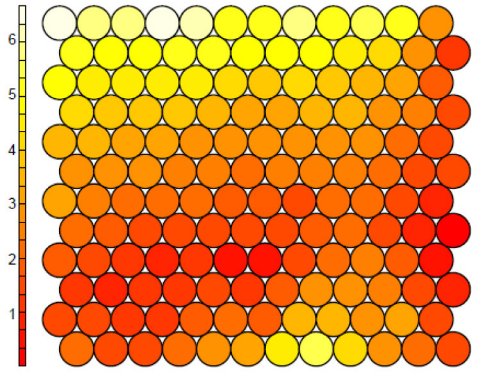

Fig. 13: Cluster results for rotation value

Source: own

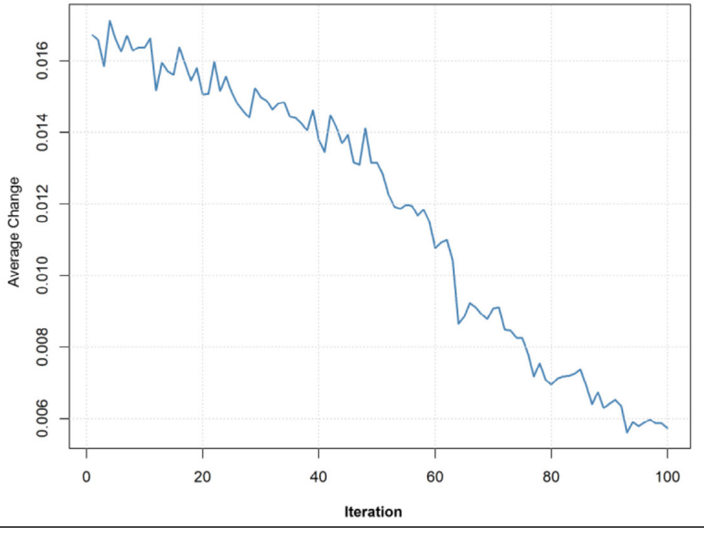

Fig. 14: SOM training progress (iteration in training)

Source: own

demand scenario with 11,255 rentals, characterised by ideal spring temperatures (25.3 °C) and no precipitation. Clusters 1–2 group the warmest days (35.5 °C to 36.9 °C), where demand drops to approximately 4,500–4,800 rentals due to extreme thermal sensation (up to 42.5 °C), confirming that heat stress discourages usage.

Regarding adverse weather, cluster 6 identifies the impact of heavy rainfall (32 mm), resulting in lower usage despite mild temperatures. Cluster 7 shows that even light drizzle (1 mm)

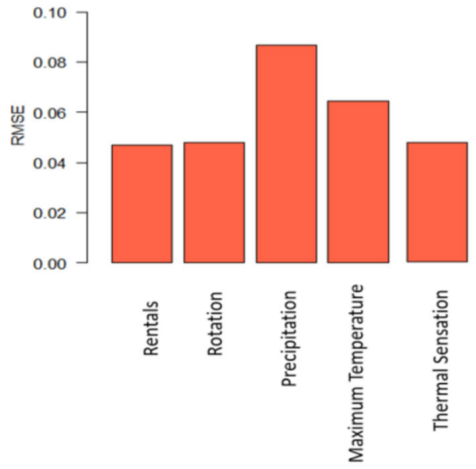

Fig. 15: **Mean squared error by variable**

Source: own

significantly impacts demand levels compared to dry days. Finally, cluster 8 represents the most unfavorable thermal scenario with temperatures near 0.7 °C, recording the absolute minimum of 98 daily rentals, so demand is more sensitive to extreme cold than to extreme heat. Overall, the clusters highlight two consistent regularities. First, precipitation systematically suppresses demand regardless of thermal conditions, confirming its role as the strongest inhibitor of shared bicycle usage. Second, a large diurnal temperature range can partially mitigate the effects of heat, as it creates short windows of thermal comfort in which users remain willing to cycle despite high daily peaks.

The results show that shared bicycle usage in Seville is strongly conditioned by weather dynamics, with self-organising maps revealing distinct daily demand profiles driven by specific combinations of thermal sensation, temperature and precipitation. In particular, warm-dry conditions are associated with the highest levels of activity, while rainfall and extreme heat consistently suppress demand, underscoring the central role of climate in shaping urban cycling behaviour. In summary, this paper aims to provide scientific results that can serve as a foundation for studying the factors influencing bicycle use, such as the city's specific climate. It also highlights the need to consider other factors in future research, including age, sex, economic status, and type of service use.

4.2 Discussion

This paper assessed the relationship between climatic conditions and bicycle-sharing demand in the city of Seville using a self-organising map (SOM) methodology. The results are largely coherent with prior research underlining the noteworthy influence of weather conditions on cycling behaviour and bicycle-sharing usage. Environmental factors such as temperature, precipitation and seasonal variability have long been recognised as key determinants of cycling activity (Corcoran et al., 2014; Heinen et al., 2010). Our results confirm that, in Seville, moderate temperatures and dry conditions are associated with higher levels of bicycle usage, whereas extreme heat and rainfall tend to decrease demand.

At the same time, our analysis provides additional insights by studying the interaction between climatic variables through an unsupervised SOM framework. In contrast to most previous studies that lie on regression-based models for demand prediction, the SOM approach lets the identification of nonlinear relationships and hidden behavioural regimes emerging from the interaction between environmental conditions and system usage. More precisely, our analysis proposes that thermal sensation, estimated by the heat index, acts as a more sensitive predictor of cycling demand than only the temperature. Furthermore, the results specify the presence of a threshold around 35 °C beyond which bicycle use decays significantly, implying that perceived thermal comfort plays a central role in determining mobility behaviour in hot-climate urban environments.

From a theoretical standpoint, these results strengthen the idea that cycling demand in bike-sharing systems is formed by the interaction between environmental conditions and perceived thermal comfort rather than by each climatic variables considered independently. This interpretation is coherent with previous studies showing that both climatic conditions and urban context influence bicycle-sharing usage patterns (Bean et al., 2021; El-Assi et al., 2017).

This paper also contributes methodologically to the study of urban mobility dynamics. By relating dimensionality reduction, clustering and visualisation, the SOM approach allows the identification of different weather-mobility regimes that might continue unseen when applying conventional modelling procedures. This ability offers a valuable framework for exploring complex mobility datasets characterised by nonlinear interactions between environmental and operational variables. In practical terms, appreciating how climatic conditions influence bicycle-sharing demand may help operators predict demand variations, enhance fleet allocation and develop adaptive management strategies for shared mobility systems under strong climatic variability.

Notwithstanding these contributions, some limitations should be recognised. First, the analysis focuses on a single case study, namely the city of Seville, which might constraint the generalisability of the findings to other urban contexts (Bean et al., 2021). Second, climatological data were acquired from a single weather station placed at Seville Airport, which may not completely take potential microclimatic variations across the urban environment (Corcoran et al., 2014). Third, the dataset does not contain socio-demographic variables such as income levels or land-use characteristics, for instance, which have been indicated to influence spatial patterns of bicycle-sharing demand (El-Assi et al., 2017; Wang et al., 2018). Lastly, the SOM approach is exploratory in nature and does not allow causal inference concerning the relationship between climatic conditions and bicycle-sharing usage.

Taken together, these results underscore the importance of considering climate-mobility interactions when examining bicycle-sharing systems in warm-climate cities and specify a foundation for future research on the relationship between environmental conditions and shared mobility demand.

Regarding local cultural factors, it is important to note that traditional festivities such as Holy Week and the April Fair significantly alter typical mobility patterns. During these periods, bike-sharing usage often shifts from commuting to leisure-oriented trips, or faces temporary service interruptions in the historic centre due to crowd management. While these events were not isolated as separate variables in the current SOM model, their occurrence during the spring months contributes to the high-demand profiles observed in cluster 4.

Conclusions

This study addressed the association between climatic conditions and bicycle-sharing demand in Seville using a self-organising map (SOM) approach. The findings suggest that cycling activity is strongly affected by mixtures of weather-related factors rather than by individual variables contemplated in isolation. Especially, perceived thermal conditions, estimated by the heat index, appear as a central determinant of system use, with an evident drop in ridership when temperatures surpass approximately 35 °C.

The study also reveals the importance of the SOM approach as an exploratory tool for detecting complex weather–mobility regimes in urban transport systems. By allowing the discovery of nonlinear relationships and hidden behavioural patterns, the approach provides a complementary standpoint to conventional regression-based methods frequently used in the analysis of shared bicycle systems.

Future research might extend this outline by including spatial and socio-demographic indicators in order to better comprehend the relation between climatic factors or urban structure, for instance. Particularly, incorporating spatial econometric methods could help to further explore how environmental and socio-economic features jointly form patterns of bicycle-sharing use.

Overall, this paper contributes to a deeper understanding of the interaction between climate and urban mobility dynamics and underscores the importance of climate-sensitive methodologies in the study of sustainable urban transport systems.

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Analyzing user perceptions and adoption of urban public transport applications through natural language processing

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Abstract: *An enhanced understanding of urban public transport app adoption has been achieved by applying innovative data mining and sentiment analysis techniques to large user review datasets from Google Play Store and Apple App Store, covering major European metropolitan areas. Natural language processing (NLP) methods were employed to perform sentiment analysis, emotion analysis, and topic modeling (LDA), extracting valuable insights from unstructured text. The results highlight the importance of citizen science and citizen participation in app development. This is in line with the growing trend of actively involving users in the development of digital services. Intermodal integration, accessibility, improving the user experience, environmental engagement, integrating digital payments seamlessly, and providing real-time information have been identified as key user priorities. The perceived usefulness of reviews was impacted by the relationship between sentiment and review features. This offered suggestions for ways to improve app development. The findings present useful recommendations for creating more inclusive, sustainable, and user-aligned services in smart city settings, as well as a conceptual framework for technology adoption in urban mobility applications.*

Keywords: *Mobility as a service (MaaS), user experience, orange data mining, sustainable mobility, urban mobility.*

JEL Classification: *C55, C88, M31, R41.*

APA Style Citation: Aguilar-Moreno, J. A., & Palos-Sanchez, P. R., & Pozo-Barajas, R. & Duarte-Atoche, T. (2026). Analyzing user perceptions and adoption of urban public transport applications through natural language processing. *E&M Economics and Management, 29*(3), 102–130. https://doi.org/10.15240/tul/001/2026-5-004

Early Access Publication Date: *April 8, 2026.*

Introduction

Public transport is at the core of the daily activities of individuals. It facilitates easy access and sustainability of cities since traffic is better controlled and less polluted compared to when private cars are used (Marsden & Rye, 2010; Solecka & Kiciński, 2022; Woods & Masthoff, 2017). This, therefore, lays emphasis on urban transportation policies that improve citizens' engagement and awareness concerning the use of public transport, fostering more environmentally sustainable urban areas (Ercan et al., 2016).

Environmental impact reduction is one of the 17 goals of the United Nations toward sustainable development. For public transportation to easily convince people to leave their private cars and use it, it should have high quality service plus cost and comfort on par with that of private transportation (Allirani et al., 2024). Since communication strategies can change these perceptions, factors that affect the choice to use public transportation should be known in order to improve marketing policies and the quality of the service as a whole (Gössling, 2020).

Earlier studies reveal that passenger contentment with public transport provisions is perceived through various aspects such as wait time, comfort, and cleanliness (dell'Olio et al., 2010), service coverage, level, and accessibility (Chen et al., 2018). Other determinants include station infrastructure, customer service, staff friendliness, vehicle comfort, and on-time performance, as well as frequency, together with station access and proximity of parking slots (Grisé & El-Geneidy, 2018). Timely transport systems should allow travelers to get to their desired places at the right moment and with regularity, hence bringing up notions like "15-minute city" (Moreno et al., 2021). In line with this idea, bus or underground pathways toward important places in a metropolis, bicycle plus walking paths and digital plans that enhance the ordinary day-to-day existence at local levels are also part of it.

Emerging information technologies and the development of concepts like the internet of things, smart cities, and mobility everywhere are seen as crucial for enhancing urban public transport services (Guo et al., 2020) as well as fostering behavioral changes in using more public transport (Andersson et al., 2018). Therefore, to make sure that users get the feeling that their needs are being addressed, public transport providers have to ensure digital integration going beyond providing passenger transport. This comprises real-time schedule information, route planning among other online ticket purchasing features (Kuo et al., 2023; Vakula & Raviteja, 2017).

Thus, this study shall use advanced data mining, text mining, sentiment analysis, and machine learning techniques on user reviews posted in the Google Play Store and Apple App Store to better unveil the perception of users located within major EU metropolitan areas regarding official public transport applications (buses, metro, trams, and subways). The goal is to improve decisions and app development that will result in even more integrated Smart Mobility apps and sustainable cities. Based on this approach, the following research questions emerge:

RQ1: Which emotions and sentiments are those that are most frequently expressed by users of official public transport apps in major European cities?

RQ2: How closely do user-assigned ratings in app stores match sentiment analysis?

RQ3: Which topics most frequently concern users?

RQ4: How can user feedback analysis contribute to the optimization of apps and improve user satisfaction in urban mobility?

Study context, objectives, and research questions are what the first section contains. That is what serves as an introduction. Methods of artificial intelligence related to sentiment analysis and text mining that have been used in this field are discussed within a literature review presented in the second section, describing the theoretical framework for smart cities. The methodology for choosing which cities will be part of this study and their applications to urban mobility follows next, including how user opinions were extracted and what software was used on the data to get statistics out of them. The results come next with return, evidence-based responses to research questions in the discussion section. Also included are final thoughts at the end with potential further paths toward similarly related domains.

1 Theoretical background

1.1 Smart city

The idea of the smart city has risen in the last few decades as a model for sustainable urban planning (Batty et al., 2012; Kourtit & Nijkamp, 2012) and, at the same time, has led to a large number of meanings and definitions (Albino et al., 2015).

The core definition is based on the application of ICT (information and communication technologies) for urban development (Caragliu et al., 2011). It is reflective of the word's emergence in the 1990s with never-ending information technology booms (Albino et al., 2015). However, this framework has been opened to include systems besides technological infrastructure that involve, primarily, education and human capital as well as environmental sustainability in urban development (Caragliu et al., 2011; Kourtit & Nijkamp, 2012).

By the most technology-oriented definitions, a smart city is one made up of everyware (Greenfield, 2010), joining together "everywhere" and "software", to denote the pervasive and ubiquitous integration of technologies that include sensors, cameras, and even apps for smartphones within urban settings (Kitchin, 2014).

Albino et al. (2015) compiled twenty-three definitions from various authors. Among them, the most relevant to the points mentioned above are presented in the following Tab. 1.

Tab. 1: Definitions of "smart city"

Definition	Source
A smart city is one that makes advanced use of technology to connect information with urban elements and people, thereby creating a more sustainable city and innovative and competitive commerce that fosters a better quality of life.	Bacik et al. (2020)
There are two trends in research: i) smart cities must utilize new thinking paradigms related to governance and economics; ii) smart cities are related to the integration of ICT, smart devices, sensor networks, and real-time data applied to all aspects of human life.	Cretu (2012)
A city is considered smart if it fosters a high quality of life and sustainable economic growth through intelligent management of natural resources and participatory governance based on investments in social and human capital and infrastructure, which can include traditional communications (transport) and modern communications (ICT).	Caragliu et al. (2011)

Source: Albino et al. (2015)

The third definition in Tab. 1 aptly illustrates the two types of communication infrastructures examined in this article: traditional infrastructures, such as transportation systems, and modern infrastructures, including ICT platforms (particularly apps that provide real-time information about these transport systems) and artificial intelligence tools that facilitate their analysis.

Considering the two main trends in the definitions of this concept, Neirotti et al. (2014) classify previous articles on smart cities into two domains: hard domains, in which ICT plays a fundamental role, and soft domains, where its role is more limited and is primarily associated with areas such as education or social welfare. Mohanty et al. (2016) also align these domains, or components, of a smart city, characterizing them with four attributes: urbanization, sustainability, smartness, and quality of life. Additionally, Tyagi and Bhushan (2023) highlight the importance of applying natural language processing (NLP) techniques, providing examples of research in fields related to smart city domains. Fig. 1 summarizes these domains, with a particular emphasis on the subdomain of transport, mobility, and logistics.

A wide variety of applications influence the smart city. The urban mobility applications often share core functionalities – departure times, stop geolocation and GPS vehicle tracking, route visualization, implemented overlays on digital maps, and online connectivity to update schedules in real-time. Value-added features may include digital ticket purchase, information in real-time about delays or early arrival, information regarding changes in routes due to unexpected events on the way, as well as a place where bicycles, scooters, motorcycles and carsharing can be picked up and dropped off (Solecka & Kiciński, 2022). Mobility as a service (MaaS) is brought about by the integration of different modes of transport under one digital platform focused on user needs (Jittrapirom et al., 2017).

The main variables are service reliability, wait time, comfort, and driver friendliness. Other less important variables include travel

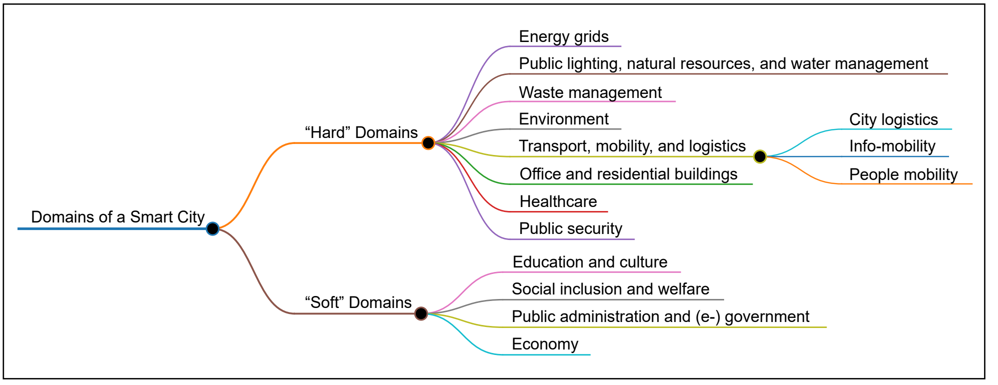

Fig. 1: Domains of a smart city

Source: own based on Neirotti et al. (2014)

time and walk time to the bus stop, safety, route deviation, vehicle cleanliness, ticket price, vehicle quality, and driver courtesy. The relative importance of these variables also changes with the socioeconomic characteristics of users such as gender, age, ownership of a private vehicle or driver's license, frequency of service use, and economic level (dell'Olio et al., 2010, 2011). Glascock (1997) described them under two heads: the design of service (minimum and maximum frequency of 15 and 30 minutes, preferably no transfers or if so necessary waiting times less than 10 minutes; acceptable bus travel times up to 50% longer than car travel time although many prefer equal times) and delivery in practice (punctuality, buses not departing before scheduled times, cleanliness and maintenance, minimal delays).

Studies of smart city transport applications articulate that these should, quite obviously, visually prepossess, attune to the needs and preferences of each user, and provide relevant contextualized data supported by statistics on how to achieve better performance from users. One approach to keep users interested is gamification. Thus, incentives are provided in the form of points or achievements toward reaching a goal (Andersson et al., 2018). This phenomenon has been analyzed in other fields, such as business management, and has the potential to increase employee motivation and improve customer service (Kacerauskas et al., 2023). In addition to highlighting the benefits of rewards, Casquero et al. (2022) stress not only the fruitfulness of rewards but also that app adoption decreases with high user concern for privacy and usability.

Papers listed in Tab. 2 have been compiled based on theoretical models of technology adoption, emphasizing factors such as attitude, social influence, functional motives, ease of use, social interaction, gamification, and environmental awareness as factors influencing the adoption of transportation apps.

Recent research places particular emphasis on the active participation of citizens to improve services, which is aligned with the paradigm of public participation and citizen science (Haklay et al., 2018). Studies employing surveys have addressed understanding user opinions and needs (Lin et al., 2020; Nili & Izadpanahi, 2024; Solecka & Kiciński, 2022). According to Solecka and Kiciński (2022), most respondents value ease of use, accurate information on public transport departures from stops, and route mapping from origin to destination. Other important features include alternative route searches, total travel time information, and the ability to purchase tickets through the app. Users also express interest in routes with minimal transfers, automatic location detection, absence of advertisements, and real-time updates on schedules and prices. Less valued features are guides or tutorials, offline mode, and integration with individual transportation modes. Meanwhile, Lin et al. (2020) are persuaded by perceptions from users. In their argument, this will help identify the gaps and lead

Tab. 2: Research based on technology adoption theories

Theory based	Conclusions	Reference	DOI
Technology acceptance model (TAM)	Attitude and social influence are the primary direct determinants of the intention to use multimodal trip planning apps.	Altay & Okumuş (2022)	https://doi.org/10.1016/j.rtbm.2021.100706
Lindenberg's goal-framing theory	Hedonic (enjoyment, social interaction, gamification), normative (environmental awareness), and functional (travel efficiency) motives influence the intention to use urban mobility management applications.	Dastjerdi et al. (2019)	https://doi.org/10.1016/j.tra.2019.06.001
The adoption of real-time information (RTI)	Due to the fact that most apps do not provide comprehensive multimodal information, people making multimodal trips must consult multiple apps. Regular passengers prefer the official operator's app, while occasional users tend to use generalist apps like Google Maps. Enhancing data integration and availability within these apps could attract new users and increase user satisfaction.	Romero et al. (2022)	https://doi.org/10.1080/15568318.2020.1871131
Technology acceptance model (TAM)	Perceived usefulness is the strongest predictor, followed by collaboration, habit, and ease of use.	Haldar & Goel (2021)	https://doi.org/10.1007/978-3-030-71945-6_14
Unified theory of acceptance and use of technology (UTAUT)	Environmental concern and social influence strongly affect user intentions, while previous smart mobility experience increases acceptance, underscoring the need for strategic collaboration.	Back et al. (2025)	https://doi.org/10.1016/j.cstp.2025.101464
Technology acceptance model (TAM)	Technophilia drives MaaS adoption, especially for men; usefulness and ease of use affect all, with gender variations. Green values and shared mobility attitudes impact adoption, but other transport attitudes are marginal.	González-Sánchez et al. (2024)	https://doi.org/10.1016/j.tranpol.2024.09.022

Source: own

to an improvement effort guided by indicators like ease of use, perceived cost, perceived risk, system quality, information quality, service quality, and usage intention. The study has found that though residents have a daily usage intention of such apps, performance satisfaction can be improved. A limitation acknowledged is that closed-response surveys did not allow identification of the reasons behind user attitudes.

This limitation can be addressed by analyzing user comments directly using text mining techniques, as proposed by Savastano et al. (2023), who studied user opinions on digital platforms related to shared mobility services (shared vehicles, bicycles, scooters, and other alternative transport means) in Milan, or Osorio-Arjona et al. (2021), who identified user suggestions for each line of the Madrid Metro network through analysis of tweets mentioning the official account. Similar methodologies are used by Zajac et al. (2022) to detect user perceptions of public transport in London, Madrid, and Prague during the COVID-19 pandemic, Liu et al. (2019) to understand passenger satisfaction in China using NLP, and Pineda-Jaramillo and Pineda-Jaramillo (2022) for the Paris Metro network with reviews published on Tripadvisor.

However, no studies were found comparing public transport apps from multiple European cities based on marketplaces reviews. Unlike those received on platforms such as Twitter or Tripadvisor, these reviews are based on digital elements and not the transportation system, hence more closely related to the idea of a "smart city".

1.2 Natural language processing (NLP)

Automated methods are required for effective analysis of the vast amount of unstructured data available online (Chan & Thein, 2018). This is made possible by the field of artificial intelligence known as natural language processing (NLP), which focuses on the study of human language (Chowdhury, 2003). Some techniques include named-entity recognition, topic modeling, speech recognition sentiments, and emotion analyses, which will be described further below (Aguilar-Moreno et al., 2024). Most companies in various industries use these techniques to support business decision-making and task optimization (Aguilar-Moreno et al., 2024). Companies are in a constant state of change, and digitalization represents a crucial factor for business survival (Brazo et al., 2025). The most relevant methods for this research are defined below.

Topic modelling uses classification algorithms to find key topics in a corpus by grouping texts or documents according to content similarity (Kherwa & Bansal, 2019). Among these methods, latent dirichlet allocation (LDA) has been widely known for its use in text clustering (Blei et al., 2003). The number of topics is identified through maximizing coherence and minimizing perplexity. Related approaches include latent semantic indexing (Deerwester et al., 1990), hierarchical dirichlet process (Teh et al., 2006), and negative matrix factorization (Sra & Dhillon, 2005).

LDA is a generative probabilistic model for a textual corpus based on a three-level hierarchical Bayesian model that uncovers the latent patterns within documents. Its principal goal is to uncover underlying topics by grouping related terms into meaningful clusters. Each topic is represented as a probability distribution over the corpus vocabulary. This implies that the most relevant words for a topic have a higher probability of appearing in documents associated with that topic (Mojica et al., 2024). The model identifies these topics through statistical associations among words. However, the number of topics (k) must be specified beforehand based on topic coherence and log-perplexity indicators (Newman et al., 2010), known as optimal-k. The balance between perplexity and coherence will give the optimal number of topics: minimizing perplexity and coherence (Pinto Gurdiel et al., 2021).

Perplexity quantifies the model's accuracy in predicting words based on the identified topic distributions. Lower perplexity means good inside information about the structure of topics, higher perplexity means worse predictive performance as well as understanding. Perplexity is commonly used with other metrics, such as coherence, for comprehensive model evaluation (Mojica et al., 2024).

Topic coherence serves as a complementary metric to perplexity, assessing topic quality from a human interpretability perspective. A highly coherent topic consists of words that collectively form a discernible semantic concept (Mei et al., 2007).

Sentiment analysis is a research area focused on analyzing opinions, attitudes, evaluations, and emotions expressed in written texts toward entities and their attributes. Also known as opinion mining, this field studies entities such as products, services, organizations, individuals, events, concerns, and topics (Liu, 2015).

There are two main variants of sentiment analysis techniques: lexicon-based methods, which determine the positive, negative, or neutral sentiment and polarity of text via matching with a predefined lexicon with varying connotations, exemplified by VADER (Hutto & Gilbert, 2014) and SentiWordNet (Esuli & Sebastiani, 2006); and machine learning-based methods, which involve training text classifiers – such as decision trees, naive bayes, or support vector machines – using labeled data in supervised learning, or automatically labeled texts via hierarchical dirichlet process in unsupervised learning, to later classify unlabeled texts (Birjali et al., 2021; Pang et al., 2002). The machine learning approach aims to overcome the limitation of lexicon-based methods, which may misclassify words having different sentiments in different contexts (Zhang et al., 2014).

To apply NLP techniques, extracted texts must undergo preprocessing, typically involving tokenization (dividing text into smaller units, usually words), stopword removal (excluding non-polar words such as prepositions), part-of-speech tagging, and lemmatization. Additional steps may be necessary depending on the text's format to achieve optimal cleaning (Birjali et al., 2021).

Beyond general sentiment polarity (positive, negative, neutral), **emotion analysis** seeks to identify underlying emotions in texts, which can be performed via lexicon-based or machine learning approaches requiring an appropriate training corpus (Naznin et al., 2024; Zhang et al., 2024). Emotions are classified based on models such as Ekman's (Ekman & Friesen, 1971), which proposes six basic emotions – anger, disgust, fear, happiness, sadness, and surprise – or Plutchik's model (Plutchik, 1980), which expands to eight paired opposing emotions: joy and sadness, anger and fear, trust and disgust, surprise and anticipation.

2 Research methodology

Tab. 3 presents the twenty-two largest metropolitan areas by population in the European Union, using demographic data from 2023 (Eurostat, 2024), plus London, for which data is based on the latest 2021 census (Office for National Statistics, 2021). For each metropolitan area and its principal cities, the public transport applications developed by official organizations are listed. For each app, the number of Google Play Store and Apple Store reviews analyzed is provided, along with the corresponding identification codes appended to the base URL. For example, the link for Madrid's application includes the generic component https://play.google.com/store/apps/details?id= followed by its respective ID: com.emtmadrid.emt, yielding https://play.google.com/store/apps/details?id=com.emtmadrid.emt. The same app in the Apple Store is accessible via https://apps.apple.com/es/app/emt-madrid/id332237215, which incorporates the country code ("es"), the application name, and its numeric identifier.

Tab. 3: Official public transport apps for each city or metropolitan area – Part 1

#	Metropolis (country)	Population	Apps	Play Store reviews	Play Store ID	App Store reviews	App Store ID
1	Paris (France)	12,388,388	Bonjour RATP	2,908	com.fabernovel.ratp	2,987	507107090
			Île-de-France Mobilités	2,785	com.applidium.vianavigo	2,610	484527651
2	London (England)	9,078,000	TfL Go: Live Tube, Bus & Rail	599	uk.gov.tfl.gotfl	791	1419541638
3	Madrid (Spain)	6,871,903	Metro de Madrid Official	173	es.metromadrid.metroandroid	104	481638277
			EMT Madrid	312	com.emtmadrid.emt	202	332237215
4	Barcelona (Spain)	5,797,356	TMB App (Metro Bus Barcelona)	1,296	com.geomobile.tmbmobile	603	387847254
			AMB Mobilitat	143	com.amb.ambtemps	176	588690805
			T-mobilitat	1,238	cat.atm.tmobilitat	3,631	1586790838
5	Berlin (Germany)	5,481,613	BVG Tickets: Bus + Bahn Berlin	1,075	de.bvg.ticket	1,550	1232772818
			BVG Fahrinfo: Routenplaner	2,457	de.eos.uptrade.android.fahrinfo.berlin	2,924	284971745
			BVG Jelbi: Mobilität in Berlín	439	com.trafi.whitelabel.bvg	293	1451106402
			S-Bahn Berlin	105	de.hafas.android.sbahnberlin	114	739843840
6	Ruhr Region (Germany)	5,147,820	mobil.nrw	301	com.mentz.mobilnrw_cibo_app	127	1588243043
7	Milan (Italy)	4,329,748	ATM Milano Official App	875	it.atm.appmobile	659	415637297
8	Rome (Italy)	4,227,059	Roma Mobilità	186	com.rsm.muoversiaroma	n.d.	n.d.

Tab. 3: Official public transport apps for each city or metropolitan area – Part 2

#	Metropolis (country)	Population	Apps	Play Store reviews	Play Store ID	App Store reviews	App Store ID
9	Athens (Greece)	3,626,216	OASA Telematics	850	com.att.android.tfa	494	1104863353
10	Hamburg (Germany)	3,423,121	Hvv – ÖPNV Tickets & Fahrinfo	3,194	de.eos.uptrade. android.fahrinfo. hamburg	1,984	501995569
11	Amsterdam (Netherlands)	3,397,323	GVB reis app	261	nl.gvb.reizigersapp	315	1544439867
12	Brussels (Belgium)	3,395,581	STIB-MIVB	371	be.stib.mivb.mobile	430	1325048789
13	Warsaw (Poland)	3,269,510	Jakdojade: public transport	3,497	com.citynav. jakdojade.pl.android	4,860	506795511
14	Marseille (France)	3,183,476	RTM	306	com.c4mprod.rtm	195	734548463
15	Budapest (Hungary)	2,999,794	BudapestGO	1,822	hu.webvalto.bkkfutar	1,194	916193835
16	Munich (Germany)	2,981,735	MVV-App	543	com.mdv.companion	953	388686726
17	Naples (Italy)	2,980,338	ANM GO	56	it.anm.anm	27	6450173718
18	Vienna (Austria)	2,971,753	WienMobil	1,806	at.wienerlinien. wienmobillab	1,907	1107918142
19	Lisbon (Portugal)	2,899,670	Carris	293	pt.carris.tecmic	114	1321889486
			Carris Metropolitana	45	pt.carrismetropolitana. mobile	15	6553675889
20	Stuttgart (Germany	2,816,924	VVS Mobil	712	com.mdv.VVSMobil	401	408372353
21	Prague (Czech Republic)	2,796,717	PID Lítačka	992	cz.dpp. praguepublictransport	715	983071129
22	Frankfurt (Germany)	2,779,727	RMVgo	2,195	com.cubic.rmvgo	2,064	1621720603
Total				31,835		32,439	

Source: own

Fig. 2 illustrates the official public transport applications corresponding to the cities examined in this study represented geographically on a map of Europe.

Once the apps for which user comments would be analyzed were identified, it was necessary to extract these reviews. Extraction was performed using Python programming language libraries: “app-store-scraper” for the App Store and “google_play_scraper” for the Google Play Store. The original reviews are written in multiple languages. Reviews in each country’s local language were likely written by residents, and reviews in other languages by tourists. Including all reviews was essential to ensure a diversity of perspectives, considering both residents and tourists. Therefore, to achieve consistency, all reviews were translated into English, as sentiment analysis models are more developed in this language (Mabokela et al., 2023). Translation was performed automatically using the Python library “deep-translator”.

Fig. 3 displays the structure of the resulting .xlsx file generated from the extraction and integration of data. The file includes, among others, the following highlighted fields: “username”. which provides the user’s name when available; “content”, which contains the review text, accompanied by a “score” from 1 to 5 given by the user; “thumbs up count”, which indicates how many users have marked the review as helpful; and “Translated_Review”, the English translation of the original review.

After data extraction, reviews were filtered according to the selection criteria: only those published between 2020 and 2024 and with

Fig. 2: Official public transport apps in European cities

Source: own on OpenStreetMap map

reviewId	userName	userImage	content	score	thumbsUpCount	reviewCreated	at	replyConte	repliedAt	appVersio	Translated_Review	app	city	country	Marketplace
ad4a6402-	Ein Google	https://pla	no se puede poner la direc	1	1	4.3.1	2020-02-01 22:22:13	Buenos día	2020-02-10	4.3.1	Cannot set destination address	AMB Mobilitat	Barcelona	Spain	Play Store
a4e38d60-	Roland B	https://pla	De nuevo no acierta con e	1	1	5.2.5	2023-04-07 21:44:45	Gracias po	2022-07-05	5.2.5	Once again, the bus time is not correct.	AMB Mobilitat	Barcelona	Spain	Play Store
b63758dd-	Mercè Ros	https://pla	jolibú!!! fantàstic!!!	5	1	5.2.4	2023-02-27 08:37:48			5.2.4	jolibú!!! fantastic!!!	AMB Mobilitat	Barcelona	Spain	Play Store
d396aa7e-	Victoria M	https://pla	hem demanat un taxi en d	5	1	5.2.4	2023-01-28 23:56:32			5.2.4	We ordered a taxi on Saturday night an	AMB Mobilitat	Barcelona	Spain	Play Store
eef1ae2d-	Xavi	https://pla	Fàcil de usar	5	4	5.1.7	2022-10-31 18:18:45			5.1.7	Easy to use	AMB Mobilitat	Barcelona	Spain	Play Store
61597b44-	Alejandro	https://pla	No se m'obre: es tanca in:	1	1	5.1.5	2022-09-10 15:57:34	Hem detec	2022-09-21	5.1.5	It won't open for me: it closes instantly	AMB Mobilitat	Barcelona	Spain	Play Store
db39bf89-	Andrea Mo	https://pla	El dia que funcioni bé l'apl	1	1	4.6.0	2022-05-19 07:28:56	A causa de	2022-05-19	4.6.0	The day the app works properly will be	AMB Mobilitat	Barcelona	Spain	Play Store
306704a4-	Marc Cast	https://pla	Molt bona aplicació	5	3	5.1.1	2022-04-29 10:36:50			5.1.1	Very good application	AMB Mobilitat	Barcelona	Spain	Play Store
741461dd-	Merce For	https://pla	M' encanta es molt util	5	3	4.6.0	2021-12-30 22:20:50			4.6.0	I love it, it's very useful.	AMB Mobilitat	Barcelona	Spain	Play Store
e11b4b35-	Lluís Villar	https://pla	Últimament no càrrega el:	1	2	4.5.1	2021-12-01 15:22:48			4.5.1	Lately it's not loading the waiting times	AMB Mobilitat	Barcelona	Spain	Play Store
ada75ac6-	Jordi Serra	https://pla	No incorporen als FCG. Co	2	3	4.5.1	2021-10-13 09:11:43			4.5.1	They don't incorporate into the FCG. As	AMB Mobilitat	Barcelona	Spain	Play Store
d3c9f446-	Cristina Ca	https://pla	Molt pràctic	5	1	4.4.0	2021-06-02 15:33:00			4.4.0	Very practical	AMB Mobilitat	Barcelona	Spain	Play Store
d3e25c55-	Isaac Barc	https://pla	No funciona. Diu que no a	1	1	4.4.0	2021-05-10 08:34:20			4.4.0	It doesn't work. It says it doesn't updat	AMB Mobilitat	Barcelona	Spain	Play Store
1e4f86a1-	Noemí Gai	https://pla	No funciona fa dies.	1	1	4.4.0	2020-11-02 14:25:27			4.4.0	It hasn't been working for days.	AMB Mobilitat	Barcelona	Spain	Play Store
95a99b95-	Gemma Pe	https://pla	Acostuma a anar bé.	5	1	4.4.0	2020-10-25 00:37:42			4.4.0	It usually goes well.	AMB Mobilitat	Barcelona	Spain	Play Store
70920568-	Marina Seg	https://pla	Està bé, l'única cosa és qu	4	7	4.4.0	2020-08-02 15:02:52			4.4.0	It's okay, the only thing is that sometim	AMB Mobilitat	Barcelona	Spain	Play Store
1a7a4c89-	Un usuari (	https://pla	¡Hola! Nunca he tenido pr	4	4	4.4.0	2020-03-26 21:06:56	Hola Virgir	2020-03-30	4.4.0	Hello! I have never had any problems w	AMB Mobilitat	Barcelona	Spain	Play Store
e3ea0d1f-	Un usuari (	https://pla	Darrerament, menys fiabl	1	1	4.3.1	2020-02-06 07:18:11	Hola, Santi	2020-02-10	4.3.1	Lately, less reliable than a fairground sh	AMB Mobilitat	Barcelona	Spain	Play Store
27bbe76c-	Un usuari (	https://pla	Pèssima, no t'informa sob	1	1	4.3.1	2020-02-03 12:27:11	Hola, Ariac	2020-02-10	4.3.1	Terrible, it doesn't inform you about th	AMB Mobilitat	Barcelona	Spain	Play Store
6146f7e6-	Un usuari (	https://pla	Fa dies que no hi ha mane	1	1	4.1.5	2020-01-16 18:59:28	Hola, Isabe	2020-01-20	4.1.5	It hasn't worked for days, it hangs befo	AMB Mobilitat	Barcelona	Spain	Play Store
e2b9bca6-	Mordred M	https://pla	ACTUALIZACIÓN 14 DE OC	1	1	5.2.14	2024-10-14 13:50:20			5.2.14	UPDATE 14 OCTOBER 2024. You can't r	AMB Mobilitat	Barcelona	Spain	Play Store
9cc144f4-!	Daniel	https://pla	Voy a escribir la reseña er	1	1	5.2.13	2024-08-27 21:15:30			5.2.13	I'm going to write the review in Spanish	AMB Mobilitat	Barcelona	Spain	Play Store
9b01b60b-	jennireth r	https://pla	Va super bien! Indica los h	5	2	5.2.8	2024-04-05 07:43:10			5.2.8	It works great! It indicates the correct I	AMB Mobilitat	Barcelona	Spain	Play Store
41bd9767-	Maria Laui	https://pla	esta aplicación es excelen	5	1	5.2.8	2024-02-07 00:50:25			5.2.8	This application is excellent, it shows yo	AMB Mobilitat	Barcelona	Spain	Play Store
56c0d3d8-	Nikola Mu	https://pla	No està perfecta, pero me	4	1	5.2.8	2024-01-19 17:37:41			5.2.8	It's not perfect, but it's better than oth	AMB Mobilitat	Barcelona	Spain	Play Store
0253fbe9-	Gonzalo Sa	https://pla	Si queréis usar la app usac	1	9	5.2.6	2023-12-13 19:26:51			5.2.6	If you want to use the app, use it, but if	AMB Mobilitat	Barcelona	Spain	Play Store

Fig. 3: Scraped review files

Source: own

at least one helpful vote ("thumbs up count") were selected to ensure the selected comments were relevant and pertained to recent app versions.

The translated files are loaded into Orange Data Mining v3.38.1 (Demšar et al., 2013), a comprehensive tool based on the Python programming language with an interactive graphical interface for performing data mining, sentiment analysis, and machine learning tasks. Recent studies have also utilized Orange to analyze Play Store App reviews (Mojica et al., 2024; Palos-Sanchez et al., 2025; Perea-Khalifi et al., 2024). The text corpus is preprocessed for analysis by removing stopwords, converting uppercase to lowercase, and eliminating accents and other non-informative characters, as shown in Fig. 4.

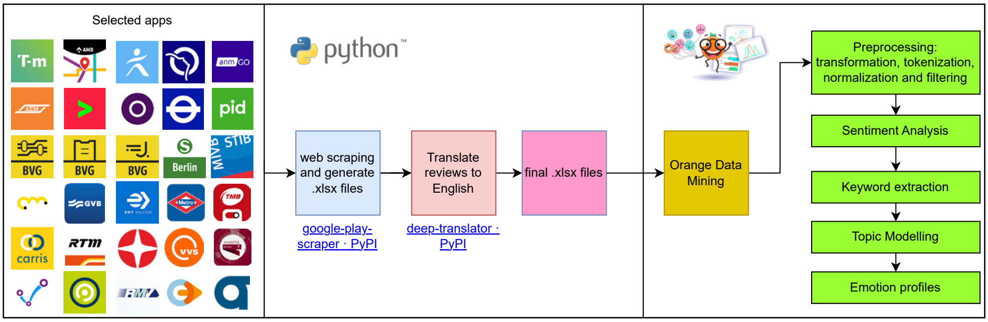

Fig. 4: Methodology of app selection and review processing

Source: own

3 Results and discussion

3.1 Results

Most of the cities analyzed show a high level of intermodal integration within their public transport applications, although there are exceptions such as Madrid, where "EMT Madrid" manages urban bus services and "Metro de Madrid Oficial" covers the metro network. Despite this division, unified travel passes allow passengers to use both modes with a single card. For example, in Lisbon, there are two different apps: "Carris" for the former concerning the urban network and "Carris Metropolitana" for the latter concerning the metropolitan area. A comparable example is Berlin. There, for the huge public transport system including buses, trams, ferries, and U-Bahn, altogether five apps exist, offered by Berliner Verkehrsbetriebe (BVG): "BVG Fahrinfo: Routenplaner", comprehensive ticketing and route planning; "BVG Tickets: Bus + Bahn Berlin", ticketing only; "BVG Jelbi: Mobilität in Berlin", with app-based payment current forms of mobility like car sharing, electric scooters, and moped, etc.; "BVG Muva: Mobilität für alle", butler service to mobilities; and "PROFILapp" for stakeholders' corporate communication. Berlin also offers a unique app for its S-Bahn services. Budapest also offers two apps: "BKK Futár", with real-time information, and "BudapestGO", for standard urban mobility, which allows both ticket purchase and route planning. "MOL Bubi" is used to manage shared mobility services focused on e-bikes.

At the same time, Vienna constitutes an absolutely perfect example of very high integration because this is a service integrating classic public transport with alternative mobility offers such as car sharing, shared bikes, taxis, etc., on one single platform. The bicycles are considered in Stuttgart as complementary to buses, subways, and trams. "VVS Radroutenplaner" is an application through which planning for a bike route is integrated with other means of transport, respecting local rules for carrying bikes can be done. "VVS Smarte Haltestelle" and "VVS Mobil", main public transportation apps via QR codes, deliver real-time stop information. Similar functionality is provided by Munich's "MVV – Radroutenplaner".

Besides the primary public transport app "STIB-MIVB", Brussels' "Floya" brings all means of transport available into one platform. While Vienna's "WienMobil Hüpfer Liesing" (Apple) and "WienMobil Hüpfer Donaustadt" (Android) enable wheelchair users to book accessible electric minibuses, Marseille's "RTM Guidage" supports visually impaired travelers in finding their way around the metro system. All such applications are being provided by public operators or official authorities and cover particular metropolitan areas. An exception is Warsaw, where its public transport system operator Warszawski Transport Publiczny does not have any specific application. Instead, schedules and ticket purchases are handled through general multi-city platforms such as "Jakdojade", which is part of this study.

The trend toward integrating all modes of transportation into a single app to improve the user experience with digital ticketing and real-time information is evident in European cities. Another noteworthy development is the incorporation of alternative mobility services, particularly e-bikes and carsharing, offering citizens a wider range of options for getting around the city.

Evolution of the number and variation of reviews between 2020 and 2024

Tab. 4 displays the number of comments for each app by year within the sample period. Over these four years, the total number of comments has increased annually.

Sentiment analysis

Tab. 5 presents the sentiment (negative, neutral, positive) of the set of reviews for each app according to the VADER sentiment analysis algorithm. Of the 64,274 comments

Tab. 4: Evolution and percentage variation in the number of comments in the period 2020–2024 – Part 1

App	2020	2021	Variation (%)	2022	Variation (%)	2023	Variation (%)	2024	Variation (%)
AMB Mobilitat (Picmi)	55	58	5.45	108	86.21	57	−47.22	41	−28.07
ANM GO	0	0	0.00	0	0.00	9	0.00	74	722.22
ATM Milano Official App	136	160	17.65	172	7.50	321	86.63	745	132.09
BVG Fahrinfo ÖPNV Berlin	506	498	−1.58	492	−1.20	568	15.45	3,317	483.98
BVG Jelbi Mobilität in Berlin	140	97	−30.71	148	52.58	239	61.49	108	−54.81
BVG Tickets Bus + Bahn Berlin	302	464	53.64	606	30.60	417	−31.19	836	100.48
Bonjour RATP	831	1,468	76.65	1,257	−14.37	1,131	−10.02	1,208	6.81
BudapestGO	196	166	−15.31	1,354	715.66	603	−55.47	697	15.59
Carris	45	35	−22.22	182	420.00	81	−55.49	64	−20.99
Carris Metropolitana	0	0	0.00	0	0.00	0	0.00	60	0.00
EMT Madrid	139	127	−8.63	46	−63.78	56	21.74	146	160.71
GVB reis app	0	168	0.00	159	−5.36	139	−12.58	110	−20.86
Jakdojade Timetables	649	970	49.46	1,131	16.60	2,538	124.40	3,069	20.92
MVV-App	179	271	51.40	235	−13.28	585	148.94	226	−61.37
Metro de Madrid Oficial	48	57	18.75	59	3.51	50	−15.25	63	26.00
OASA Telematics	197	125	−36.55	286	128.80	191	−33.22	545	185.34
PID Lítačka	330	298	−9.70	283	−5.03	442	56.18	354	−19.91
RMVgo	0	0	0.00	451	0.00	2,722	503.55	1,086	−60.10
RTM	153	95	−37.91	91	−4.21	99	8.79	63	−36.36
Roma Mobilità	88	46	−47.73	14	−69.57	28	100.00	10	−64.29

Tab. 4: Evolution and percentage variation in the number of comments in the period 2020–2024 – Part 2

App	2020	2021	Variation (%)	2022	Variation (%)	2023	Variation (%)	2024	Variation (%)
S-Bahn Berlin	21	8	−61.90	51	537.50	33	−35.29	106	221.21
STIB-MIVB	136	115	−15.44	93	−19.13	189	103.23	268	41.80
T-mobilitat	0	490	0.00	1,657	238.16	1,919	15.81	803	−58.16
TMB App (Metro Bus Barcelona)	150	206	37.33	412	100.00	426	3.40	705	65.49
TfL Go Live Tube, Bus & Rail	45	215	377.78	403	87.44	346	−14.14	381	10.12
VVS Mobil	232	203	−12.50	182	−10.34	226	24.18	270	19.47
WienMobil	1,374	440	−67.98	1,060	140.91	413	−61.04	426	3.15
hvv Hamburg Bus & Bahn	323	2,663	724.46	1,237	−53.55	519	−58.04	436	−15.99
mobil.nrw	0	107	0.00	122	14.02	106	−13.11	93	−12.26
Île de France Mobilités	479	1,150	140.08	761	−33.83	1,200	57.69	1,805	50.42
Total	6,754	10,700	58.42	13,052	21.98	15,653	19.93	18,115	15.73

Source: own

analyzed, 38.77% have a negative connotation (compound values between −1 and −0.25), 28.77% are neutral (compound between −0.25 and +0.25), and 32.46% are positive (compound between +0.25 and +1).

VADER (valence aware dictionary and sentiment reasoner) is a lexicon-based sentiment analysis tool designed for short, informal texts such as user reviews. It assigns sentiment scores to words and phrases using a lexicon and combines these scores with contextual rules to determine the overall sentiment of a text. The compound score is VADER's main metric, representing the overall sentiment as a normalized value ranging from −1 (most negative) to +1 (most positive) (Hutto & Gilbert, 2014). In this research, reviews with compound scores between −1 and −0.25 are classified as negative, those between −0.25 and +0.25 as neutral, and those between +0.25 and +1 as positive.

The most positive sentiment was found for "S-Bahn Berlin" (62.1% of its 219 reviews), "TfL Go Live Tube, Bus & Rail" in London (44.89% positive out of 1,390 reviews), "Bonjour RATP" in Paris (42.51% positive out of 5,895 reviews), and "Jakdojade Timetables" (41.12% positive out of 8,357 reviews), according to the detailed analysis by app. In contrast, the apps "Roma Mobilità" (52.69%, albeit a small sample), "VVS Mobil" in Stuttgart (48.25% negative reviews), "T-mobilitat" in Barcelona (47.73% negative), "MVV-App" in Munich (47.26%) and "TMB app" in Barcelona (46.66% negative) have the highest percentage of negative comments. T-mobilitat and Roma Mobilità also exhibit the greatest disparity, with the number of negative comments tripling the number of positive ones.

The number and percentage of reviews where the user-assigned "score" (1–5) matches or does not match the sentiment identified by the VADER algorithm are compared in Fig. 5. The distribution reveals that 49.6% of reviews with a score of 1 and 43.5% with a score of 2 are classified as negative by VADER. For scores considered positive, the correspondence between user ratings and positive sentiment detected by sentiment analysis is even higher: 55.4% for score 4 and 74.3% for score 5.

Sentiment word cloud and bigrams

Bigram word clouds generated from both positive and negative reviews are shown in Fig. 6, highlighting the most frequent and relevant topics. Each bigram's size in this visualization indicates its relative frequency in the reviews, while the colors are random and have no connotation. Bigrams like "real time", "credit card", "google maps", "ticket app", "navigo pass" and "buying tickets" are prominent in the positive review cloud. This suggests that users especially value the integration of digital payment services, ticket purchasing, and navigation apps

Tab. 5: Descriptive statistics of sentiment analysis

App	Negative	Neutral	Positive	Negative (%)	Neutral (%)	Positive (%)	Total reviews
TfL Go Live Tube, Bus & Rail	408	358	624	29.35	25.76	**44.89**	1,390
ANM GO	38	30	15	45.78	36.14	18.07	83
BVG Jelbi Mobilität in Berlin	271	175	286	37.02	23.91	23.91	732
Carris Metropolitana	18	19	23	30	31.67	38.33	60
STIB-MIVB	275	261	265	34.33	32.58	33.08	801
hvv Hamburg Bus & Bahn	2,370	1,267	1,541	45.77	24.47	29.76	5,178
ATM Milano Official App	638	458	438	41.59	29.86	28.55	1,534
BudapestGO	1,074	884	1,058	35.61	29.31	35.08	3,016
EMT Madrid	182	160	172	35.41	31.13	33.46	514
OASA Telematics	486	544	314	36.16	40.48	23.36	1,344
Île de France Mobilités	2,168	1,578	1,649	40.19	29.25	30.57	5,395
Bonjour RATP	1,810	1,579	2,506	30.7	26.79	**42.51**	5,895
AMB Mobilitat (Picmi)	120	91	108	37.62	28.53	33.86	319
BVG Fahrinfo ÖPNV Berlin	2,274	1,338	1,769	42.26	24.87	32.87	5,381
S-Bahn Berlin	42	41	136	19.18	18.72	**62.10**	219
RTM	200	146	155	39.92	29.14	30.94	501
VVS Mobil	537	313	263	**48.25**	28.12	23.63	1,113
Metro de Madrid Oficial	80	94	103	28.88	33.94	37.18	277
RMVgo	1,728	1,107	1,424	40.57	25.99	33.44	4,259
TMB App (Metro Bus Barcelona)	886	554	459	**46.66**	29.17	24.17	1,899
Roma Mobilità	98	58	30	**52.69**	31.18	16.13	186
PID Lítačka	601	512	594	35.21	29.99	34.8	1,707
Jakdojade Timetables	2,278	2,643	3,436	27.26	31.63	**41.12**	8,357
GVB reis app	226	179	171	39.24	31.08	29.69	576
mobil.nrw	161	104	163	37.62	24.3	38.08	428
WienMobil	1,581	1,038	1,094	42.58	27.96	29.46	3,713
BVG Tickets Bus + Bahn Berlin	1,156	723	746	44.04	27.54	28.42	2,625
MVV-App	707	388	401	**47.26**	25.94	26.8	1,496
Carris	182	145	80	44.72	35.63	19.66	407
T-mobilitat	2,324	1,707	838	**47.73**	35.06	17.21	4,869
Total	24,919	18,494	20,861	**38.77**	**28.77**	**32.46**	**64,274**

Note: The highest percentages of positive and negative reviews and the totals appear in bold.

Source: own

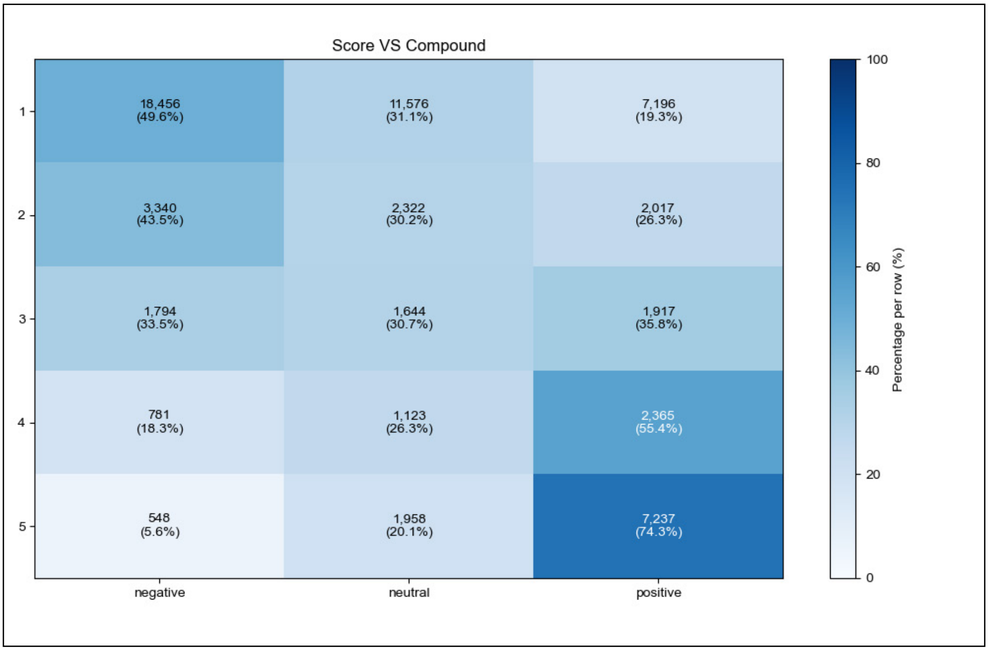

Fig. 5: **Relationship between score and compound**

Source: own

like Google Maps for trip planning and tracking, as well as the availability of real-time schedule information in bigrams like "departure time" and "app time". The importance of user experience is evident in high-frequency bigrams such as "update app", "user friendly", "app easy", "qr code", "previous version", "dark mode" and "apple watch". These reflect user opinions on various app functionalities, interface, and overall experience.

The most common bigram in the negative review bigram cloud is "error message", followed by similar bigrams such as "error occurred" and "app crashes", which refer to technical issues that caused user dissatisfaction, as indicated by terms such as "wasted time". Similar to the positive bigram cloud, bigrams such as "ticket app", "departure times", "Navigo pass", "ticket purchase", "real-time", "Google Maps", "credit card" and "payment method", among others, have negative connotations that may imply problems with ticket purchases, credit card payments, or inaccurate information about delays. Another important bigram is "customer service", demonstrating that many users are dissatisfied with customer support.

Spearman correlations

Spearman correlations between sentiment analysis results, user-assigned scores, comment length, and the "thumbs up" from other users who found the review useful are shown in Tab. 6. Both the character count and word count have a negative correlation with the VADER compound score (−0.137 and −0.133) and a moderately positive correlation with negative sentiment (0.197 and 0.185, respectively), indicating that longer comments usually express more negativity. The negative correlations between word and character count and the user-assigned score (−0.167 and −0.165) further support this, showing that longer comments are typically linked to lower ratings, perhaps because of unsatisfied users going into greater detail in their criticisms.

There is also a positive correlation between comment length (in both words and characters) and the number of "thumbs up" received

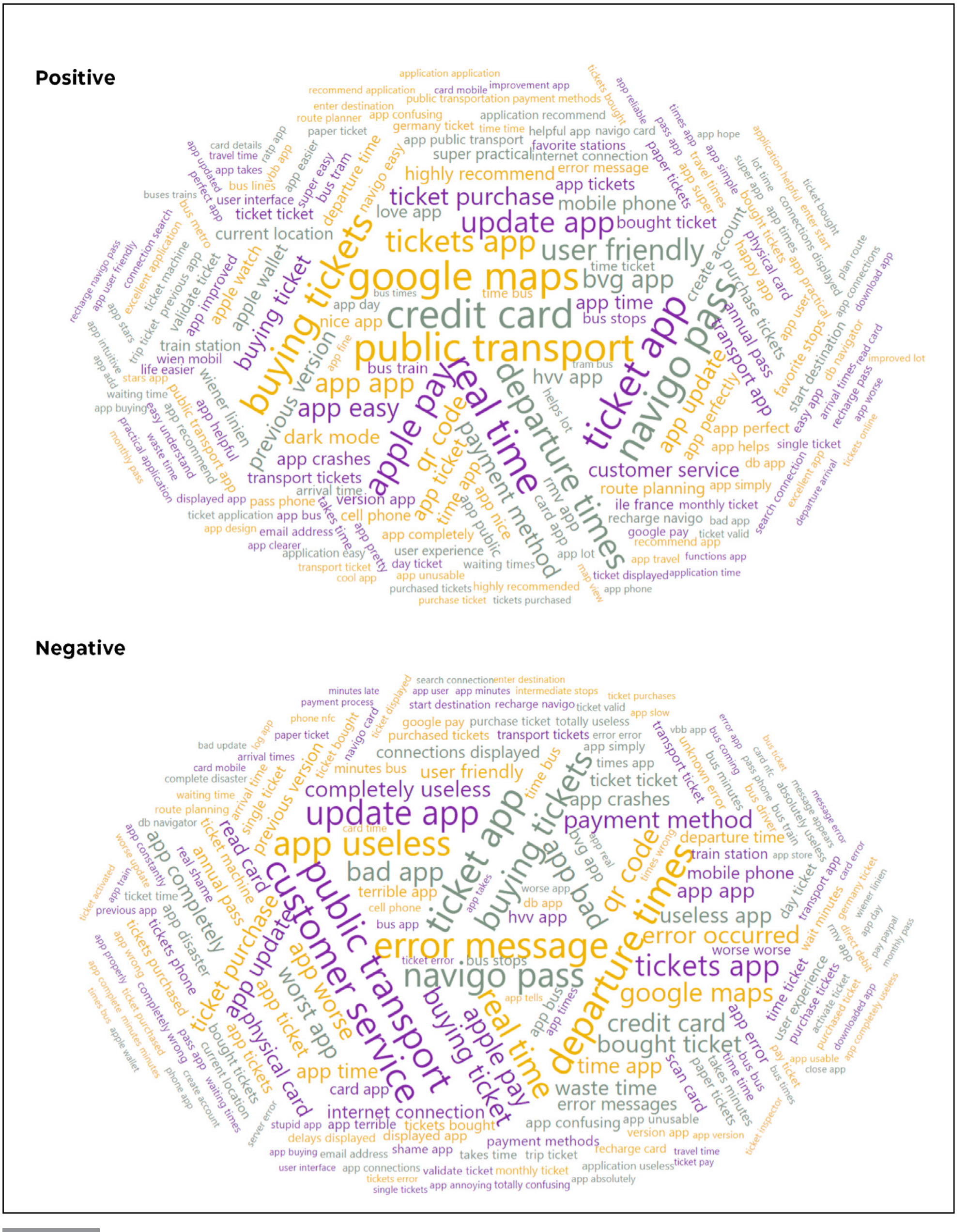

Fig. 6: **Positive and negative reviews bigrams clouds**

Source: own

Tab. 6: Spearman correlations

Feature 1	Feature 2	Correlation	Uncorrected p	FDR
Character count	Negative	**0.197**	0	0
Word count	Negative	**0.185**	0	0
Word count	Score	**−0.167**	0	0
Character count	Score	**−0.165**	0	0
Word count	ThumbsUpCount	**0.159**	0	0
Character count	ThumbsUpCount	**0.155**	0	0
Character count	Compound	**−0.137**	1.16841e-266	2.62893e-266
Word count	Compound	**−0.133**	7.8938e-253	1.69153e-252
Compound	ThumbsUpCount	**0.016**	5.33981e-05	6.67476e-05

Note: The correlation values mentioned in the text are shown in bold.

Source: own

(0.159 and 0.155). This pattern suggests that longer comments may be perceived as more useful by other users, regardless of their tone, as the sentiment of the review has a minimal impact on perceived usefulness, as shown by the low correlation (0.016) between the compound score and the "thumbs up" count.

Emotion analysis

A relational semantic analysis was carried out, focusing on the reviews' emotional content in order to understand user emotions. Based on Plutchik's classification (Plutchik, 1980), the NRC Emotion Lexicon was used to analyze expressed emotions. These were divided into eight groups: four positive ("trust", "anticipation", "joy" and "surprise") and four negative ("fear", "anger", "sadness" and "disgust").

Joy was the most common emotion overall, accounting for 38.74% of all comments examined and being the main emotion in 27 apps as shown in Tab. 7. Sadness followed with 30.89%, prevailing in three apps (EMT Madrid, T-mobilitat, and AMB Mobilitat), and trust accounted for 18.57%. The frequency of the other emotions was considerably lower: anger (0.53%), disgust (1.65%), surprise (6.33%), fear (2.11%), and anticipation (1.19%).

When looking at the emotional distribution by application, the highest percentage of positive emotions is found in Jakdojade Timetables (74.33%), S-Bahn Berlin (73.97%), TfL Go Live Tube, Bus & Rail (71.87%), and Bonjour RATP (70.42%). On the other hand, the most negative reviews are found for hvv Hamburg Bus & Bahn (41.10%), BVG Tickets Bus + Bahn Berlin (41.14%), MVV-App (41.38%), and ANM GO (45.78%).

In terms of particular emotions, the highest levels of joy were found in Carris Metropolitana (43.33%), PID Lítačka (43.70%), Île de France Mobilités (44.91%), and ANM GO (42.17% of all app comments). ANM GO (38.55%), BVG Tickets Bus + Bahn Berlin (37.94%), and MVV-App (37.50%) had the highest rates of sadness, which may be a sign of discontent or annoyance with the services received.

Topic modelling

Large collections of documents may contain hidden topics that can be found using topic modelling. Latent topics of interest to application users were discovered using the generative LDA model. Five was determined to be the optimal *k* value for topics, as it offered the best balance, maximizing topic coherence (0.491) and generating low log perplexity (17.93), as shown in Fig. 7.

The five identified topics are presented in Tab. 8 and in Fig. 8.

Topic 1: efficiency and effectiveness of transport services. This topic has the highest marginal probability (23.626%) and is associated with comments on the efficiency and effectiveness of public transport services, including references to timetables, punctuality, and the usefulness of available information.

Tab. 7: Emotion frequency – Part 1

App	Dom. emot.	KPI/emotion	Ang.	Antic.	Disg.	Fear	Joy	Sad.	Surp.	Trust	Total	P. E.	N. E.
AMB Mobilitat	Sad.	Reviews	2	10	4	3	97	118	18	67	319		
		Freq. (%)	0.63	3.13	1.25	0.94	30.41	36.99	5.64	21.00		60.19	39.81
ANM GO	Joy	Reviews	0	0	4	2	35	32	2	8	83		
		Freq. (%)	0.00	0.00	4.82	2.41	**42.17**	**38.55**	2.41	9.64		54.22	**45.78**
ATM Milano Official App	Joy	Reviews	8	23	31	32	616	506	71	247	1,534		
		Freq. (%)	0.52	1.50	2.02	2.09	40.16	32.99	4.63	16.10		62.39	37.61
Bonjour RATP	Joy	Reviews	23	92	110	119	2,425	1,492	429	1,205	5,895		
		Freq. (%)	0.39	1.56	1.87	2.02	41.14	25.31	7.28	20.44		**70.42**	29.58
BudapestGO	Joy	Reviews	13	48	50	71	1,149	1,004	208	473	3,016		
		Freq. (%)	0.43	1.59	1.66	2.35	38.10	33.29	6.90	15.68		62.27	37.73
BVG Fahrinfo ÖPNV Berlin	Joy	Reviews	21	47	92	108	2,149	1,980	284	700	5,381		
		Freq. (%)	0.39	0.87	1.71	2.01	39.94	36.80	5.28	13.01		59.10	40.90
BVG Jelbi Mobilität	Joy	Reviews	4	2	19	18	293	234	38	124	732		
		Freq. (%)	0.55	0.27	2.60	2.46	40.03	31.97	5.19	16.94		62.43	37.57
BVG Tickets Berlin	Joy	Reviews	16	25	43	25	1,090	996	153	277	2,625		
		Freq. (%)	0.61	0.95	1.64	0.95	41.52	**37.94**	5.83	10.55		58.86	**41.14**
Carris	Joy	Reviews	2	11	4	11	125	125	20	109	407		
		Freq. (%)	0.49	2.70	0.98	2.70	30.71	30.71	4.91	26.78		65.11	34.89
Carris Metropolitana	Joy	Reviews	0	0	1	4	26	17	5	7	60		
		Freq. (%)	0.00	0.00	1.67	6.67	**43.33**	28.33	8.33	11.67		63.33	36.67
EMT Madrid	Sad.	Reviews	3	24	5	7	159	161	18	137	514		
		Freq. (%)	0.58	4.67	0.97	1.36	30.93	31.32	3.50	26.65		65.76	34.24

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Tab. 7: Emotion frequency – Part 2

App	Dom. emot.	KPI/emotion	Ang.	Antic.	Disg.	Fear	Joy	Sad.	Surp.	Trust	Total	P. E.	N. E.
GVB reis app	Joy	Reviews	5	5	11	8	217	203	32	95	576		
		Freq. (%)	0.87	0.87	1.91	1.39	37.67	35.24	5.56	16.49		60.59	39.41
Hvv Hamburg	Joy	Reviews	26	49	112	84	2,054	1,906	247	700	5,178		
		Freq. (%)	0.50	0.95	2.16	1.62	39.67	36.81	4.77	13.52		58.90	**41.10**
Île de France Mobilités	Joy	Reviews	18	91	120	69	2423	1613	324	737	5395		
		Freq. (%)	0.33	1.69	2.22	1.28	**44.91**	29.90	6.01	13.66		66.27	33.73
Jakdojade Timetables	Joy	Reviews	64	117	72	306	2,995	1,703	717	2,383	8,357		
		Freq. (%)	0.77	1.40	0.86	3.66	35.84	20.38	8.58	28.52		**74.33**	25.67
Metro de Madrid	Joy	Reviews	2	4	3	8	104	75	16	65	277		
		Freq. (%)	0.72	1.44	1.08	2.89	37.55	27.08	5.78	23.47		68.23	31.77
mobil.nrw	Joy	Reviews	1	1	7	3	175	156	22	63	428		
		Freq. (%)	0.23	0.23	1.64	0.70	40.89	36.45	5.14	14.72		60.98	39.02
MVV-App	Joy	Reviews	7	12	27	24	618	561	77	170	1,496		
		Freq. (%)	0.47	0.80	1.80	1.60	41.31	**37.50**	5.15	11.36		58.62	**41.38**
OASA Telematics	Joy	Reviews	22	31	22	43	443	352	109	322	1,344		
		Freq. (%)	1.64	2.31	1.64	3.20	32.96	26.19	8.11	23.96		67.34	32.66
PID Lítačka	Joy	Reviews	7	18	25	42	746	576	104	189	1,707		
		Freq. (%)	0.41	1.05	1.46	2.46	**43.70**	33.74	6.09	11.07		61.92	38.08
RMVgo	Joy	Reviews	16	24	71	67	1,729	1,406	228	718	4,259		
		Freq. (%)	0.38	0.56	1.67	1.57	40.60	33.01	5.35	16.86		63.37	36.63
Roma Mobilità	Joy	Reviews	0	3	1	5	64	57	15	41	186		
		Freq. (%)	0.00	1.61	0.54	2.69	34.41	30.65	8.06	22.04		66.13	33.87

Tab. 7: Emotion frequency – Part 3

App	Dom. emot.	KPI/emotion	Ang.	Antic.	Disg.	Fear	Joy	Sad.	Surp.	Trust	Total	P. E.	N. E.
RTM	Joy	Reviews	2	10	5	19	197	158	25	85	501		
		Freq. (%)	0.40	2.00	1.00	3.79	39.32	31.54	4.99	16.97		63.27	36.73
S-Bahn Berlin	Joy	Reviews	2	1	2	4	84	49	16	61	219		
		Freq. (%)	0.91	0.46	0.91	1.83	38.36	22.37	7.31	27.85		**73.97**	26.03
STIB-MIVB	Joy	Reviews	2	11	12	20	331	219	61	145	801		
		Freq. (%)	0.25	1.37	1.50	2.50	41.32	27.34	7.62	18.10		68.41	31.59
TfL Go app (London)	Joy	Reviews	2	7	18	38	552	333	109	331	1,390		
		Freq. (%)	0.14	0.50	1.29	2.73	39.71	23.96	7.84	23.81		**71.87**	28.13
TMB App (Barcelona)	Joy	Reviews	12	21	19	33	708	668	83	355	1,899		
		Freq. (%)	0.63	1.11	1.00	1.74	37.28	35.18	4.37	18.69		61.45	38.55
T-mobilitat	Sad.	Reviews	19	48	49	99	1,408	1,486	303	1,457	4,869		
		Freq. (%)	0.39	0.99	1.01	2.03	28.92	30.52	6.22	29.92		66.05	33.95
VVS Mobil	Joy	Reviews	8	11	22	19	437	391	70	155	1,113		
		Freq. (%)	0.72	0.99	1.98	1.71	39.26	35.13	6.29	13.93		60.47	39.53
WienMobil	Joy	Reviews	32	21	98	64	1,451	1,278	262	507	3,713		
		Freq. (%)	0.86	0.57	2.64	1.72	39.08	34.42	7.06	13.65		60.36	39.64
Total	Joy	Reviews	339	767	1,059	1,355	24,900	19,855	4,066	11,933	64,274		
		Freq. (%)	**0.53**	**1.19**	**1.65**	**2.11**	**38.74**	**30.89**	**6.33**	**18.57**		64.83	35.17

Note: Highlighted values are mentioned in-text; dom. emot. – dominant emotion; freq. – frequency; ang. – anger; antic. – anticipation; disg. – disgust; sad. – sadness; surp. – surprise; P. E. – positive emotions; N. E. – negative emotions.

Source: own

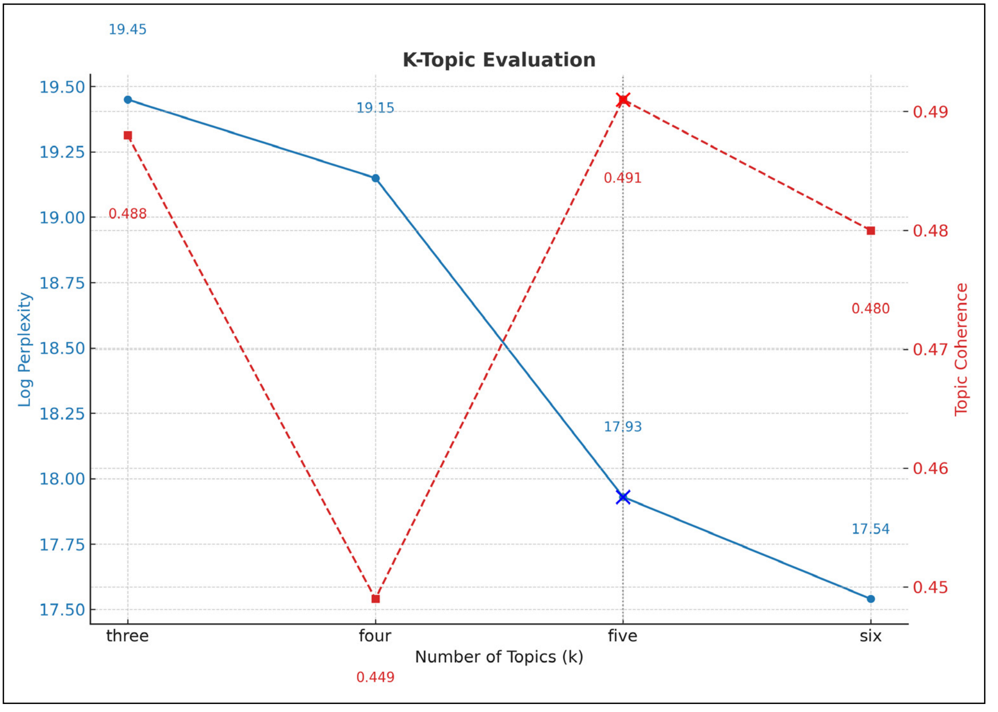

Fig. 7: Topic modelling evaluation

Source: own

Topic 3: payment and top-up for transport passes. This topic, with the next highest marginal probability (23.31%), focuses on payment issues and processes in apps. Keywords like "impossible", "error", "pay", "payment" and "purchase" suggest that users are having trouble purchasing tickets, possibly due to interface issues or technical errors.

Topic 5: ease of use, connectivity, usability, and route search. This topic focuses on user experience, particularly app functionality and connectivity. Keywords indicate issues with route search and map display, connection problems, and login errors. The use of words like "update" implies that app updates might not fix the issues or even cause new ones: This emphasizes the importance of the app being easy to use.

Topic 2: data accuracy and updates. With keywords like "bad", "embarrassing", "user", "version" and "data", this theme reveals dissatisfaction with the latest versions of apps and suggests concerns about the reliability of real-time schedule tracking.

Topic 4: app stability, interface, and features. As keywords like "app", "bugs", and "account" suggest, this topic has the lowest marginal probability and also relates to user experience, but from a wider viewpoint, addressing the interface and core features. Users want apps to be more stable and reliable.

3.2 Discussion

Citizen opinion is confirmed as a fundamental element for the design and improvement of cities, proving to be a valuable source of information for optimizing urban services. Citizen interest in urban transportation apps has grown over time, as evidenced by the increase in reviews in recent years (Tab. 3). According to Haklay et al. (2018), this phenomenon is consistent with the transition toward more digital and participatory societies, where citizen

Tab. 8: Identified topics and reviews examples

Topic	Marginal topic probability (%)	Keywords	Reviews examples
Topic 1: efficiency and effectiveness of transport services	**23.626**	Bus, times, useless, time, minutes, message, timetables, practical, buses, routes	"*The N9 at 9:45 pm on Friday, June 23, 2023, after waiting for him, he ran past me. I have evidence and I will take this to the police. It is not the first time that public transport acts in this miserable way just because of the rush to get to the route sooner. I warned him before he turned around and the man jumped me.*"
Topic 2: data accuracy and updates	17.573	Transport, app, bad, version, user, public, shame, data, people, change	"*I used to love this app because it had all the real-time data in just a few clicks. Now since the UI update, everything became more difficult and the local depatures are harder to find. I really hope that they bring (some parts of) the old design back.*"
Topic 3: payment and top-up for transport passes	**23.301**	Card, ticket, tickets, impossible, phone, pay, error, purchase, read, payment	"*Impossible to add a payment method! Some business you're running, when people can't even pay you! The irony is German! ?? The app is laggy and not responsive. When I try to add SEPA payment it keeps "redirecting" for an unknown period of time. When I try to add a credit card, it freezes right after I switch to my bank app to confirm the 0.00 Eur payment.*"
Topic 4: app stability, interface, and features	15.322	Application, iphone, pass, navigo, account, apple, train, service, day, crashes	"*The new updated app is unusable, you can no longer move the favorites in the order you want, the old ones that it saved have tripled. The home page is too chaotic, with too much "information" that is not useful in that part. It crashes all the time.... the old app is better. If I could I wouldn't even give it a star...disappointed.*"
Topic 5: ease of use, connectivity, usability, and route search	19.603	Update, connection, log, easy, connections, enter, route, search, app, map	"*I changed my rating to positive because since the last update, we can, as before, search by bus numbers and bookmark schedules. Thank you for taking into account users' comments.*"

Note: The marginal probability values of the two most frequent topics are shown in bold.

Source: own

science and citizen participation actively improve the urban environment.

Regarding *RQ1*, sentiment analysis reveals a significant balance in ratings (Tab. 4), with favorable examples in European cities such as Berlin, Paris and London, where happiness also dominates the analysis of emotions (Tab. 7). In these applications, certain user groups have positively rated some features that go beyond the basic ones. London's TfL Go Live Tube, Bus & Rail, in addition to being an intermodal app, integrates real-time information on station congestion so users can avoid the busiest stations. It also provides relevant information for people with reduced mobility on step-free access, platform width, step height, and available boarding methods. In this sense, it is aligned with one of Andersson et al.'s (2018) conclusions mentioned in the literature review, which indicates that transport apps should adapt to individual needs and preferences by providing contextualized and relevant data, backed by statistics. Other apps that facilitate the use of public transport for people with disabilities are also part of this research, but were developed as complementary applications external to the main app rather than fully integrated into it: "RTM Guidage" to guide blind people using the Marseille metro, and "WienMobil Hüpfer Donaustadt" to enable wheelchair users to request a ride on an accessible electric minibus in Vienna.

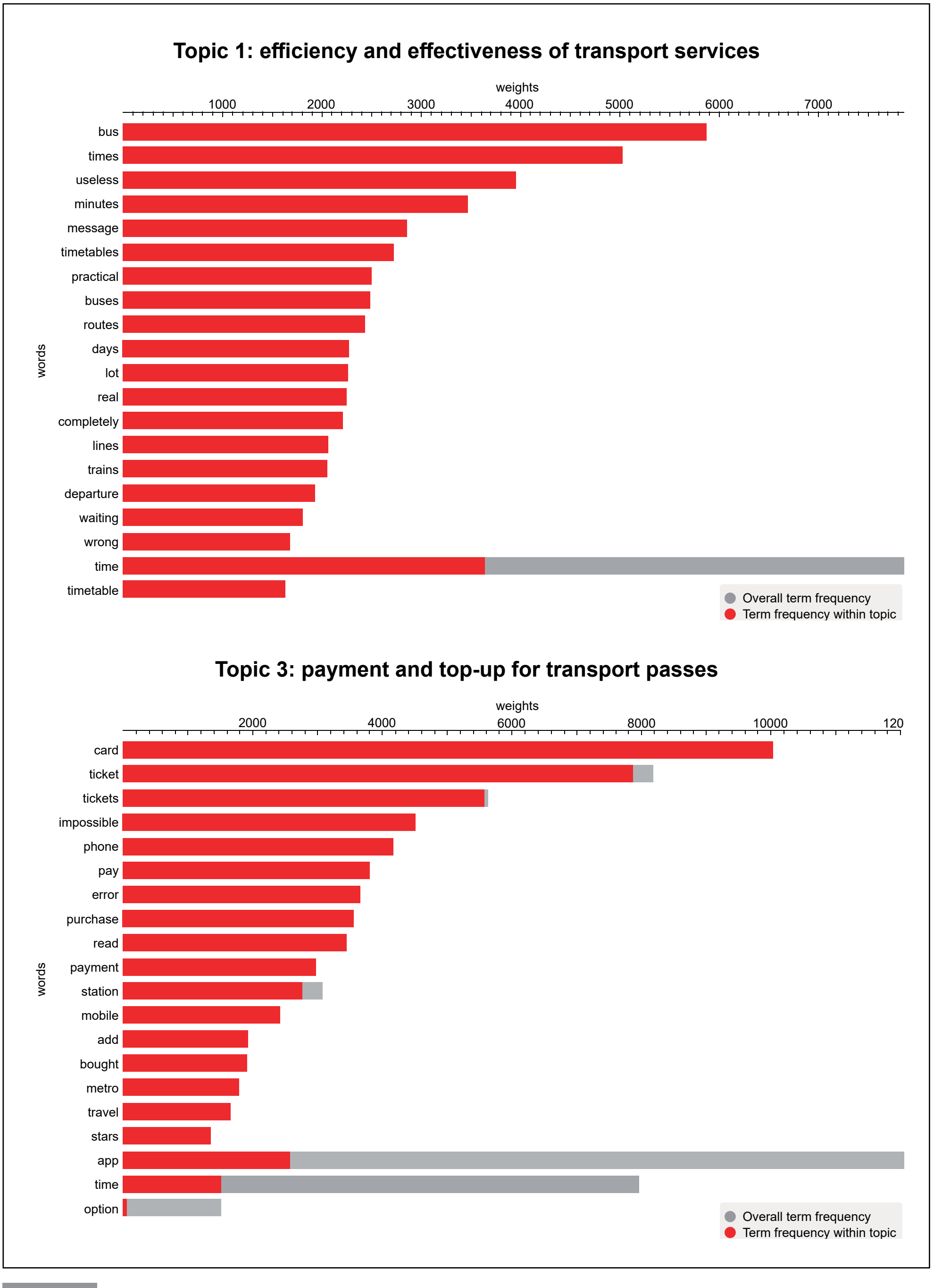

Fig. 8 **Topics 1 and 3 keywords: examples of the two LDA topics with highest marginal probability**

Source: own

Paris's Bonjour RATP app integrates, within the same app, the possibility of renting shared bicycles and scooters, as well as booking a private vehicle with a driver. This fact exemplifies the trend toward developing intermodal applications that integrate different transport modes (Altay & Okumuş, 2022; Romero et al., 2022), including alternatives such as bicycle and car sharing (Solecka & Kiciński, 2022) in line with other recent research suggesting that these solutions can replace inefficient regional fixed-route lines, improving accessibility and urban sustainability (Džupka et al., 2025). Other examples analyzed included "BVG Jelbi: Mobilität in Berlin" an external app to the main "BVG Fahrinfo: Routenplaner" and "MOL Bubi" in Budapest, an additional app to the main "BudapestGO." Other apps, such as "WienMobil" in Vienna and "VVS Radroutenplaner" in Stuttgart, have integrated bike-sharing and carsharing booking functions into the same app as buses and conventional public transport.

Emphasis is placed on the accessibility of applications for people with disabilities, the incorporation of gamification elements (Andersson et al., 2018; Casquero et al., 2022), and the promotion of sustainability, topics that reflect the main concerns of users, supported by theoretical models of technology adoption (Back et al., 2025; Dastjerdi et al., 2019; González-Sánchez et al., 2024). Addressing *RQ3*, these theoretical models are aligned with the most frequent bigrams (Fig. 6) and topic modeling (Tab. 7 and Fig. 8), coinciding with the most relevant topics for the users of the analyzed applications with the efficiency of the service studied by Dastjerdi et al. (2019), based on Lindenberg's goal-framing theory, the conclusion was that in addition to functional aspects, hedonic motives also contribute to usage intention, especially among occasional users, such as being rewarded with bonus points for eco-friendly behavior. However, functional motives such as punctuality and trip efficiency (related to Topic 1 of this research, "efficiency and effectiveness of transport services"), personalized information, obtaining alternative routes during service disruptions (related to Topic 2, "data accuracy and updates"), and payment and ticket top-up aspects, coinciding with Topic 3, "payment and top-up for transport passes", are the most relevant for frequent users. Payment through the app or with NFC systems within the app has the advantage of eliminating cash payments, which can cause delays in bus departures and create complications for drivers and passengers. However, for user adoption, the payment system must be simple and use secure authentication systems that mitigate risk aversion (Liébana-Cabanillas et al., 2019). Concerns about privacy and reliability are the greatest reluctance among users to use this payment method, while convenience and time savings are the greatest incentives (Fontes et al., 2017). The importance of app usability is in line with different research works (González-Sánchez et al., 2024; Haldar & Goel, 2021), based on the technology acceptance model (TAM). In relation to this aspect, in Topic 4, "app stability, interface, and features" and Topic 5, "ease of use, connectivity, usability, and route search", users value that the app is easy and intuitive, with a simple interface, that it does not present connection problems, login errors or failures in route search or display on the map, and that updates improve the stability and reliability of the app.

This alignment between the theoretical models and the analysis highlights the necessity of implementing the improvements suggested by users in apps. Relating this to *RQ4* reflects an approach that prioritizes user feedback and aims to enhance their overall satisfaction. The usefulness of natural language processing (NLP) techniques in analyzing large volumes of user-generated data is highlighted: This represents a significant contribution to the intelligent management of urban mobility systems and a research gap that has not been widely explored in studies carried out to date regarding the adoption of urban public transport app technology, although there are works that use similar methodologies applied to the transport service itself (Liu et al., 2019; Osorio-Arjona et al., 2021; Savastano et al., 2023; Zajac et al., 2022). The correspondence observed between sentiment analysis and user ratings (Fig. 5) answers *RQ2* and indicates that sentiment analysis using the VADER model tends to be more consistent with user opinions when these are clearly positive or negative. Furthermore, correlation analysis shows that longer comments tend to contain a higher degree of negativity and receive more helpfulness votes from other users, suggesting that longer comments may be perceived as more helpful.

Conclusions

The rising discussion around the development of smart cities has increasingly put citizen science at the forefront of research as an information source to enhance urban mobility applications. Citizen reviews act as an important information channel for planners and developers who want to optimize urban mobility applications. Many users note that the perceived value of an urban mobility app goes far beyond its core function of trip planning. Features that help connect different modes, make them available for disabled people, and show environmental consciousness seem to increase the perceived usefulness of such systems. Since these features are important in future policy directions in urban transport, public institutions and private developers may be keen on features that combine accessibility, intermodal integration, user experience, environmental commitment, sustainability, and overall usability.

A key focus of current research is the study of analytical methods that can identify user feedback. Applying natural language processing (NLP) to user reviews offers a way to investigate the sentiment and emotional aspects of app adoption. Thus, computational techniques are still limited because, while fast developing, interpretations performed automatically may very easily be thrown off by irony, sarcasm, or linguistic variability. It, therefore, places importance on such analyses being meticulously located within specific cultural and infrastructural contexts. This research thereby insists that its findings to be read as a technological moment from major European cities that continuously needs revalidation as the mobility ecosystems alter.

From a design perspective, they should be real multimodal applications: those that combine buses, subways, bicycles and scooters plus carsharing services within an easy interface. Apart from removing hindrances for the disabled, inclusive design principles must be adopted. Accessibility should be considered a primary aspect of the mobility experience rather than an added feature. The technical basis of such platforms has to ensure security as well as reliability particularly in terms of mobile payments and ticket recharging systems. Travel tickets have to be visible even offline and be able to be bought and recharged through the app or by NFC.

Customization options and clear info organization strongly affect user satisfaction. Users feel that the app is responsive to their needs when they have options on how data appearance setup controls relate to them. Engagement can be fostered by making very minor design choices, such as gamified tasks rewarding sustainable travel, but updates should be implemented very slowly because most of the time they create confusion and reduce confidence in the system’s stability.

Tab. 9: Recommendations and future research

Domain	Recommendations	Future research
Policy	Promote inclusive and multimodal urban mobility policies that integrate citizen feedback based on apps	Investigate how local regulations and public-private partnerships facilitate interoperability between public, shared, and on-demand services
Academic	Advanced computational models for aspect-based sentiment analysis in mobility apps reviews, considering cultural and linguistic contexts	Develop and validate transport-specialized NLP models using multilingual datasets of European cities to improve the accuracy of review analysis and enhance the accuracy of identifying sarcasm and irony
Managerial	Prioritize accessibility, user experience, cybersecurity, and environmental awareness	Examine the effectiveness of gamification and adaptive design in fostering sustainable travel behaviors and long-term commitment

Source: own

Looking forward, how to digitally synchronize public, shared and on-demand mobility services to achieve operational intermodality, the major challenge, constitutes several research directions. Answering this question requires a view on both the institutional collaboration that has to be initiated for technical integration and seamless user experience. Payment infrastructures that are transparent and safe should receive equal attention. As long as privacy and usability are maintained, technologies like blockchain, tokenization, and biometric verification have the potential to boost consumer confidence in purchases. The pursuit of inclusive design shares relevance with adaptive interfaces supporting multimodal interaction by voice, gesture or tactile feedback plus contextual assistance. Gamification and green travel habits is another avenue that can be considered. The combination of predictive analytics and artificial intelligence in real time route optimization possibilities, personalization of mobility services, and system efficiency improvement offers very exciting challenges. Tab. 9 summarizes the recommendations and future research by policy, academic and managerial perspectives.

Statement: *During the preparation of this work the authors used Chat Generative Pre-trained Transformer in order to refine the Python code development for web scraping and data extraction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.*

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Are sustainable cities attractive to digital nomads? A machine learning approach

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Abstract: *This study explores the determinants of urban sustainability for digital nomads by predicting the nomad_score, a composite indicator of city attractiveness for remote workers, using supervised machine learning. Data were collected from NomadList and open city datasets, covering 668 destinations and 27 quantitative variables related to cost of living, connectivity, safety, social inclusion, and lifestyle. Gradient boosting, random forest, neural network, decision tree, AdaBoost, linear regression, and partial least squares (PLS) were evaluated using 20-fold cross-validation and metrics such as mean squared error (MSE), root MSE (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and R^2. Our results show that ensemble methods based on boosting outperform other modes, with the best results being reported with AdaBoost (R^2 = 0.50 in training and 0.68 in prediction). The analysis of global predictors revealed that gender equality and entrepreneurship (startup_score and female_friendly) were the main features, whereas SHAP-based (SHapley Additive exPlanations) local explanations showed that Airbnb cost and safety were the most important ones. Policy implications point to the need to strengthen green infrastructure, expand digital connectivity, and promote social equity to make cities more attractive in the new remote-work economy.*

Keywords: *Digital nomads, sustainable cities, machine learning, artificial intelligence, AdaBoost, urban connectivity, sustainable housing, public transport and mobility.*

JEL Classification: *C55, O18, Q01, R11, Z32.*

APA Style Citation: Palos-Sanchez, P. R., Lezcano-Calderon, Y. Folgado-Fernandez, J. A., & Giraldez-Puig, P. (2026). Are sustainable cities attractive to digital nomads? A machine learning approach. *E&M Economics and Management*, *29*(3), 131–149. https://doi.org/10.15240/tul/001/2026-3-007

Introduction

There has been a notable increase in digital nomads over the last decade, driven by digitisation, labour flexibility, and the desire for a more sustainable way of life. These professionals and entrepreneurs, who work remotely while exploring different cities, have begun to leave their mark on the places where they temporarily reside (Bahri, 2024).

This emerging phenomenon brings both opportunities and challenges for host cities of digital nomads. On the one hand, they bring economic activity, knowledge, and innovative capacity but, on the other hand, attracting and retaining them requires affordability, a culture of openness and inclusivity, and a strong digital connectivity infrastructure (Holleran, 2022; Sequera, 2025). Therefore, the challenge for these cities is to design public policies that promote sustainability, social inclusion, and strong digital infrastructure to enhance their attractiveness to these global citizens. However, while research on sustainable and smart cities has advanced considerably (Bibri & Krogstie, 2017; Jabareen, 2006; UN-Habitat, 2020), little is known about how urban sustainability influences the mobility decisions of digital nomads or how cities can leverage sustainability to enhance their attractiveness.

In this context, this study aims to define and empirically assess the characteristics that make a city sustainable and appealing to digital nomads, integrating perspectives from urban sustainability theory, smart-city and data-driven governance, and social sustainability and inclusion. More specifically, this article proposes the methodological development and validation of the *nomad_score*, which is an index that helps to assess the degree of sustainability of a city from the perspective of digital nomads. Using supervised machine learning, the study identifies behavioural patterns and provides policy recommendations for urban managers seeking to attract and retain talent from this new class of mobile professionals.

The research questions (RQs) proposed aim to answer the question of how cities can transform themselves to meet the demands of the digital nomad population.

RQ1: Can the nomad score of a sustainable city as a destination for digital nomads be predicted?

RQ2: Which sustainability factors, related to cities, have the most influence on digital nomads?

RQ3: Which machine learning model can best predict nomad score?

RQ4: From a digital nomad perspective, is it really important that a city is sustainable?

After the introduction, in which the topic and objective have been presented, the second section contains a review of the literature on digital nomads in the context of sustainable cities. The study methodology is then described and the results achieved are presented. Finally, the discussion, conclusions, and future research are presented.

1 Theoretical background

This study draws on three complementary theoretical frameworks to explain the relationship between the sustainability of cities and their attractiveness to digital nomads. First, urban sustainability theory (Jabareen, 2006; UN-Habitat, 2020) provides the conceptual basis for understanding cities as multidimensional systems that combine economic, environmental and social dimensions of liveability. Second, smart city and data-driven governance theory (Bibri & Krogstie, 2017) highlights the role of technology and artificial intelligence in promoting sustainable, efficient, and inclusive urban management. Third, the theory of social sustainability and inclusion (Kuzior et al., 2025; UN-Habitat, 2020) explains how equality, safety, and cultural openness strengthen the capacity of cities to attract global talent.

1.1 Sustainable cities and digital nomads

Being primarily focused on the environment, urban sustainability has evolved into a broader concept (Jabareen, 2006). From the perspective of urban sustainability theory, sustainability reflects a balance between environmental preservation, social inclusion, and economic viability. This multidimensional view is based on Campbell's "green, growing, and just city" framework (Campbell, 1996), which highlights the existing tensions among economic growth, environmental protection, and social equity. In sum, economic growth can harm the environment; protecting the environment may limit economic opportunities, and promoting equity may require the redistribution of resources and restraining economic growth. Urban sustainability implies the management of these tensions. Considering all these dimensions, urban sustainability now plays a key role in how cities attract and support global mobile professionals, such as digital nomads.

Among these dimensions, the social aspect of sustainability has become particularly relevant for cities seeking to attract global talent. In this context, public safety, inclusion and gender equality are fundamental to social wellbeing (UN-Habitat, 2020). A city's ability to attract global talent depends greatly on how safe and welcomed people feel in their everyday lives. Recent studies on sustainable cities and digital mobility highlight security, tolerance, and diversity as central pillars of an integrated approach to urban sustainability (Kuzior et al., 2025).

 2026, volume 29, issue 3, pp. 131–149, DOI: 10.15240/tul/001/2026-3-007

For their part, digital nomads are professionals who work from anywhere in the world, without a fixed residence. Their profile is diverse, but they can be characterised by their work autonomy, geographical mobility, intensive use of ICT, and search for quality of life. This highly mobile group has a high level of academic training and experience in sectors such as technology, marketing, finance, and consulting. Their impact influences the transformation of work models and the configuration of new global communities.

1.2 Factors influencing the performance of digital nomads

The performance of digital nomads in cities is conditioned by multiple factors; those which are most represented in the literature are: cost of living, connectivity-infrastructure, safety-political stability, social inclusion-openness, lifestyle-leisure and entrepreneurship (Gupta et al., 2024).

Cost of living

This concept marks the relationship between the nomad's income and expenses in their new work location. It is one of the main factors influencing digital nomads' choice of destination, where they must consider whether a city is expensive or cheap, based on their net income, to assess whether they can live comfortably there compared to other destinations (Zhou et al., 2024).

Through the lens of urban sustainability theory (Jabareen, 2006; UN-Habitat, 2020), affordability constitutes the economic pillar of sustainability, ensuring access to resources and equitable living standards. Cities that balance cost and quality of life achieve economic resilience and higher attractiveness for global talent. A good example is Portugal, which offers digital nomads affordable living costs and excellent transport connections, making it one of the most popular destinations for remote professionals (Abreu & Sampaio, 2025).

Digital connectivity

One key element for digital nomads is digital connectivity. This is not only about having a good internet service but, also, an entire technological ecosystem that makes remote working easier, the main factors being: solid infrastructure, co-working spaces, public wi-fi, and efficient digital services. Beyond its technical aspects, digital connectivity is also fundamental to participatory and data-driven urban governance, in line with the concept of smart cities (Nam & Pardo, 2011). Cities that aspire to attract this profile must have advanced networks, public administration with digitised procedures, and smart buildings that facilitate remote working (Batty et al., 2012). Therefore, digital connectivity is the technological backbone of sustainable cities, which is in line with smart city theories and data-driven governance (Bibri & Krogstie, 2017). Reliable infrastructure and accessible digital services foster inclusion by creating new opportunities for employment and participation. High-speed connectivity and rapid access to administrative services via mobile apps are key factors in determining whether a city is considered sustainable and attractive to digital nomads. For this group, the quality and speed of the connections determine whether it is feasible to temporarily choose a city, as it directly affects their work productivity and personal wellbeing (Jaiswal et al., 2025). Consequently, cities that aspire to be a sustainable destination for digital nomads must guarantee digital connectivity, which is capable of meeting the demanding requirements of a population dependent on the digital environment (Sequera, 2025).

Security and political stability

For digital nomads, this criterion concerns labour and tax regulations at the destination, such as visas, rental contracts, taxes, security, and accessibility. This group tends to avoid cities with high levels of conflict, public insecurity, or uncertainty in public administrations (Wang et al., 2025).

According to the theory of social sustainability (UN-Habitat, 2020), safety and institutional stability are critical to achieving social wellbeing and fostering a sense of trust and belonging. Predictable governance systems and coherent public policies enhance inclusivity and attract people seeking secure and transparent environments.

In this sense, institutional stability implies a predictable administrative environment and coherent public policies that guarantee their security and access to the services offered by the city (Holleran & Notting, 2023). Thus, security and political stability are fundamental conditions for a city to be able to adapt to international migration due to the boom in teleworking. In addition, these cities must provide participatory assemblies for their citizens, inclusive policies, and long-term urban planning, which guarantees security and tranquillity before possible changes in government structures (Jaiswal et al., 2025).

Social inclusion

The concept of social inclusion, in the context of digital nomads, is related to the degree of integration with other digital nomads and with the local population (Bahri, 2024). Following Polèse and Stren (2000), social sustainability refers to the ability of cities to maintain social cohesion, manage diversity, and ensure equitable access to opportunities. Later works by Dempsey et al. (2011) emphasised that inclusion, participation, and safety are critical dimensions of socially sustainable urban environments. This phenomenon addresses the need to establish urban policies that promote intercultural and intergenerational coexistence, equitable access to housing, and the protection of local identity (Holleran, 2022) because this is a group that is generally made up of foreigners with unconventional jobs and lifestyles.

Social inclusion, as conceived by the theory of social sustainability and inclusion (UN-Habitat, 2020; Kuzior et al., 2025), refers to a city's ability to promote equality and cohesion between its diverse groups. It involves fostering emotional security and a sense of belonging, which are fundamental pillars of social wellbeing, and, ultimately, influence the length of stay. For digital nomads, these characteristics translate into the possibility of integrating into urban life without feeling excluded due to language barriers, nationality, orientation, gender, or immigrant status (Orel, 2021). Therefore, policies aimed at promoting equality and non-discrimination, as well as ensuring access to basic services for temporary residents, are crucial for creating a genuine sense of community belonging.

Together, these perspectives align with the theory of social sustainability and inclusion, which positions equality, diversity, and emotional security as the core components of urban resilience and attractiveness. Feeling emotionally secure and connected to the community can shape how long nomads stay and how they perceive the city overall (Vukmirović et al., 2025).

Lifestyle and leisure

The presence of cultural, sporting, and social activities, which enrich the quality of life in a city, are highly valued by digital nomads (Rainoldi et al., 2025). Therefore, cities with public policies that encourage leisure and recreational activities tend to be particularly attractive to them.

In line with urban sustainability theory (Jabareen, 2006), sustainability is not only measured in environmental terms but, also, through social and cultural richness. These dimensions enhance quality of life and address people's higher-level needs, such as belonging, creativity, and personal fulfillment. The goal is to make people feel well and connected to the place where they live. The richer and more balanced the social and cultural life of a city is, the more capable of attracting and retaining international talent it will be.

Beyond seeking places where they can maintain a connected and flexible lifestyle, digital nomads value environments that allow them to enjoy cultural, social, and recreational activities (Kozak et al., 2024). For them, leisure is an essential part of their way of life, as it provides wellbeing and fosters creativity. That is why cities with vibrant cultural and social scenes become their preferred destinations (Chevtaeva & Denizci-Guillet, 2021). Moreover, leisure can also create professional networks by facilitating interaction with other nomads or local residents, leading to new ideas and business opportunities (Sánchez-Vergara et al., 2023).

Entrepreneurship

Many cities have realised that digital nomads are potential entrepreneurs, i.e., people with ideas, projects, and the ability to create local value. For this reason, digital entrepreneurship has become a key factor in attracting and retaining this type of talent (Yu et al., 2025). In line with smart city and data-driven governance theories (Bibri & Krogstie, 2017), entrepreneurship serves as a bridge for knowledge exchange and innovation within sustainable urban systems.

Collaborations between universities, businesses, and local institutions are a catalyst for the development of start-ups and digital communities, which attract talent whilst also contributing to urban sustainability (Jaiswal et al., 2025). Digital nomads, in particular, tend to bring entrepreneurial capacity along with a global mindset (Wang & Azizurrohman, 2025). Therefore, cities that promote digital entrepreneurship can become strategic hubs for this type of business initiative (Papanikolaou et al., 2025).

In summary, it is necessary to consider different perspectives in order to understand digital nomadism (Lacárcel, 2025) as an agent of sustainable urban transformation. From a theoretical standpoint, these elements converge within the framework of urban sustainability, smart city governance, and social sustainability.

2 Research methodology

2.1 Research design

This study applied supervised machine learning techniques to model the relationships between city-level characteristics and digital nomads' perceived satisfaction (*nomad_score*). The approach integrates quantitative indicators, such as cost of living, connectivity, and safety, to predict and explain the overall attractiveness of cities for remote workers. The analysis was based on an initial dataset obtained from the NomadList (Nomads.com) platform, which provides information and services for digital nomads seeking the best places to live and work remotely. Since 2014, NomadList has been recognised as the leading global community for digital nomads, offering data-driven rankings, filters, community chats, and local meetups to enhance the remote working experience (Nomads.com, 2025).

2.2 Data collection

Data were gathered from multiple sources, including NomadList and open city datasets for structured variables, as well as Kaggle.com. The dataset (Jurowetzki, 2019) covers approximately 730 cities with 27 quantitative variables, 2 qualitative variables (categorical) and 3 meta attributes (city, region and country). Ethical guidelines were followed to ensure data anonymisation and compliance with the platform terms.

Tab. 1 summarises the key thematic dimensions used to describe cities in the digital-nomad dataset. Each category groups related variables that capture complementary aspects of urban environments, which affect remote workers and location-independent professionals. The cost of living variables measure local affordability through typical consumer prices and estimated monthly living costs for locals, expatriates, and digital nomads. Connectivity and infrastructure indicators represent the availability and quality of essential resources for remote work. Safety and political stability describes how secure and well-governed a city feels, including factors such as peace, freedom, and institutional reliability. Social inclusion and openness captures how welcoming, fair, and tolerant each location is toward newcomers. Lifestyle and leisure dimensions reflect the overall liveability and cultural richness that make a city appealing to digital nomads.

One efficient way to perform outlier detection on moderately high dimensional datasets is to use the local outlier factor algorithm.

Tab. 1: Types of variables identified

Category	Variables	Meaning
Cost of living	Coffee_in_cafe, coca_cola, cost_expat, cashless_society, cost_of_living_for_local	Local prices (e.g., coffee, Coca-Cola, living costs)
Connectivity/ infrastructure	Internet_speed, places_to_work, safe_tap_water, air_quality_(year-round), walkability	Internet speed, wi-fi availability
Safety/political stability	Safety, peace_score, press_freedom_index, freedom_score, religious_government	Security, peace, government fragility, press and political freedom
Social inclusion/ openness	Female_friendly, LGBT_friendly, friendly_to_foreigners, racism, peace, healthcare, freedom_of_speech and happiness	Social tolerance, gender equality, friendliness toward foreigners
Lifestyle/leisure	Nightlife, leisure, life_score, nomad_score	Nightlife, cultural activities, liveability and nomad friendliness
Entrepreneurship	Startup_score	Startup score

Source: Jurowetzki (2019)

The algorithm computes a score reflecting the degree of abnormality (in this case, 69 values of cities) of the observations (661 final values of cities). It measures the local density deviation of a given data point with respect to its 20 neighbors (metric Euclidean).

All these dimensions provide a framework for organising urban destinations and understanding their attractiveness to digital nomads.

2.3 Data preprocessing

The dependent variable, *nomad_score*, measures the overall attractiveness of a city for digital nomads. It is a numerical composite index ranging from 0 to 5, derived from the global evaluation question: "*Overall, this city is an excellent place to live and work remotely*". *Nomad_score* is primarily a measure of satisfaction or perceived livability, rather than a strict metric of objective sustainability. However, it is important to say that sustainability for nomads is human-centered.

Fig. 1 presents the *nomad_score* box plot. The results indicate a mean of 3.92, which is closely aligned with the median (3.98), while the interquartile range between Q1 (3.64) and Q3 (4.26) is also close to these values, suggesting a symmetric distribution. This pattern indicates that most cities are rated favourably in terms of their sustainability for remote work, although a few outliers below 2.5 reveal less attractive destinations. We found no missing data, and conducted outlier detection using the local outlier method with Euclidean distance, resulting in the exclusion of 62 cities. The final sample consisted of 668 destinations.

2.4 Machine learning models

The regression models included: gradient boosting, random forest, neural network, decision tree, AdaBoost, linear regression, and partial least squares (PLS). These models were trained using an 80/20 train–test split with 20-fold cross-validation. As performance metrics, we considered mean squared error (MSE), root MSE (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and R^2, which are standard indicators in machine learning studies.

All these models belong to the family of supervised learning algorithms, which learn patterns from data that already include both the input features and the outcome to be predicted. Their goal is to make the most accurate predictions possible by reducing error (e.g., MSE or RMSE) or improving the model's explanatory power (R^2).

These models can detect complex, nonlinear relationships that traditional methods often miss. However, to achieve reliable results, they need to be validated and fine-tuned through processes such as cross-validation and hyperparameter adjustment, ensuring they do not overfit the data.

They were chosen for this study because they are particularly well suited for predicting continuous values, which makes them ideal for estimating the *nomad_score* as a numerical outcome.

2.5 Validation and robustness

To ensure the models were robust and reliable, we fine-tuned their hyperparameters and analysed feature importance through SHAP (SHapley Additive exPlanations) values. Fig. 2 shows the hyperparameter tuning results for a random forest model, aimed at identifying the optimal parameter combination that maximizes accuracy while minimizing error. As shown in Fig. 2, the green line corresponds to

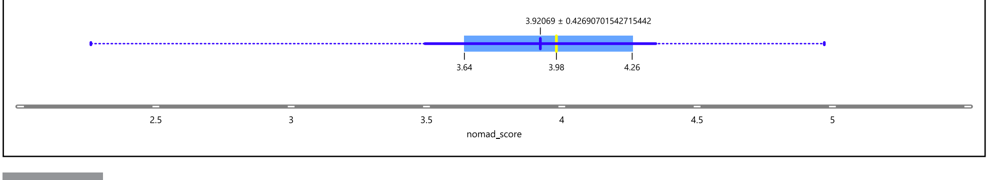

Fig. 1: Boxplot nomad score

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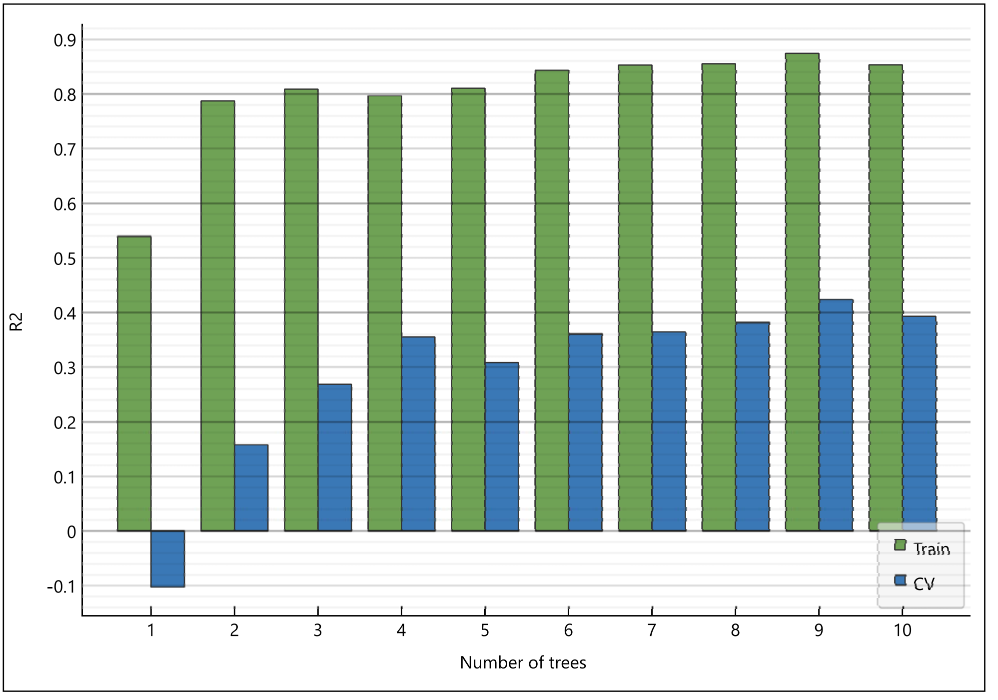

Fig. 2: Hyperparameter tuning random forest

Source: own

the model's training performance, and the blue one reflects its validation results. The best performance is observed between four and six trees, where the validation R^2 reaches its peak (at around 0.35).

We assessed validation and robustness using the SHAP library, applied to both classification and regression models. This library uses the input data to compute the contribution of each feature to the prediction of a selected class, providing a model-agnostic explanation of how predictions are formed.

In particular, it provides two complementary perspectives: global SHAP values, which show the average importance of each feature across the entire model, and local SHAP explanations, which reveal how specific features affect the prediction for an individual case.

Fig. 3 shows how the SHAP method explains a single prediction made by the *nomad_score* model, which estimates how attractive a city is for digital nomads. The base value (≈3.98) represents the model's average score across all cities, while the final prediction for this specific case (3.81) reflects how each feature pushes the score up or down. Blue bars show the factors that make the city more attractive, while red bars show those that lower its attractiveness.

In this case, a relatively high monthly Airbnb cost (≈3,904 USD) and a moderate female-friendly rating (=2) contribute positively, suggesting that costlier cosmopolitan cities tend to be more attractive to digital nomads. In contrast, *startup_score* (=3) and safety (=3) exert slight negative effects, implying that average entrepreneurial and safety conditions provide limited differentiation.

In general, the SHAP analysis underscores that economic accessibility, inclusiveness, and safety jointly shape the appeal of a city's digital ad, consistent with previous findings on mobility and urban liveability (Reichenberger, 2018; Thompson, 2021).

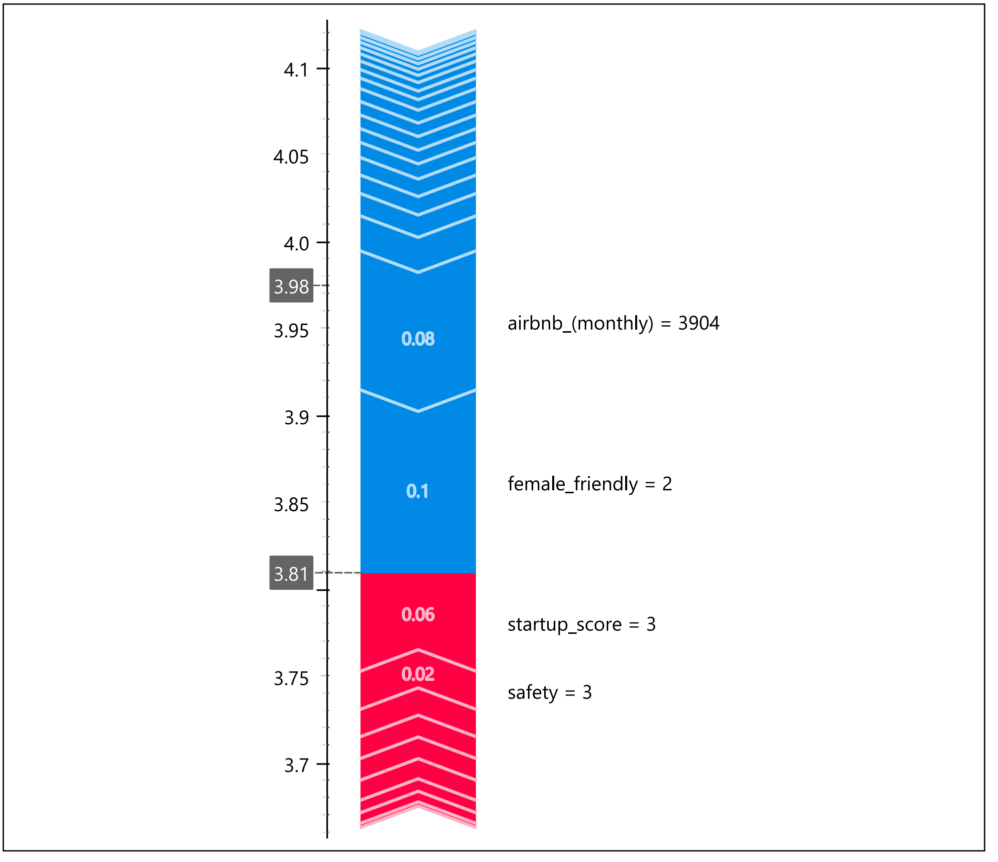

Fig. 3: **SHAP-based feature importance analysis**

Source: own

2.6 Tools and environment

All analyses were conducted in Python 3.11 using Pandas, gradient boosting (scikit-learn, XGBoost), SHAP libraries and Orange Data mining (Demsar et al., 2013).

3 Results and discussion

3.1 Results

Tab. 2 presents the statistics of the variables related to the sustainability of cities.

Fig. 4 shows that the correlation analysis reveals a strong relationship between *nomad_score* and key factors of urban sustainability. The variable exhibits a high correlation with *startup_score* (0.575) *female_friendly* (0.497), *internet* (0.429) and *peace* (0.402), indicating that cities attractive to digital nomads tend to be entrepreneurs and innovators, open to equality and women's rights, with quality of life, peaceful, and provide reliable access to internet. It is also positively associated with *walkability* (0.232), highlighting the importance of connectivity and sustainable mobility. Additionally, *startup_score* correlates strongly with *quality_of_life* (0.359), *racial_tolerance* (0.352), *LGBT_friendly* (0.378) and *freedom_of_speech* (0.308), which shows that entrepreneurial ecosystems thrive in inclusive and democratic environments.

This decision tree (see Fig. 5) visually explains how different urban and social factors influence the *startup_score* of cities for digital nomads. The top split, nightlife ≤ 2, indicates that vibrant nightlife tends to separate startup environments with higher scores from quieter ones.

Tab. 2: Univariate statistics related to the sustainability of cities preferred by digital nomads

Feature	Mode	Mean	Median	Dispersion	Min	Max
Adult_nightlife	2.00	2.107	2.00	0.170	2.000	4.00
Air_quality_(year-round)	50.00	40.609	24.00	1.084	1.000	368.00
Airbnb_(monthly)	1,312.00	1,711.780	1,495.00	0.550	275.000	7,839.00
Cashless_society	2.00	1.914	2.00	0.384	1.000	3.00
Cost_of_living_for_expat	787.00	1,444.250	1,302.00	0.513	374.000	414.00
Female_friendly	2.00	2.443	2.00	0.402	1.000	4.00
Freedom_of_speech	1.00	1.848	2.00	0.464	1.000	4.00
Friendly_to_foreigners	3.00	2.757	3.00	0.298	1.000	4.00
Fun	2.00	2.309	2.00	0.371	1.000	4.00
Happiness	3.00	2.496	3.00	0.352	1.000	4.00
Healthcare	3.00	2.436	3.00	0.446	0.753	4.00
Internet	4.00	21.336	18.00	0.864	0.000	300.00
LGBT_friendly	1.00	1.992	2.00	0.482	1.000	4.00
Nightlife	2.00	1.992	2.00	0.410	0.890	4.00
Peace	3.00	2.489	3.00	0.406	1.000	4.00
Quality_of_life	3.00	2.888	3.00	0.125	1.000	4.00
Racial_tolerance	2.00	2.138	2.00	0.415	1.000	4.00
Safety	3.00	2.760	3.00	0.328	1.000	4.00
Startup_score	3.00	2.927	3.00	0.231	1.000	4.00
Traffic_safety	4.00	3.474	4.00	0.273	1.000	4.00
Walkability	4.00	3.273	4.00	0.370	1.000	4.00
Nomad_score	4.27	3.906	3.97	0.111	2.260	4.97

Source: own

When nightlife is limited, factors such as governance type and quality of life become more relevant. In contrast, in cities with a vibrant nightlife, safety perceptions, female inclusiveness, and the cost of living for expatriates provide the strongest contribution to explaining the *nomad_score*. Additional splits such as *friendly_to_foreigners*, *cashless_society*, and *coffee* or *coca_cola* prices reflect economic openness and modern infrastructure. The model shows that, overall, social inclusion and affordability are key elements in explaining the potential attractiveness of cities for digital nomads.

3.2 Predictive model performance

The random forest model achieved scikit-learn and XGBoost. Key predictors were cost of living, internet speed, and safety, followed by inclusion and leisure.

When comparing the different predictive models, AdaBoost (MSE = 0.091, R^2 = 0.50) stood out, achieving the highest predictive accuracy in estimating the *nomad_score*. Its low mean squared error (MSE) and mean absolute error (MAE) indicate strong generalisation ability and a good balance between bias and variance (Friedman, 2001).

Since gradient boosting is also a boosting-based method, it achieved similarly good results (R^2 = 0.47), as was expected (Natekin & Knoll, 2013). Linear prediction methods such as linear regression (R^2 = 0.42) and partial least squares (PLS, R^2 = 0.39) showed limited predictive ability to capture complex

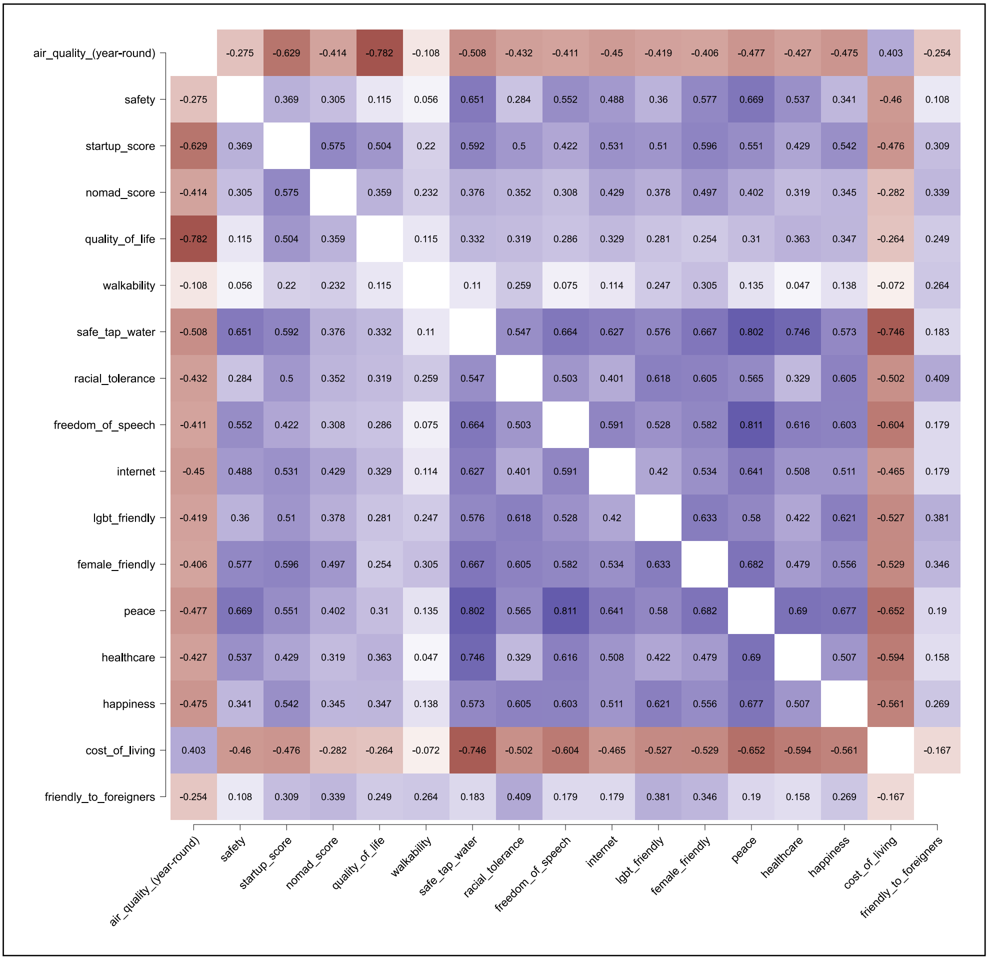

Fig. 4: **Pearson's correlation heatmap**

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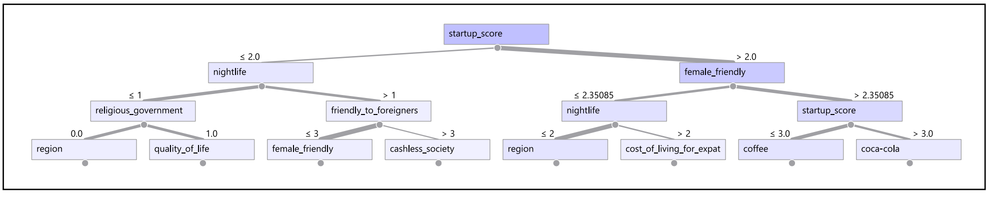

Fig. 5: **Model tree results**

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Tab. 3: Test and score

Model	MSE	RMSE	MAE	MAPE	R^2
AdaBoost	0.091	0.302	0.221	5.936	0.502
Gradient boosting	0.098	0.312	0.236	6.299	0.468
Linear regression	0.106	0.325	0.239	6.391	0.423
PLS	0.110	0.332	0.249	6.661	0.398
Random forest	0.111	0.333	0.246	6.557	0.395
Tree	0.143	0.379	0.284	7.514	0.219
Neural network	0.149	0.385	0.288	7.503	0.190

Note: Cross loading folds 20 subsample method.

Source: own

interactions between socioeconomic and quality-of-life variables (James et al., 2021). It is likely that the random forest (R^2 = 0.39) and simple decision tree (R^2 = 0.21) models were not able to adequately capture global relationships between the variables, as they showed higher average errors (MAE ≈ 0.25–0.28), possibly due to slight overfitting and suboptimal hyperparameter tuning (Breiman, 2001).

Finally, the neural network (R^2 = 0.18), whilst being theoretically powerful, showed the weakest performance. This is a common result when the dataset is too small or when the hyperparameters are not well-tuned, making it difficult to capture complex patterns without overfitting (Goodfellow et al., 2016).

The coefficient of determination (R^2) represents the proportion of variance explained by the model; values of around 0.5 are generally considered acceptable in social science and urban prediction contexts (Hair et al., 2019).

Tab. 4: Key performance metrics

Metric	Interpretation	Reference
MSE (mean squared error)	Penalises large errors; lower values indicate a better overall fit	Hyndman and Koehler (2006)
RMSE (root MSE)	Represents the average error in the same units as the dependent variable; values < 0.35 indicate moderate accuracy	Chai and Draxler (2014)
MAE (mean absolute error)	Average absolute error; more robust to outliers than MSE	Willmott and Matsuura (2005)
MAPE (mean absolute percentage error)	Relative percentage error; values < 10% are considered a good fit	Hyndman and Koehler (2006)

Source: own

Overall, the results confirm that boosting-based models (AdaBoost and gradient boosting) are particularly well suited for predicting the *startup_score*, as they are better able to handle nonlinearity, noise, and interdependent relationships between variables (Friedman, 2001; Natekin & Knoll, 2013).

In contrast, linear and tree-based models performed less effectively, limited by their rigid structure or insufficient optimisation. In the context of predicting quality of life, innovation, and urban sustainability, an R^2 of around 0.5 represent a moderate but meaningful level of explanatory power (Hair et al., 2019).

Although the AdaBoost model achieved an R^2 of 0.68 on the 20% prediction set, this value is higher than the cross-validated R^2 obtained on the training folds ($R^2 \approx 0.50$, Tab. 3). We carefully re-examined the data preparation pipeline and confirmed that the train-test split was performed at the city level before any model fitting, scaling, or hyperparameter tuning, and that no duplicated observations appear across the training and prediction sets. This rules out data leakage between the folds and the test set. The higher R^2 on the prediction subset is consistent with the fact that this sample is somewhat less heterogeneous and contains fewer extreme cases than the full dataset, which tends to inflate goodness-of-fit metrics. For this reason, we interpret the cross-validated R^2 around 0.50 as the most conservative estimate of the model's generalisation performance, and we consider the prediction-set R^2 as an upper bound conditional on this particular split.

3.3 Feature importance scores

The permutation feature importance technique showed the most relevant factors for the classification and regression models.

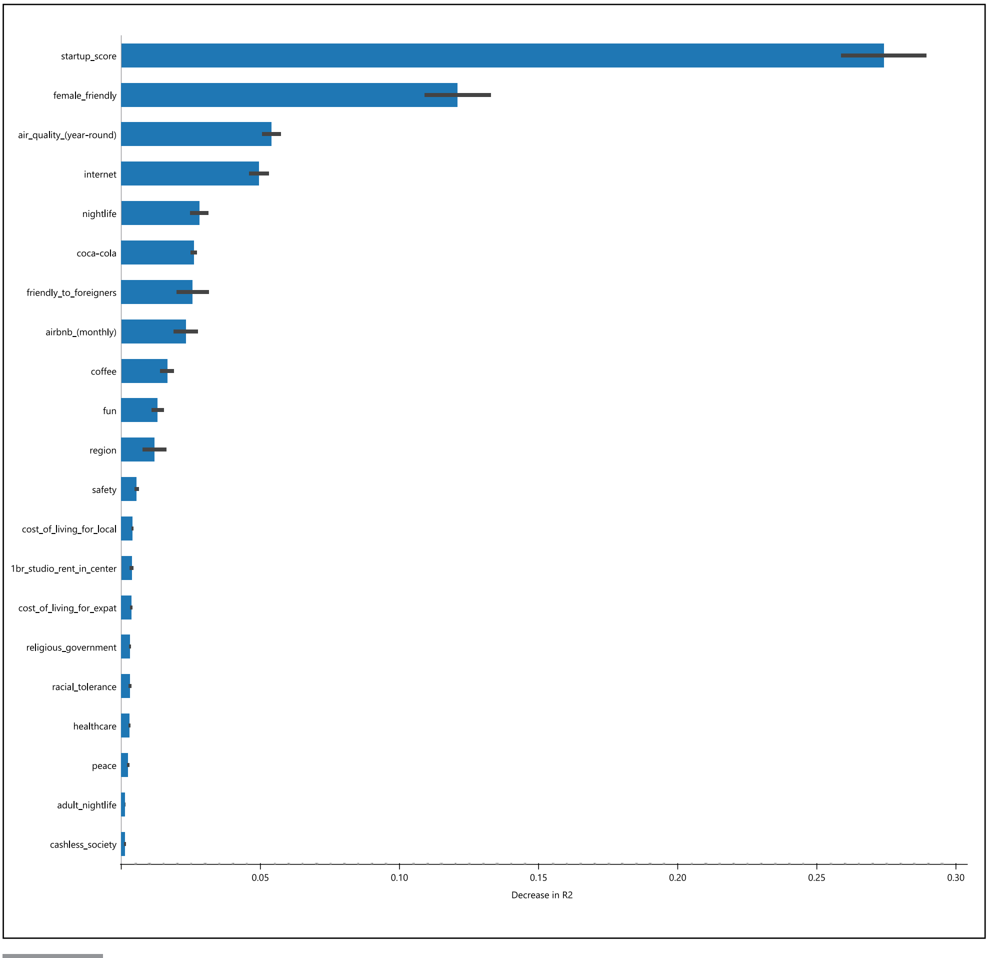

Fig. 6: **Feature importance**

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Tab. 5: Feature importance variables

Variable	Mean	Std. dev.
Startup_score	0.274	0.015
Female_friendly	0.121	0.011
Air_quality_(year-round)	0.053	0.003
Internet	0.049	0.003
Nightlife	0.028	0.003
Coca-Cola	0.026	0.001
Friendly_to_foreigners	0.025	0.006
Airbnb_(monthly)	0.023	0.004
Coffee	0.016	0.002
Fun	0.013	0.002
Region	0.012	0.004
Safety	0.005	0.001

Source: own

From the main dataset, a baseline model was trained using permutation feature importance, which is a method that measures how much the model's performance worsens when the relationship between a given variable and the target is disrupted.

Feature importance scores are shown in Fig. 6 and Tab. 5. The most relevant variable was *startup_score*, with an R^2 drop of 0.27, followed by *female_friendly*, which showed a decrease of 0.18. Variables such as *air_quality*, *internet*, and *nightlife* had moderate importance, with mean values of 0.053, 0.049, and 0.028, respectively, whereas factors such as *peace*, *healthcare*, and *racial_tolerance* showed almost no contribution.

3.4 Interpretation of AdaBoost model

Finally, the AdaBoost machine learning model, selected during the training phase conducted on 80% of the sample, achieved an R^2 = 0.68 when predicting the remaining 20% of the cities.

AdaBoost (adaptive boosting) is a supervised ensemble meta-algorithm that improves prediction accuracy by combining several weak models into a stronger overall one (Freund & Schapire, 1997). This algorithm trains several simple models sequentially, usually decision trees, and recalibrates the sample weights at each step so that each new model corrects the errors made by the previous ones (Schapire, 2013). The final prediction combines the output of all individual models, weighting

Tab. 6: Comparison of results (global feature importance vs. local SHAP analysis)

Aspect	Feature importance (global)	SHAP analysis (local)
Goal	Identifies which variables contribute most to global predictive accuracy	Explains how each variable affects an individual city's prediction (direction and magnitude)
Interpretation	*Startup_score* and *female_friendly* are globally the most influential factors	Airbnb cost and safety had positive/negative local effects depending on each city
Insight	Connectivity and inclusivity drive global performance	Specific interactions (e.g., high Airbnb cost but high inclusivity) adjust local predictions

Source: own

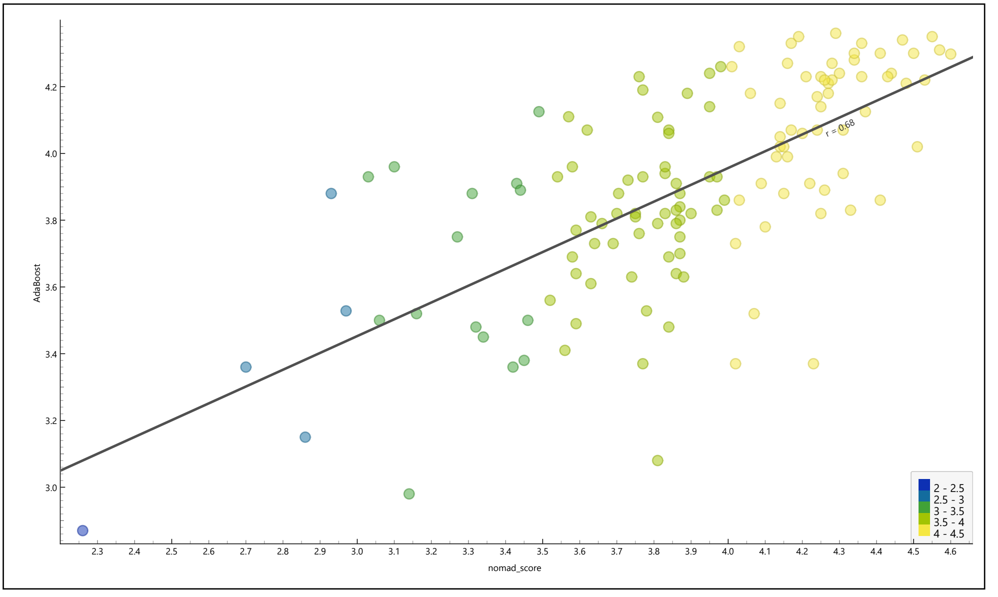

Fig. 7: **Scatter plot (cost of living colours)**

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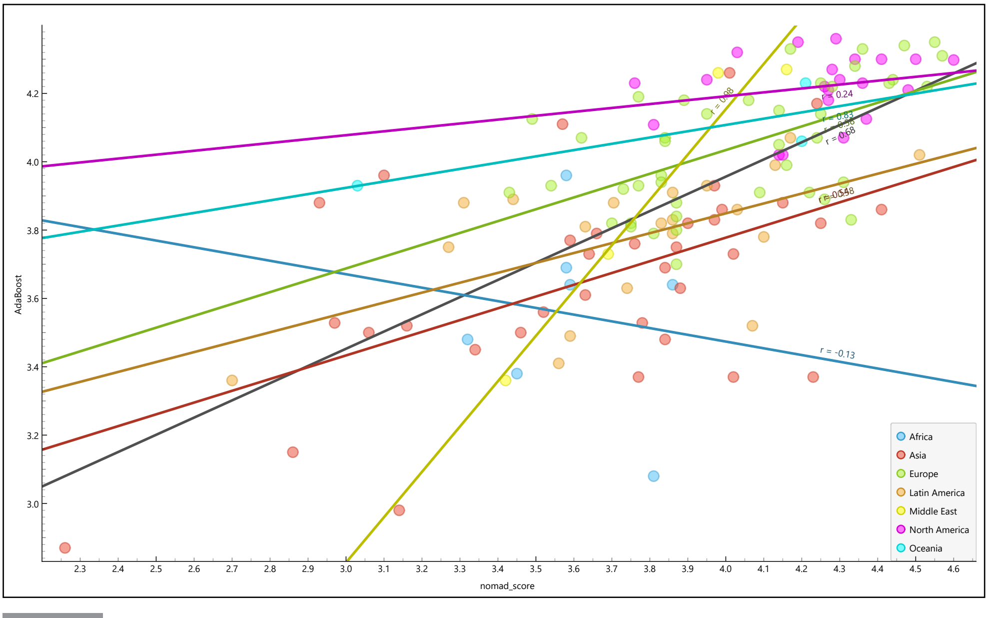

Fig. 8: **Scatter plot (region colours)**

Source: own

them according to their accuracy, which helps reduce errors and improve generalisation.

Although AdaBoost was originally developed for binary classification, it can be effectively applied to multiclass and regression problems, providing robust results in complex or heterogeneous datasets.

Fig. 7 shows the regression between the actual *nomad_score* values (X-axis) and those predicted by the AdaBoost model (Y-axis). The coefficient of determination (R^2 = 0.68) indicates that the model explains 68% of the total variance. The relationship is positive but shows some dispersion, particularly for scores below 0.3 and in the mid-range, where the model tends to overestimate *nomad_score*. The model performs better in cities that are more attractive to digital nomads, and the best predictions occur for *nomad_score* values above 0.4.

Fig. 8 presents the regional classification of the prediction trend. The relationship is positive and consistent across all regions, as the points follow an upward pattern, indicating that the model effectively captures the overall relationship.

However, some regional dispersion is observed: the colour gradient reveals that certain regions (e.g., blue tones) tend to cluster around higher *nomad_score* values, whereas others (yellow/green tones) are more widely dispersed, suggesting regional differences in prediction accuracy.

3.5 Discussion

Previous studies have examined the importance of digital nomads (Lezcano-Calderon & Palos-Sanchez, 2025; Palos-Sanchez et al., 2025) and urban sustainability mainly from environmental or economic perspectives, focusing on the well-being of local residents or green infrastructure (Bibri & Krogstie, 2017; Jabareen, 2006; UN-Habitat, 2020). Drawing on urban sustainability, smart-city, and social inclusion theories, this study analyses the multidimensional determinants of the' attractiveness of cities for digital nomads using an international sample of 661 cities. Our analysis supported the main hypothesis that the *nomad_score* can be effectively predicted using supervised machine learning techniques based on sustainability indicators. The results confirmed that *startup_score* and *female_friendly* are the strongest predictors, followed by *air_quality*, *internet_speed*, and *nightlife*. These findings are consistent with previous research showing that cities that foster entrepreneurship, through supportive services, infrastructure, and cultural values, and promote inclusiveness tend to enhance both urban liveability and competitiveness (Kuzior et al., 2025; UN-Habitat, 2020). In line with urban sustainability theory, our findings suggest that a city's resilience and quality of life depend on how its economic, environmental, and social dimensions work together, in balance.

Other variables, such as *Airbnb_prices,* have a positive correlation due to the fact that cities with higher prices act as proxies for cosmopolitan centers of high quality, connectivity and infrastructure. In the case of *safety* variable, which already has a high average *nomad_score* of 3.75 in SHAP results and 0.339 in correlation plot, it acts as a pre-existing condition or a baseline factor, and therefore, is not a differentiating element between already attractive cities.

A similar pattern can be observed for other "threshold" variables such as *peace* and *healthcare*. Because NomadList mainly features cities that are already viable options for digital nomads, most destinations in our sample meet minimum standards of security and access to basic services. As a result, these indicators display relatively low variability across cities. This helps to explain why they remain strongly correlated with the *nomad_score*, yet exhibit very limited permutation importance: they operate as necessary background conditions rather than as key differentiating drivers of perceived attractiveness.

Furthermore, drawing on the theoretical frameworks of smart cities and data-driven governance (Bibri & Krogstie, 2017), the high predictive power of the AdaBoost model supports the idea that artificial intelligence is not only useful for prediction but it can also serve as a strategic tool to plan and manage cities more intelligently, relying on data and empirical evidence. By applying predictive methods, this study turns the idea of sustainability into something that can be measured and analysed, going beyond previous research that only described it (Batty et al., 2012; Bibri & Krogstie, 2017).

Our results also reveal that digital nomads value human and social aspects over purely environmental ones. These findings support the theory of social sustainability, which emphasises equality, inclusion, and safety as essential pillars of urban wellbeing (UN-Habitat, 2020). Our study extends this theoretical framework by showing that social sustainability plays a growing role in shaping global urban mobility patterns among digital nomads.

In the same vein, this study contributes to the inclusive governance perspective of UN-Habitat (2020), which highlights safety, equality, and access to opportunities as key elements of urban resilience. Our evidence shows that economic affordability does not determine the preferences of digital nomads on its own (Batty et al., 2012; Bibri & Krogstie, 2017). Rather, they are attracted to cities that combine technological progress with strong social cohesion and tolerance. Moreover, the regional asymmetries observed in our model, where predictive accuracy decreases in less developed areas, reveal that not all regions benefit equally from digital progress. This persistent technological gap shows that urban sustainability cannot solely rely on digitisation, but must ensure equitable access to digital opportunities and resources. In line with Kuzior et al. (2025), our findings emphasise the importance of social participation, gender equality, and cultural diversity as underexplored, and yet essential, dimensions of sustainable urban development.

In general, by integrating urban sustainability, smart-city, and social inclusion theories, our study contributes to the literature by linking environmental and economic metrics with social perceptions and digital infrastructure. It shows that truly sustainable cities are not only green or efficient but they are also inclusive, well-connected, and centred on human wellbeing. These insights provide both theoretical and practical guidance for developing AI-driven tools that can support more sustainable urban planning and help cities attract global digital talent.

Conclusions

Urban sustainability has become a central theme in the global agenda, yet few studies have examined it from the perspective of digital nomads, a rapidly growing segment of the global workforce. This study addresses this gap by analysing the key determinants that make cities attractive to this group. To this end, it integrates the theoretical frameworks of urban sustainability, smart-city governance, and social inclusion, applying machine learning techniques to a sample of 668 cities worldwide.

The results show that *startup_score* and *female_friendly* exert the strongest influence on the *nomad score*, followed by *air_quality*, *internet_speed*, and *nightlife*. Together, these findings confirm that the most attractive cities are those that combine entrepreneurial activity, environmental quality, and inclusive social environments. Finally, the predictive power of the AdaBoost model (R^2 = 0.68) demonstrates the usefulness of artificial intelligence in quantifying sustainability and anticipating emerging urban trends.

Implications for theory. This study offers several theoretical contributions. First, it contributes to urban sustainability theory (Jabareen, 2006; UN-Habitat, 2020) by providing empirical evidence that sustainability is a multidimensional phenomenon. By developing a predictive model that combines economic, social, technological, and environmental factors, it offers practical guidance for managing sustainability through quantifiable, data-driven indicators.

Second, it advances the theory of smart cities and data-driven governance (Bibri & Krogstie, 2017) by showing how artificial intelligence can turn traditional sustainability models into proactive tools for urban policy and planning. Using machine learning, we demonstrate that technology can not only predict and assess the impact of different urban factors but also support more transparent, evidence-based, and sustainable decision-making.

Third, this study contributes to the theory of social sustainability and inclusion (UN-Habitat, 2020) by showing that social factors such as tolerance and inclusiveness are fundamental pillars of urban attractiveness, beyond purely environmental or economic dimensions. Altogether, these findings deepen the conceptual understanding of sustainability by linking environmental resilience with human-centred values.

Implications for practice. The results have relevant implications for urban policy makers and city managers. To begin with, policymakers should recognise that attracting and retaining digital nomads requires a sustainability strategy that prioritises not only economic competitiveness but also social cohesion, technological inclusion, and entrepreneurial initiative. These values must be embedded in society and accessible to everyone equally, regardless of origin or background.

From a more prescriptive perspective, the boosting-based model also helps to identify combinations of factors that generate the largest gains in predicted *nomad_score*. Our results suggest that simultaneous improvements in high-speed connectivity (e.g., internet and places to work), entrepreneurial ecosystems (*startup_score*), and inclusive social environments (*female_friendly*, *friendly_to_foreigners*) have a greater impact when implemented together than isolated changes in any single dimension. This nonlinear complementarity implies that integrated policy packages that jointly invest in digital infrastructure, support for startups, and social inclusion are likely to be more effective than fragmented interventions.

Second, local governments could use AI-based tools to create sustainability dashboards that monitor key indicators and predict trends in real time. This would allow them to anticipate how policy decisions might affect urban liveability, social inclusion, and resilience.

Last, but not least, universities and research networks can play a key role in promoting data-driven urban governance by developing open-access sustainability dashboards and helping local governments build the skills needed to use them effectively. Aligning these initiatives with the United Nations' SDG 11 ("Sustainable Cities and Communities") can strengthen evidence-based policymaking and support a more inclusive transition toward smart and sustainable cities.

Limitations and future research. As with any empirical research, this study has a few limitations that should be acknowledged. The dataset is based on secondary information from NomadList which, although extensive, may include selection biases linked to user perceptions. In particular, the platform tends to highlight cities that are already attractive or at least acceptable for digital nomads, which compresses variation in basic "threshold" indicators such as *peace* and *healthcare*. This sampling process reinforces the role of these variables as baseline conditions in our models and helps to explain their relatively low contribution in the permutation-importance analysis, despite their strong correlations with perceived attractiveness. In addition, the cross-sectional design restricts the analysis of temporal changes and causal relationships in urban sustainability. Future studies could address this by using longitudinal or spatial econometric approaches to observe how sustainability evolves across time and regions.

Although the study covers a broad global sample, future research could focus on regional comparisons to better understand contextual influences such as regulatory frameworks, cultural norms, and disparities in digital infrastructure. Finally, qualitative approaches, such as interviews with digital nomads or local policymakers–could provide valuable insights into the social and emotional dimensions that shape urban sustainability.

In general, this study provides a pioneering contribution to the intersection of sustainability, technology, and global mobility. It offers empirical evidence that the cities most attractive to digital nomads are those capable of integrating economic opportunity, environmental quality, and social inclusion into coherent and measurable strategies. By combining artificial intelligence with human-centred urban design, cities can move toward a model of sustainable development that is not only smart but also equitable, resilient, and globally connected.

Acknowledgments: *The authors acknowledge the financial support of the research project Ref. PID2021-128420OB-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", and a research project funded by Consejería de Universidad, Investigación e Innovación (Junta de Andalucia, PAIDI 2021) Ref. ProyExcel_00934.*

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Fostering regional competitiveness through European joint study programmes: Insights from European university alliances

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Abstract: *European university alliances are evolving into instruments of internationalisation, as well as vehicles for reducing regional disparities and strengthening innovation capacity across Europe. The present study examines the manner in which joint study programmes developed within European university alliances contribute to both the academic integration of higher education institutions (HEIs) and the innovation performance of the regions in which they operate. Utilising a comprehensive set of data sourced from the EQAR (External Quality Assurance Results), ETER (European Tertiary Education Register) and the European Innovation Scoreboard databases, together with an illustrative contextual example from the Ulysseus European University alliance (with the Technical University of Košice as a member), this study employs analytical techniques encompassing spatial visualisation, clustering methods and statistical analysis. The primary objective of this integrated approach is to discern and identify patterns of collaboration and innovation across diverse geographical regions and countries. The findings of this study demonstrate that universities participating in alliances have a significantly higher number of joint study programmes, and that the innovation performance of a country is positively associated with the prevalence of such programmes. Concurrently, the findings suggest that alliances are not confined to high-innovation regions, but also extend to institutions in less innovative areas, thereby fostering cross-regional partnerships. The integration of human capital development with regional innovation ecosystems is facilitated by joint study programmes, which function as a strategic tool for balanced European integration. The study provides a foundation for further research on how European joint programmes can enhance the sustainability and competitiveness of both universities and regions. The study also offers policy-relevant insights on how university alliances can be leveraged not only as a mechanism for academic excellence but also as an instrument of cohesion policy, helping to spread knowledge, good practices and innovation capacity to less-developed regions. The study aligns with the journal's focus on regional innovation through European university alliances and joint programmes.*

Keywords: *Higher education networks, cross-border collaboration, knowledge transfer, institutional innovation, academic mobility.*

JEL Classification: *I23, O31, R11, O52, O57.*

APA Style Citation: Stefanikova, T., & Fedak, V. (2026). Fostering regional competitiveness through European joint study programmes: Insights from European university alliances. *E&M Economics and Management*, *29*(3), 150–164. https://doi.org/10.15240/tul/001/2026-3-008

Introduction

European higher education has undergone significant transformation over the past decade. The establishment of university alliances under the aegis of the European Universities Initiative has been identified as a leading instrument for the promotion of enhanced integration of higher education institutions (HEIs) across national borders. The primary objectives of these alliances encompass two key aspects: the internationalisation of education and the establishment of stronger connections between universities, regional businesses and communities. A significant outcome of this process is the establishment of joint study programmes, which facilitate the collaboration of curricula, teaching staff and students from multiple institutions and countries.

While there has been extensive discussion of joint programmes in the context of internationalisation, their potential contribution to regional development and innovation capacity has received far less scholarly attention. Existing studies have typically focused either on the international dimension of higher education or on measuring innovation performance at the national or regional level. However, there has been a paucity of research examining the interplay between the two. The present article addresses this gap by analysing how joint study programmes within European university alliances relate to the innovation performance of the regions in which they operate.

The study utilises data from the EQAR (European Quality Assurance Register for Higher Education) (EQAR, 2024), DEQAR (Database of External Quality Assurance Results) (DEQAR, 2024) and ETER (European Tertiary Education Register) (ETER, 2024) databases, the European Innovation Scoreboard (EIS, 2024), and a case study of the Ulysseus European University to identify patterns of collaboration and innovation across countries and regions. It develops hypotheses and provides an empirical basis for further research on how European joint programmes can enhance the sustainability and competitiveness of both universities and regions.

1 Theoretical background

In recent years, European higher education has undergone significant changes. Universities today increasingly collaborate with foreign universities and connect their capacities within European university alliances. One visible result of this cooperation is the creation of joint study programmes that link multiple universities from different countries, giving students the opportunity to study across borders, experience new approaches to education, and gain experience from various academic and cultural environments. Such programmes are often more flexible and better respond to the needs of today's world. They combine different fields of study, merge theory with practice, and create new opportunities for both students and teachers.

Joint study programmes represent an important indicator of the internationalisation of higher education institutions, as their implementation requires institutional cooperation, curriculum harmonisation, student mobility, and the involvement of multiple actors across countries. The creation of such programmes is often linked to the effort of universities to collaborate more effectively in addressing key regional and European challenges. In this context, joint programmes can be seen not only as a tool for internationalisation, but also as a means of supporting the innovation potential of regions through human capital and academic collaboration. As Charles (2006) emphasises, universities are playing an increasingly important role as centres of knowledge in regional innovation systems.

This article focuses on the question of what impact joint study programmes may have on the innovation performance of the regions where the participating universities operate. It is based on the idea that universities no longer function solely as places for education and research but are increasingly involved in the life of their surroundings. They cooperate with companies, local governments, and the nonprofit sector, often playing an important role in spreading new ideas, solutions, and technologies. Such involvement of universities in regional life enables them to explore new innovations that create links between research and practice, thereby contributing to the development of regional innovation ecosystems (Goenaga Beldarrain et al., 2018). Therefore, we are interested in whether and how this connection with the region can be strengthened precisely through joint programmes that arise within European university alliances.

The motivation for this research is to contribute to a better understanding of the links between educational innovations and regional development. The main research question (*RQ*) is therefore:

RQ: Is there a relationship between joint study programmes and the innovation activity of regions?

To answer this question, we work with data from the EQAR and ETER databases and analyse the case of a specific alliance, the Ulysseus European University. This article represents the first step in a broader research plan and serves as a basis for formulating hypotheses and designing the methodological framework for subsequent phases of the research.

As Europe places increasing emphasis on cross-country collaboration and the societal impact of education, university alliances are playing an increasingly important role in shaping and developing universities. Ulysseus European University is a European University Alliance launched in 2020 under the European Universities initiative, with its formal kick-off held on 17 December 2020 (Ulysseus European University, 2020). The alliance includes eight full member universities: the University of Seville (Spain), Université Côte d'Azur (France), the University of Genoa (Italy), the Technical University of Košice (Slovakia), MCI|The Entrepreneurial School (Austria), Haaga-Helia University of Applied Sciences (Finland), the University of Münster (Germany), and the University of Montenegro (Montenegro) (Ulysseus European University, 2024). In this paper, Ulysseus is referenced to provide contextual insight into the time- and coordination-intensity involved in developing joint study programmes, which is particularly relevant given TUKE's membership in the alliance (Ulysseus European University, 2024).

University alliances are no longer just about student exchange; there is a growing expectation that they will also contribute to building regional strategies, sharing innovations, and developing joint solutions to societal challenges. Their multidisciplinary and international nature creates space for universities to become active players in shaping regional policies, such as in the field of smart specialization. Their contribution is particularly important in strategic planning and the implementation of regional development strategies. In this way, universities help define priorities and transfer knowledge into practice (Jonkers et al., 2018).

In this particular context, there are several theoretical perspectives that are of particular utility in comprehending the evolving role of universities. The notion of a "Third Mission" in higher education underscores the dissemination of knowledge, technology, and societal engagement that extends beyond the conventional domains of teaching and research (Secundo et al., 2017). The knowledge spillover perspective emphasises how universities act as hubs of knowledge dissemination within regions (Kijek & Kijek, 2019). The mode 3/quadruple helix framework is a theoretical model that illustrates the multi-level interactions between universities, industry, government, and society at large. It provides a lens for understanding the complex, networked nature of higher education's contribution to innovation systems (Carayannis & Campbell, 2016).

The establishment of alliances within the European Universities Initiative (EUI) has opened up space for testing so-called "inter-university campus" formats, which connect teaching, mobility, research, and institutional governance within a single coordinated structure. In such models, joint study programmes play an important role as a practical way to bring long-term cooperation between universities to life, while also demonstrating how alliances can have a real impact on society. The evaluation of these impacts is increasingly shifting from purely academic metrics to assessing their influence on local communities, regional development, and environmental sustainability (Corazza et al., 2024).

At the same time, the approach universities take to internationalization is also changing, with an increasing emphasis on making the international dimension a natural part of teaching even without the need to travel abroad (de Wit & Altbach, 2021). When universities engage in international cooperation, they should also consider how to stay connected to the people and needs of their own regions. Joint study programmes can support this balance they allow universities to open up to the world and bring in global knowledge, while remaining rooted in local contexts and contributing to regional development (Jones et al., 2021). Joint programmes created within alliances enable students and teachers to participate in global knowledge networks without the necessity of physical relocation. This approach not only removes barriers but also promotes broader inclusion and the development of intercultural competencies across the entire spectrum of higher education.

It is also important to consider the practical aspects of implementing joint study programs. As shown by the case study of cooperation between the Technical University of Braunschweig and Vilnius Gediminas Technical University, the process of creating and accrediting such programs requires effective coordination among partners, harmonization of standards, and transparent administrative procedures (Hou et al., 2020). At the same time, the quality and international recognition of joint degrees have a crucial impact on their success and on how they can contribute to the development of the regions where the participating universities operate.

Finally, university alliances also serve as platforms for connecting the academic and social environments. Their potential to create value for the regions in which they operate lies in their ability to link educational innovations with the needs of communities, small and medium-sized enterprises, and local governments. It is precisely through joint study programs and initiatives focused on social impact that these alliances become active players in regional innovation ecosystems.

The emergence of European university alliances represents one of the key steps taken by the European Commission towards building a stronger, more interconnected, and more competitive European Education Area. Currently, there are 50 such alliances, bringing together more than 430 institutions from 35 countries, covering a wide geographical, cultural, and academic spectrum (European Commission, 2025).

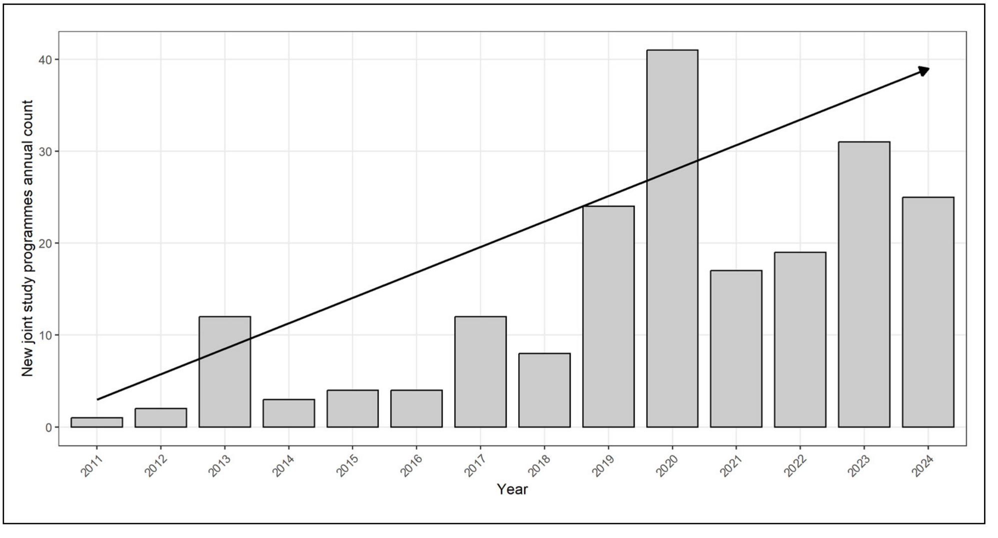

Fig. 1: Development of joint study programmes in Europe (annual counts 2010–2024)

Source: own based on ETER (2024)

Fig. 1 reports the annual number of newly established joint study programmes recorded across Europe over the last fifteen years. The early 2010s show relatively low year-to-year counts, whereas from around 2020 the annual number of newly established programmes increases markedly. This timing coincides with the launch of the first European University Alliances under the European Universities Initiative, suggesting an association between the new policy framework for structured inter-university cooperation and higher annual activity in joint programme development. Importantly, the figure should be interpreted as annual flow rather than a cumulative stock: fluctuations between consecutive years reflect changes in the number of programmes established in a given year, not the disappearance of previously existing programmes. Overall, the chart provides descriptive evidence of an acceleration in joint programme creation in the early 2020s and motivates further analysis of how alliance-based cooperation may relate to broader objectives such as curricular integration, mobility and regional impact.

The main goal of these alliances is to support long-term cross-border cooperation between universities, aimed at integrating European higher education, promoting shared values, increasing quality and inclusivity, as well as strengthening the sustainability and innovation potential of higher education institutions (European Commission, 2025). These goals reflect a broader shift in the understanding of the role of universities, which are no longer merely providers of education but also active drivers of social and economic change in the regions where they operate (Van Der Wende, 2002).

The main core objectives of establishing European university alliances can be summarized as follows. First, alliances aim to support the internationalisation of higher education. Through alliances, universities connect across countries and create joint programmes that strengthen student and academic mobility, develop intercultural understanding, and enable the acquisition of degrees with international recognition (de Wit & Deca, 2020; Vellamo et al., 2023). Such connections open universities to the outside world and make them more attractive to students and researchers from abroad.

Second, the alliances enhance the quality, competitiveness, and visibility of universities. The formation of alliances strengthens universities' ability to collaborate on research projects and share infrastructure and know-how, while better coordination among partners eases access to EU funding streams such as Erasmus+ and Horizon Europe (European Commission, 2025). Evidence from alliance cases also shows steps towards pooling research infrastructures and shared services (Lenkauskaitė, 2024). Third, the alliances increase social impact and foster stronger regional integration by creating conditions for more intensive collaboration with local stakeholders and territorial innovation ecosystems (e.g., living-lab and challenge-based formats). Joint programmes help attract international students and talent and are associated with stronger regional demand for services and knowledge; international mobility also improves graduates' international job profiles, strengthening local innovation capacity (Carrascal Incera et al., 2022; Knutsen et al., 2024). Fourth, alliances contribute to the development of flexible and interdisciplinary forms of education. Within alliances, new types of study programmes are emerging that combine disciplines across traditional fields and often include project-based learning, internships, or direct involvement in research and entrepreneurial initiatives. These forms of education better respond to the needs of the modern labour market (European Commission, 2025). Universities create value beyond teaching when they engage as core actors in regional innovation ecosystems and collaborate with business, public authorities, and civil society (Kozirog, 2022).

Finally, alliances promote European identity and shared values. European universities are not just academic institutions; within alliances, they become bearers of values such as cooperation, openness, and solidarity. Joint programmes reflect the effort to unify education standards while simultaneously supporting political and cultural integration (European Commission, 2025).

Alliances are not just a technical means for universities to collaborate; they are primarily a strategic instrument that helps transform higher education in Europe. They bring new opportunities to open universities to the world, strengthen their impact on society, and at the same time give them a stronger role in supporting innovation in the regions where they operate.

1.1 Advantages and disadvantages of creating joint study programs

In the context of these ambitions, it is important to consider the specific advantages and challenges that the creation of joint study programs brings for various stakeholders universities, companies, and regions. These programs not only support the internationalization of education but also become a means of connecting the academic sphere with the economic and social environment.

For higher education institutions, joint study programmes represent an opportunity to strengthen their academic attractiveness and visibility at the international level (de Wit & Altbach, 2021). They allow universities to share expertise, infrastructure, and know-how, thereby enhancing the quality of teaching and research (Esparza Masana & Woolford, 2023).

Such programmes can also open access to joint projects and international grants strengthening financial stability and enabling long-term cooperation while giving universities valuable experience with innovative governance models and curriculum internationalisation (de Wit & Altbach, 2021).

For companies, joint study programmes offer the opportunity to gain graduates with international experience, foreign language skills, and the ability to navigate global environments (de Wit & Altbach, 2021). Businesses have the chance to actively participate in designing and implementing these programmes, ensuring that they better meet labour market needs (Corazza et al., 2024). Through collaboration on internships, project assignments, and innovation activities, a close link is established between universities and companies, supporting the transfer of knowledge into practice and facilitating innovation both locally and globally.

For regions, the development of joint study programmes is an opportunity to strengthen their attractiveness and competitiveness (Vellamo et al., 2023). International students contribute to diversity and to regional economic activity through higher local demand for services and knowledge (Carrascal Incera et al., 2022), while university cooperation with local stakeholders can stimulate the emergence of innovation ecosystems (Esparza Masana & Woolford, 2023). Educational activities of alliances can be directly focused on supporting sustainable development and addressing specific regional challenges, thereby contributing to their long-term resilience (Corazza et al., 2024).

However, the creation and implementation of joint study programmes also bring significant challenges. For universities, these primarily include the need to harmonise curricula, ensure compatibility of credit systems, and manage complex accreditation processes (Hou et al., 2020). It also requires considerable administrative capacity and the ability to coordinate activities in the long term across different institutional and national frameworks (Esparza Masana & Woolford, 2023).

For companies, the time and organisational demands of collaboration with academia can be challenging, as well as the risk that the graduates' profiles may not fully meet their current needs (de Wit & Altbach, 2021). This requires close and continuous communication between the two sectors.

From the perspective of regions, it is crucial to ensure that the outputs of joint programmes genuinely contribute to local development and do not exclusively flow to global centres.

The growing importance of university alliances and joint study programmes in Europe shows that internationalisation no longer simply means students travelling abroad; it is gradually becoming an integral and essential part of the higher education system. Through deeper cooperation between universities and active connections between the academic and regional environments, new models of teaching and research are emerging that respond to the needs of modern society. Joint study programmes within alliances thus represent a concrete tool to support not only academic quality and attractiveness but also regional development and innovation performance.

However, the question remains to what extent these programmes truly contribute to increasing the innovation potential of the regions where universities operate. The key to a better understanding of these relationships lies in examining the connection between the development of joint study programmes and the innovation performance of regions. As highlighted by the Joint Research Centre of the European Commission, systematic assessment of the innovation impact of universities on regions is essential for formulating effective policies. Regional engagement of universities must be regarded as an important indicator of their performance, not as a secondary aspect (Esparza Masana & Woolford, 2023).

Therefore, the next phase of this research will focus on testing the main research question: *Is there a relationship between joint study programmes and the innovation activity of regions?* Through quantitative analysis of data from the EQAR, ETER, and European Innovation Scoreboard databases, as well as a case study of the Ulysseus European University alliance, we aim to identify patterns and relationships in this context and assess the real contribution of internationalised educational models to regional innovation ecosystems (EIS, 2024; EQAR, 2024; ETER, 2024; RIS, 2024).

2 Research methodology

In the empirical analysis, we worked with data from EQAR/DEQAR, ETER (2023, 2024) and the European Innovation Scoreboard (EIS 2024, 2025), which were linked at the university and country levels. From EQAR/DEQAR, we extracted information on joint study programmes and on universities' membership in European University Alliances. Based on these records, we constructed the key analytical variables: the number of joint study programmes, initially assigned to individual universities and subsequently aggregated to the country level; alliance membership as a binary variable (1 = the university is a member of an alliance, 0 = the university is not a member of an alliance); and the type of cooperation according to the innovation performance of the participating territories (high-high, high-low, low-low), which was used to analyse patterns of cooperation (DEQAR, 2024; EIS, 2024, 2025; EQAR, 2024; ETER, 2023, 2024; RIS, 2024)

From ETER (2023, 2024), we used the most recent identification and structural information on higher education institutions, in particular the list of universities by country and the attributes required for unambiguous linkage of institutions across databases (e.g., institutional identification and country assignment). At the start of the analysis, ETER 2023 was available and was subsequently updated to ETER 2024. Since no substantial changes were observed between these two versions in the key variables relevant to this study, both releases were used primarily to ensure data currency and to check the stability of results.

Country-level innovation performance indicators were taken from the European Innovation Scoreboard (EIS 2024, 2025). In the analysis, we used both a continuous country innovation performance indicator (innovation performance score) and the EIS categorisation of countries into innovation leaders, strong innovators, moderate innovators and emerging innovators. The time span of the joint study programme data used in this study covers the period 2020–2025 (EIS, 2024, 2025; EQAR, 2024; ETER, 2023, 2024; RIS, 2024)

Tab. 1 provides an overview of the hypotheses and the empirical strategy. To test the research hypotheses, we applied a combination of parametric (Welch's *t*-test, simple linear regression) and non-parametric (Spearman's rank correlation, the Kruskal-Wallis test, chi-square tests) statistical methods, with variables derived from EQAR/DEQAR, ETER and EIS. Welch's *t*-test was used to test *H1* by comparing the mean number of joint study programmes between universities involved in alliances and universities outside alliances; the number of programmes and alliance membership were taken from EQAR/DEQAR, while university identification and country assignment were based on ETER. To test *H2*, we used Spearman correlation to examine the relationship between country innovation performance (innovation performance score from EIS) and the number of joint programmes (EQAR/DEQAR), complemented by a simple linear regression in which the number of joint programmes was the dependent variable and innovation performance was the explanatory variable. Differences in joint programme intensity across groups of countries by innovation performance were analysed using the Kruskal-Wallis test; intensity was measured as the number of programmes aggregated to the country level based on EQAR/DEQAR, and country groups were defined according to the EIS categorisation. *H3* was tested using a chi-square test of independence examining the distribution of universities' alliance membership (EQAR/DEQAR) across countries with different levels of innovation performance (RIS categories), while the counts of universities in each country were taken from ETER. Finally, *H4* was tested using a chi-square test applied to a cross-tabulated count of cooperation types (high-high, high-low, low-low), derived from a combination of joint programme information from EQAR/DEQAR and innovation performance according to RIS (DEQAR, 2024; EIS, 2024, 2025; EQAR, 2024; ETER, 2023, 2024; RIS, 2024).

Tab. 1 specifies, for each hypothesis, the statistical test applied, the dependent and independent variables, the level of analysis, and the underlying data sources.

H1: Alliance membership increases likelihood of joint study programmes.

Test and variables: alliance membership (member vs. non-member; EQAR/DEQAR) and the number of joint study programmes per university (EQAR/DEQAR), with institutional identification and country assignment supported by ETER (DEQAR, 2024; EIS, 2024, 2025; EQAR, 2024; ETER, 2023, 2024; RIS, 2024).

H1 was tested using Welch's *t*-test comparing the mean number of joint programmes between alliance and non-alliance universities.

H2: Innovation performance of country correlates with number of joint study programmes.

Tab. 1: Overview of hypotheses, statistical tests, variables, and data sources

Hypothesis	Test	Dependent variable	Independent variable/ groups	Level of analysis	Data source
H1	Welch's *t*-test	Number of joint study programmes	University membership in an alliance (yes/no)	University	Joint programmes: DEQAR; alliances: DEQAR; institution identification: ETER 2023/2024
H2	Spearman correlation	Number of joint study programmes at country level	Country innovation performance (EIS score)	Country	Joint programmes: DEQAR; innovation: EIS 2024/2025
	Linear regression	Number of joint study programmes at country level	Country innovation performance (EIS score)	Country	Joint programmes: DEQAR; innovation: EIS 2024/2025
	Kruskal-Wallis test	Intensity of joint study programmes (number per country)	Country groups by EIS category	Country	Joint programmes: DEQAR; groups: EIS 2024/2025
H3	Chi-square test	Distribution of university alliance membership	Region innovation performance category	University	Alliances: DEQAR; innovation: RIS 2024/2025; universities: ETER
H4	Chi-square test	Type of collaboration (high-high/high-low/ low-low)	Innovation level of partner regions	Programme / partnership	Partnerships: DEQAR; innovation: RIS 2024/2025

Source: own

Tests and variables: country innovation performance was measured using the EIS innovation performance score and the EIS innovation performance groups (innovation leaders, strong innovators, moderate/emerging innovators). Joint programme activity was measured as the number of joint study programmes aggregated to the country level from EQAR/DEQAR records. *H2* was assessed using Spearman's rank correlation and complemented by a simple linear regression model, with the country-level number of joint programmes as the dependent variable and innovation performance as the explanatory variable. In addition, differences across innovation performance groups were examined using the Kruskal-Wallis test. Here, joint programme intensity was measured at the country level as the total number of joint study programmes aggregated for each country from the EQAR/DEQAR records (DEQAR, 2024; EIS, 2024, 2025; EQAR, 2024; ETER, 2023, 2024; RIS, 2024).

H3: Members of university alliances are unevenly distributed across regions with high and low innovation performance.

Test and variables: *H3* was tested using a chi-square test of independence applied to a cross-tabulated counts of universities' alliance membership status (member vs non-member; EQAR/DEQAR) with the innovation performance group of the university's region (RIS categories). The unit of analysis is the university; each university was assigned an RIS group based on its region. University counts by region (including non-alliance universities) were obtained from ETER (ETER, 2024).

H4: Universities from high-innovation regions are more likely to establish joint study programmes with each other within alliances.

Test and variables: cooperation types were derived by combining joint programme co-participation information (EQAR/DEQAR) with innovation performance categories (RIS) to classify collaborations as high-high, high-low, or low-low. *H4* was tested using a chi-square test applied to the cross-tabulated counts of cooperation types (EQAR, 2024).

Finally, regions were classified into three categories based on the Regional Innovation Scoreboard evaluation. Innovation leaders include countries with innovation performance above the EU average, strong innovators are those with innovation performance around the EU average, and moderate and emerging innovators represent countries with innovation performance below the EU average. This classification helped to better understand how a country's innovation performance relates to university activity in joint study programme development.

3 Results and discussion

3.1 Results

This section presents the main empirical results on the distribution and intensity of joint study programmes across Europe. We start with a descriptive overview of the temporal development of joint programmes, measured as annual counts of newly established programmes. The data show a clear increase from 2020 onwards. This rise coincides with the first wave of European University Alliances launched under the European Commission's European Universities Initiative; nevertheless, the observed overlap is descriptive and does not in itself imply a causal effect. Overall, the pattern suggests an acceleration in joint programme creation in the early 2020s, providing context for the subsequent spatial and statistical analyses. Based on the network visualisations, we constructed a country-level cooperation indicator derived from EQAR/ETER-linked records. First, we built an adjacency matrix for alliance member universities that have at least one joint study programme, and we mapped nodes by the cities in which these universities are located. A line between two nodes indicates co-participation in the same joint study programme. Joint study programmes are predominantly transnational rather than within-country, meaning that most lines connect universities located in different states. Importantly, a single joint programme may involve universities from two or more countries, which simultaneously generates multiple cross-border links (i.e., all pairwise connections among the participating institutions/cities): programmes involving three universities form closed triangular patterns, while programmes involving four universities generate closed four-node structures through pairwise links

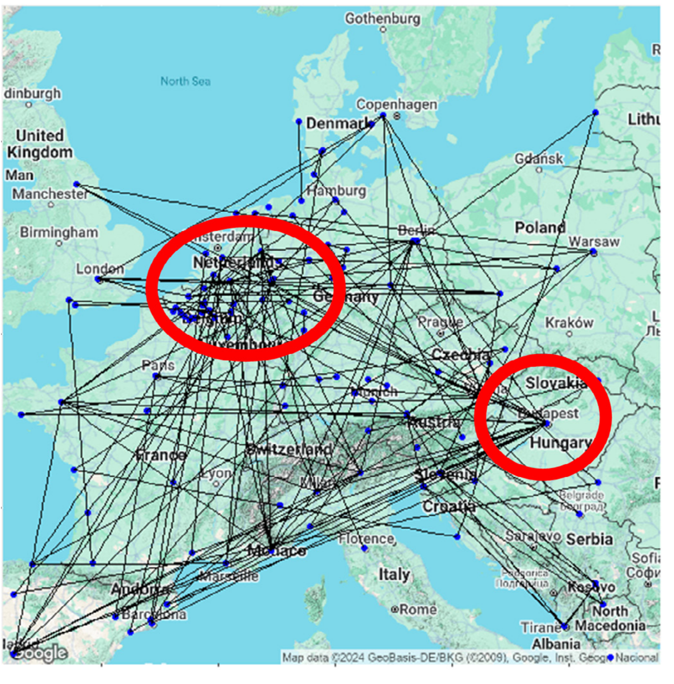

Fig. 2: Regional clusters in joint study programmes-map

Source: own based on ETER (2024) and EQAR (2024) among all partners. We then aggregated this university/city-level network to the country level by summing the cross-border links associated with institutions located in each country, yielding a measure of the intensity of international cooperation. The dense areas visible on the map (e.g., around Benelux/France/Germany and around Budapest) thus reflect higher concentrations of inter-university links, while the clustering results capture similarities in the underlying country-level cooperation indicators rather than mere geographic proximity.

***H1*: Alliance membership increases likelihood of joint study programmes**

To test *H1*, we applied Welch's *t*-test comparing the mean number of joint study programmes between universities that are members of European University Alliances and those that are not. The results indicate a statistically significant difference ($p < 0.01$), with alliance-member universities exhibiting a higher average number of joint programmes. This result is consistent with *H1* and suggests that alliance membership is associated with greater joint programme activity.

***H2*: Innovation performance of country correlates with number of joint study programmes**

To assess *H2*, we examined the relationship between countries' innovation performance and the country-level number of joint study programmes. Spearman's rank correlation revealed a positive and statistically significant association ($\rho = 0.61$, $p < 0.01$). This relationship was further supported by a simple linear regression, which showed that innovation performance is a significant predictor of the number of joint programmes ($\beta = 0.45$, $R^2 = 0.38$, $p < 0.01$). In addition, the Kruskal-Wallis test indicates statistically significant differences in joint programme intensity across innovation performance groups ($\chi^2 = 12.6$, df = 2, $p < 0.01$), with post-hoc comparisons showing that Innovation Leaders have significantly higher joint programme intensity than the other groups. Taken together, these results support *H2*.

Tab. 2: Testing hypotheses *H1* and *H2*

Hypothesis	Statistical test used	*p*-value	Result
H1: Alliance membership increases likelihood of joint study programmes	Welch's *t*-test	8.77×10^{-12}	Significant difference in average number of joint study programmes (alliances > non-members)
H2: Innovation performance of country correlates with number of joint study programmes	Spearman correlation	0.00025	Statistically significant positive correlation
	Simple linear regression	6.01×10^{-5}	Significant relationship, coefficient = 0.61
	Kruskal-Wallis test	6.4×10^{-7}	Statistically significant differences between innovation groups

Source: own

In summary, our findings strongly support both hypotheses, as shown in Tab. 2. Membership in European university alliances is associated with a greater likelihood of developing joint study programmes. Moreover, countries with higher innovation scores foster more academic partnerships at the international level. These results highlight joint programmes not only as a tool for internationalization but also as a strategic mechanism for strengthening regional development and innovation capacity within the European Higher Education Area.

H3: Members of university alliances are unevenly distributed across regions with high and low innovation performance

Based on the previous findings, we formulated hypothesis *H3*. This hypothesis builds on the assumption that high-innovation regions (e.g., research hubs in Western and Northern Europe) may dominate alliance membership. However, alliances are also expected to function as instruments of regional cohesion, connecting institutions from less innovative regions as well.

Based on the Regional Innovation Scoreboard, regions were classified into four main groups according to their innovation performance: emerging, moderate, strong, and leader. This categorization is derived from an innovation score index that includes indicators such as research activity, number of patents, public-private collaboration, and the level of digital transformation. For the purposes of our analysis, we simplified this classification regions labelled as leader were grouped under high innovation regions, while regions categorized as emerging and moderate were combined into the low innovation regions group. This dichotomy enabled us to test for disparities in the presence of universities participating in alliances across high- and low-innovation regions. To test this hypothesis, we used regional data from the Regional Innovation Scoreboard (RIS) and identified institutions involved in alliances based on the DEQAR database, focusing exclusively on alliance members. Regions were classified into two categories based on their innovation performance: high (leaders) and low (emerging + moderate). We then conducted a chi-squared test of independence to evaluate the relationship between innovation performance and the presence of alliance member institutions.

The results showed a clear overrepresentation of alliance members in low-innovation regions. The chi-squared test confirmed that this distribution is not random ($X^2 = 5{,}942.4$, df = 1, $p < 0.001$), indicating a statistically significant imbalance.

The results show that university alliances do not group together only institutions from more innovative regions of Europe (Tab. 3). On the contrary, a large share of their members comes from less-developed areas. This suggests that alliances may play an important role in connecting stronger and weaker regions, thereby helping to reduce disparities not only in research and innovation, but also in higher education. In this way, they can contribute to greater regional balance across Europe.

Tab. 3: Testing hypothesis *H3*

Hypothesis	Statistical test used	*p*-value	Result
H3: Members of university alliances are unevenly distributed across regions with high and low innovation performance	Chi-squared test	$p < 0.001$	Significant association; more alliance members in low-innovation regions

Source: own

H4*: *Universities from high-innovation regions are more likely to establish joint study programmes with each other within alliances

Building on the previous findings, we introduced a *H4*. To test this hypothesis, pairs of universities participating in the same joint programmes were created and categorized according to the innovation performance of their regions: high-high (both universities from high-innovation regions), low-low (both from low-innovation regions), and high-low (mixed pairs). A chi-squared test was then applied to examine whether the distribution of pairs across these categories was random or systematic.

Tab. 4: Testing hypothesis *H4*

Hypothesis	Statistical test used	*p*-value	Result
H4: Universities from high-innovation regions are more likely to establish joint study programmes with each other within alliances	Chi-squared test	$p < 2.2e^{-16}$	Universities from high-innovation regions do not form the largest number of joint programmes among themselves

Source: own

The results showed that most joint programmes are created between universities from different regions (high-low: 9,553,099 pairs), followed by low-low (7,851,268 pairs), with the fewest being high-high pairs (3,791,513). The chi-squared test was highly statistically significant ($p < 2.2e^{-16}$), confirming that the differences between categories are not random.

In conclusion, the hypothesis was not confirmed as we can see in Tab. 4. Universities from high-innovation regions do not form the largest number of joint programmes among themselves. On the contrary, the dominant pattern is collaboration between universities from regions with different levels of innovation performance (high-low). This finding suggests that university alliances may serve as a mechanism for connecting stronger and weaker regions, thereby helping to reduce disparities in innovation capacity and supporting a more balanced development of the European Higher Education Area.

3.2 Discussion

Our findings show that joint study programmes within European university alliances are not only about internationalisation but also play a key role in knowledge transfer, strengthening human capital, and building regional innovation ecosystems. Recent work shows the same pattern, membership in European University Alliances brings more structured, long-term collaboration via shared platforms and designed curricula, which strengthens universities roles in regional innovation ecosystems (Zenkiene & Leišytė, 2024). We drew on theoretical frameworks such as the universities' "Third Mission" (Secundo et al., 2017), the concept of knowledge spillovers (Kijek & Kijek, 2019), and the mode 3/quadruple helix model (Carayannis & Campbell, 2016), all of which emphasise the connection of universities with businesses, public administration, and communities. In line with this, European HEIs are moving from isolated, short-term efforts to ongoing organised ecosystem services brokering partnership, co-designing training and sharing infrastructure (Compagnucci & Spigarelli, 2024). Our data show that joint study programmes are exactly this kind of practical mechanism.

Universities that are members of alliances may develop more joint study programmes for several practical reasons. Alliances provide stable partner networks and basic coordination structures, which makes it easier to agree on programme content, share responsibilities, and navigate approval or accreditation processes. Alliance participation may also improve access to European funding and internal institutional support, reducing the time and resources needed to develop joint programmes. In addition, being part of an alliance can increase international visibility, which strengthens incentives to offer joint programmes as part of an internationalisation strategy. Finally, universities located in stronger innovation environments often have greater capacity and experience, which can help them initiate and sustain more complex cross-border educational cooperation. These explanations are consistent with our findings; however, given the observational design, the results should not be interpreted as causal evidence. Based on this perspective, we examined whether universities participating in alliances have more joint programmes and whether countries with higher innovation performance have more universities involved in alliances. Our statistical analyses confirmed these assumptions: universities in alliances have, on average, significantly more joint programmes than other institutions, and there is a clear relationship between a country's innovation performance and the number of such programmes. This adds a quantitative confirmation at the system level to findings from case studies and qualitative research, that alliance participation goes hand in hand with deeper curricular integration and shared collaboration platforms (Zenkiene & Leišytė, 2024) and shows that joint study programmes are a concrete vehicle for this shift (Compagnucci & Spigarelli, 2024). We also found that Europe's innovation leaders have statistically significantly more joint programmes than countries with weaker innovation performance. This aligns with recent evidence on capacity differences: stronger systems use alliances to scale links between research, education and innovation, while weaker systems need targeted support to achieve similar benefits (Zenkiene & Leišytė, 2024).

Our hypotheses testing confirmed that universities participating in alliances have significantly more joint programmes (*H1*), countries with higher innovation performance have more universities involved in alliances and more joint programmes (*H2*), alliance members are not concentrated only in highly innovative countries but also to a large extent in less developed areas (*H3*), and the most common cooperation model is high-low, i.e., linking universities from regions with different levels of innovation performance rather than only high-high (*H4*). Studies show that alliances act like "communities of practice" reach less-developed regions and use local formats such as living labs to engage stakeholders. This aligns with our evidence. Members are not only in leading regions and high-low cooperation dominates (Palmowski, 2025). We quantify these patterns at the system level and show they are statistically significant.

These results suggest that joint programmes within alliances could be used much more actively as a policy tool for regional development and for reducing disparities between regions. On this basis, we recommend supporting knowledge transfer between regions, since joint programmes demonstrably link stronger and weaker regions. EU and national policies should deliberately use these programmes as a tool of regional cohesion and disparity reduction, for example by supporting high-low partnership projects. Removing barriers is also crucial, because the most common cooperation model is not only high-high but also high-low, and it is even more important to harmonise accreditation and legislative frameworks so that less-developed regions can participate in joint programmes on an equal footing. Furthermore, it is essential to link these programmes with practice by introducing funding mechanisms that support the involvement of local businesses, municipalities, and civil society in joint programmes, thereby increasing their direct regional impact. Another recommendation is to strengthen monitoring and evaluation by incorporating indicators tracking the regional impact of joint programmes and alliances into European frameworks such as the EIS and RIS to identify which forms of cooperation best contribute to reducing regional disparities. Finally, more stable funding is needed to ensure long-term sustainability of programmes and to create mechanisms that do not depend solely on short-term projects. Overall, these steps align with recent calls to move from isolated projects to stable ecosystem based cooperation and to use alliances as platforms for spreading good practice from leading to less-developed regions (Compagnucci & Spigarelli, 2024; Palmowski, 2025; Zenkiene & Leišytė, 2024).

If these recommendations are implemented, European university alliances will be able to fulfil their "Third Mission" even more effectively, acting as hubs of knowledge dissemination and supporting not only the internationalisation of higher education but also balanced regional development, innovation, and sustainable growth in Europe.

Conclusions

In conclusion, the results indicate that alliance membership is associated with higher joint programme activity, and that joint programme activity is positively linked to innovation performance. Moreover, the results suggest that alliances and joint programmes often bring together universities from regions with different levels of innovation within the European Higher Education Area. This highlights joint programmes as a practical way for structured inter-university cooperation to support regional innovation and strengthen territorial cohesion.

Based on the conducted analyses, the findings for each hypothesis can be summarized as follows.

Hypothesis 1 (*H1*) assumed that membership in university alliances increases the likelihood of creating joint study programmes. The results of Welch's *t*-test confirmed a significant difference in the average number of joint programmes between member and non-member universities, with alliances showing higher values. This means that alliance membership indeed fosters more intensive collaboration through joint programmes.

Hypothesis 2 (*H2*) examined whether a country's innovation performance correlates with the number of joint study programmes. Several statistical tests (Spearman correlation, linear regression, Kruskal-Wallis test) indicated statistically significant positive relationship. This suggests that in countries with higher innovation performance, the number of joint programmes is also greater, although the effect is not very strong.

Hypothesis 3 (*H3*) assumed that members of university alliances are unevenly distributed across regions with high and low innovation performance. The chi-squared test confirmed a significant association, with the results showing that alliances have more members in low-innovation regions. This indicates that alliances may contribute to strengthening less developed areas and are not exclusively concentrated in high-performing regions.

Hypothesis 4 (*H4*) tested the assumption that universities from high-innovation regions would form more joint programmes among themselves. However, the analysis of university pairs by innovation performance showed the opposite – the most frequent pattern of collaboration was between mixed pairs from high- and low-innovation regions (high-low), followed by low-low, and the fewest were high-high. The chi-squared test confirmed that these differences are not random. Thus, the hypothesis was not supported, and the results suggest that alliances function more as a mechanism for linking regions with different levels of innovation capacity.

Overall, it can be concluded that university alliances significantly support the creation of joint study programmes, and their functioning is not based exclusively on cooperation among high-innovation regions, but rather on connecting diverse regions and universities. This finding indicates that alliances are not only internally important for the participating institutions but also play a crucial role in the broader European context, as they contribute to reducing disparities in innovation performance across regions.

In this way, alliances represent a mechanism that can promote balanced development of higher education in Europe, not only through academic collaboration but also as part of regional and innovation policy. The creation of joint programmes between universities from high- and low-innovation regions suggests that there is a transfer of knowledge, experience, and good practices, which can strengthen the ability of less developed regions to participate in international educational and research initiatives.

These findings open space for discussion on the long-term sustainability of alliances and their strategic role. On the one hand, they can function as a tool of internationalization and prestige enhancement for the participating universities, while on the other hand, they can serve as an instrument of cohesion policy, supporting the reduction of disparities between regions. From a practical perspective, it is therefore important that policymakers and universities perceive alliances not only as a means of cooperation but also as a tool for strengthening the European integration and innovation space.

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Urban vulnerability to extreme heat: An assessment of Slovak cities

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Abstract: *Although cities are now home to more than half of the world's population, these concentrations of people, assets, and economic activities are subject to increasing risks as the consequences of climate change begin to take effect. As a result, the concept of urban vulnerability has gained renewed prominence in academic discourse and policy discussion, as it is a crucial means of understanding and addressing the impacts of climate change on cities. Within this context, the paper focuses on urban vulnerability and examines how it can be measured and evaluated in a comprehensive and systematic manner. The research focuses on a climate-related hazard which is particularly salient in urban environments – heatwaves. We present a composite index that incorporates climate, land-cover, socio-economic and governance indicators to provide a comprehensive assessment of the vulnerability of various Slovak cities to extreme heat conditions. The study applies robust quantitative methods and integrates three different methodological approaches to develop a final database outlining 15 partial indicators for 141 Slovak cities. The contribution of the paper lies in the methodological framework that proposes assessing urban vulnerability to heatwaves, but the research also has a practical application; the results identify the Slovak cities which are most vulnerable to extreme heat conditions, providing evidence-based data which can be used by decision-makers to formulate informed and targeted risk-assessment policies and climate adaptation measures.*

Keywords: *Composite index, heatwaves, urban planning, resilience assessment, local policy.*

JEL Classification: *R58, Q54.*

APA Style Citation: Toth, V. Sebova, M., & Saboslajova, T. (2026). Urban vulnerability to extreme heat: An assessment of Slovak cities. *E&M Economics and Management*, *29*(3), 165–183. https://doi.org/10.15240/tul/001/2026-3-009

Introduction

Cities will emerge as key actors in climate mitigation efforts, as various sectors that are crucial for urban stability face increasing impacts as the effects of climate change take hold (Scholze et al., 2023). The precise ways in which climate change manifests itself in specific cities depend on multiple factors, including buildings and their capacity for thermal storage, the ratio of permeable and impermeable surfaces, the prevalence of green areas, wind tunnels, and the impact of shading, radiation, trees and terrain on ambient temperatures (Yang et al., 2023). As a result, various microclimatic phenomena can occur in cities, most prominently so-called urban heat islands (UHI), urbanized areas with higher temperatures than their rural surroundings.

Hot and dry urban environments can have a harmful impact on human health, urban ecosystems, and economic activity. Heatwaves can cause substantial heat-related mortality (Ballester et al., 2023; Robine et al., 2008; Výberči et al., 2015), although their impact varies across European cities. While people in Northern Europe are more sensitive to heat, the thresholds at which heat-related mortality begins to increase, tend to be higher in cities with higher average temperatures (Baccini et al., 2011; Gosling et al., 2007). This suggests that acclimatization to higher temperatures is, at least to some degree, possible, and acclimatization and adaptation strategies aimed at reducing urban vulnerability to heat stress have already been observed in Finland and the United Kingdom (Arbuthnott et al., 2020; Ruuhela et al., 2017).

Climate change will likely impact different groups of urban residents disproportionally. There is unambiguous evidence of higher heat-related mortality among the elderly, especially those suffering from cardiovascular, respiratory, or renal diseases and mental health issues (EEA, 2020). Women are also more vulnerable than men, as they are less able to respond to heat stress because of their reduced sweating capacity and greater likelihood of living alone (D'Ippoliti et al., 2010). Other studies have indicated that low birth weight may be linked to air pollution and heat exposure (Dadvand et al., 2014).

The direct impacts of heat on urban infrastructure are generally less severe compared with precipitation-related hazards such as flooding, although elevated temperatures can still affect transport systems and infrastructure performance (Christodoulou & Demirel, 2018).

Efforts to address climate change in urban policies can be focused either on mitigation, essentially on reducing the magnitude of the changes, or on adaptation strategies that seek to minimize the harmful impacts and maximize the beneficial aspects (Aboagye & Ayyoob, 2024). Reactive adaptation is executed ex-post and proactive adaptation is prepared ex-ante as part of a wider effort to reduce vulnerability or take advantage of the forthcoming changes (Mehryar et al., 2022). While the costs of adaptation measures are immediate, their benefits might take longer to materialize.

In general, Central European cities are expected to face both higher frequencies of heatwave days and higher heatwave maximum temperatures. Slovak cities are no exception in this respect (OECD, 2023), and the main focus of our analysis is therefore the vulnerability of various urban centers in Slovakia to extreme heat. The study will set up a framework for a comprehensive assessment of urban vulnerability and identify the most vulnerable cities in Slovakia.

Our paper is organized as follows. Section 1 provides the contextual background and reviews the relevant literature on urban vulnerability and its measurement. Section 2 presents the data, describes the selection of indicators, and outlines the methodological framework applied in the study. Section 3 introduces and compares the three approaches used to construct the composite indices and displays the main empirical findings. The final section concludes by discussing the results and highlighting the policy implications for climate adaptation planning.

1 Theoretical background

1.1 Urban vulnerability

Vulnerability and resilience are the two core concepts that frame contemporary urban climate research. According to the widely cited definition by Meerow et al. (2016), urban resilience refers to the ability of an urban system and its interconnected socio-ecological and socio-technical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to transform systems that constrain current or future adaptive capacity. This definition underscores the fact that resilience is not merely the capacity to “bounce back”; in many cases, a return to the pre-shock state may be undesirable if existing systems already contain structural inequalities or environmental degradation. Cities should therefore be understood as complex adaptive systems capable of reorganization, learning and transformation.

Building on these insights, Amirzadeh et al. (2022) propose a conceptual framework of urban resilience that highlights the dynamic interactions among exposure, urban functions, system performance and adaptive responses. Their framework emphasizes that resilience emerges from the continuous interplay between physical infrastructure, social systems, governance structures and environmental processes. More importantly, it recognizes the impact of feedback loops and non-linear dynamics, reinforcing the idea that resilience is a multidimensional and evolving property of urban systems. This perspective complements the complex-systems understanding of cities and further supports the need for integrated, cross-sectoral approaches to assessing and building urban resilience.

Vulnerability can be considered as a counterpart to resilience. Evidence from the VulneraCity project (Stolte et al., 2024), which identified 1,460 vulnerability drivers reported in over 400 articles, highlights the multi-layered and dynamic nature of vulnerability, which stems from a wide set of physical, social, economic, institutional and behavioural drivers that interact in non-linear and sometimes contradictory ways. Research into territorial disparities demonstrates that peripherality is closely associated with higher levels of vulnerability, as peripheral regions typically face structural disadvantages such as weaker economic bases, limited accessibility and lower institutional capacity (Bănică et al., 2024).

A widely used framework for vulnerability was developed through the Intergovernmental Panel on Climate Change (IPCC). This structure conceptualizes vulnerability as a function of exposure, sensitivity and adaptive capacity, and the conceptual clarity and practicality of this framework mean that it has seen widespread use in research in the field (BMZ, 2017; Estoque et al., 2023).

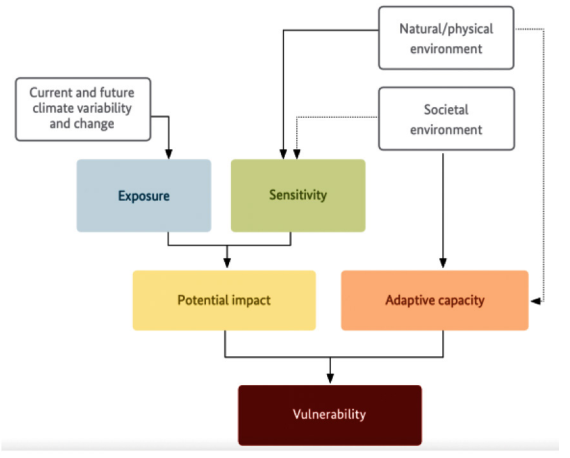

Fig. 1: Conceptualization of vulnerability

Source: BMZ (2017)

Urban resilience and vulnerability research often builds on the four-pillar framework which emphasizes the social, economic, environmental, and governance dimensions of sustainability in urban systems (Fajardo-Gonzalez et al., 2025). These pillars reflect the multiple pathways through which climate impacts are manifested: i) social characteristics shape sensitivity to hazards, economic resources determine adaptation potential; ii) environmental structures influence exposure and microclimatic effects; and iii) governance shapes collective responses and long-term planning capacity. Empirical studies highlight the fact that weak institutional capacity and fragmented governance structures often hamper cities' ability to prepare for or respond to climate risks. The governance dimension is strongly influenced by institutional quality, multilevel governance interactions, and the capacity for strategic planning, management and policy implementation (Birchall et al., 2025). The institutional dimension can make a difference, however, and even larger cities that face higher exposure could be subject to lower overall vulnerability if they implement more comprehensive and better-integrated adaptation strategies (Farkas et al., 2024). This aspect also envisages greater involvement of local citizens in policy-making. The social pillar integrates issues such as climate justice and inequality, with appropriate consideration of these factors, ensuring that inappropriate mitigation policies can be avoided (Markkanen & Anger-Kraavi, 2019).

Vulnerability and resilience are deeply interconnected but they are also conceptually distinct. Vulnerability is shaped by dynamic and multi-dimensional drivers, while resilience reflects the capacity of urban systems to absorb, adapt and transform themselves in the face of climate shocks.

1.2 Heat vulnerability indices

Tab. 1 shows a selection of academic papers that have formulated heat vulnerability indices (with a single exception addressing climate change vulnerability more broadly), which assess vulnerability at the global, national or local scale. Vulnerability to heat can be generally conceptualized as “a function of exposure to heat and the sensitivity of people” (Wolf & McGregor, 2013). Exposure is linked to area-based risk factors (such as high population density, temperature or green spaces), while sensitivity is determined by individual characteristics as for example age, gender, health condition, immigration background, income or social network (Räsänen et al., 2019).

The methodological approach used in the majority of the studies is principal components analysis (PCA), reflecting its ability to generate indicator weights endogenously, a particularly valuable characteristic when striving for objectivity. Expert-derived weights can be seen as subjective, especially when only a small number of experts are involved, but this can be mitigated by consulting a panel of experts, as was used in the study by Räsänen et al. (2019).

Another method for addressing the issue of reliable weighting is the benefit-of-the-doubt approach applied by methods such as data envelopment analysis (DEA) (Edmonds et al. 2020). This approach allows each entity to have its own set of optimal indicator weights, thereby enabling country-specific scores that better reflect their specific context. Uncertainties in model structures or indicator selection are addressed in some studies by comparing the index with an outcome variable, such as heat-related mortality (Kim et al., 2017).

Studies from Central and Eastern Europe highlight the importance of environmental exposure, socio-economic disparities, and adaptive capacity, emphasizing the need for context-sensitive vulnerability assessments (Farkas et al., 2024; Fekete et al., 2025).

The reviewed studies predominantly focus on large metropolitan areas, highlighting the need for vulnerability assessment frameworks applicable to medium-sized and smaller cities.

Tab. 1: Literature review of heat vulnerability indices

Year	Author(s)	Method	Area
2013	Wolf & McGregor	PCA	London
2016	Inostroza et al.	PCA	Santiago, Chile
2016	Macnee & Tokai	PCA	Osaka
2017	Kim et al.	Regression	Korea
2018	Nayak et al.	PCA	New York State
2018	Méndez-Lázaro et al.	PCA	Puerto Rico
2019	Räsänen et al.	Expert panel weighting	Helsinki
2020	Edmonds et al.*	DEA	Global
2021	Wang et al.	PCA + validation	China
2022	Chen et al.	PCA	Taipei

Note: * Addresses general climate change vulnerability, not heat-specific issues.

Source: own

1.3 Conceptual framework for urban heat vulnerability assessment

In this study, we adopted a simple, non-hierarchical framework of climate change vulnerability, which drew primarily on the IPCC-based conceptualization described by Estoque et al. (2023). This framework perceives vulnerability as a function of three core components: exposure, sensitivity, and adaptive capacity.

In order to operationalize these conceptual components at the urban level, the empirical structure of the index was organized around four broader analytical dimensions derived from the four-pillar framework of sustainable cities (Fajardo-Gonzales et al., 2025; Gursoy Haksevenler et al., 2025): climate hazard, land cover, socio-economic context, and governance-related factors. The original four-pillar framework also includes social development, economic development, environmental management, and urban governance, but these were combined into a single socio-economic dimension given the close interconnections between social and economic aspects in the context of urban vulnerability. In addition, a separate climate hazard dimension was incorporated in order to explicitly capture exposure to extreme heat.

While the conceptual framework is thus based on the three-component IPCC understanding of vulnerability, the empirical dimensions represent a series of broader operational categories by which these components can be measured. Their relationship to the underlying vulnerability framework is summarized in Tab. 2.

The framework expands upon earlier OECD-oriented approaches in terms of their adaptation to city-level analysis and the incorporation of locally relevant governance-related proxy indicators reflecting behavioural and civic dimensions of adaptive capacity.

Tab. 2: Relationships between empirical dimensions and vulnerability components

Empirical dimension	Vulnerability component	Interpretation
Climate hazard	Exposure	Represents current and projected exposure to extreme heat
Land cover	Exposure/sensitivity	Reflects physical urban characteristics influencing heat accumulation
Socio-economic context	Sensitivity/adaptive capacity	Depicts demographic and economic vulnerability
Governance and civic engagement	Adaptive capacity	Reflects behavioural and civic conditions potentially associated with adaptation

Source: own

2 Data and methods

The selection of indicators was informed by previously published urban heat vulnerability studies and broader vulnerability assessment frameworks identified in the relevant literature. In particular, the selection process was guided by studies emphasizing climatic exposure, demographic sensitivity, land-cover characteristics, socio-economic disadvantage, and adaptive capacity as key determinants of urban heat vulnerability (Nayak et al., 2018; OECD, 2023; Wang et al., 2021; Wolf & McGregor, 2013). The indicators used in this analysis reflect four crucial dimensions of urban heat vulnerability: climate hazard, physical environment, socio-economic context, and governance and civic engagement. The selection of indicators was also influenced by the discourse on social equity in urban resilience planning, as outlined in Meerow et al. (2016). In particular, the framework aimed to account for vulnerable population groups, socio-economic disadvantage, and forms of civic participation potentially associated with adaptive capacity.

The selection of variables was also guided by the availability for all 141 Slovak cities, resulting in a complete dataset with no missing values and no need for imputation. Second, indicators were required to exhibit sufficient variability to distinguish different levels of vulnerability across cities.

Although previous studies often include health-related indicators such as heat-related

Tab. 3: Indicators

Area	Indicator	Description	Direction	Data source
Climate hazard	Current extreme heat (days)	Average number of tropical heat days (1991–2020)	Positive	SHMI
	Current extreme heat (nights)	Average number of tropical heat nights (1991–2020)	Positive	SHMI
	Future extreme heat (health definition)	Average heat increase in days (between decades 2016–2025 and 2046-2055) in RCP 4.5 scenario (health definition)	Positive	Copernicus
	Future extreme heat (climatological definition)	Average heat increase in days (between decades 2016–2025 and 2046–2055) in RCP 4.5 scenario (climatological definition)	Positive	Copernicus
Land cover	Tree cover density	Share of land covered by trees (reference period: 2018)	Negative	Copernicus
	Impermeable surfaces	Share of land covered by impermeable surfaces (reference period: 2018)	Positive	Copernicus
	Water surfaces	Share of land covered by water bodies (reference period: 2018)	Negative	Copernicus
Socio-economic context	Population density	Population per inhabited area (reference period: 2019)	Positive	IEP (not published)
	Vulnerable population	Share of people who are below 4 or over 70 years old (reference period: 2021)	Positive	SOSR, 2021 Population and Housing Census
	Unemployment rate	Unemployment rate (reference period: 2021)	Positive	SOSR
	Municipal income	Municipal income per capita (reference period: 2021)	Negative	IEP
	Healthcare	Travel distance to the nearest hospital (reference period: 2022)	Positive	IEP
Governance and civic engagement	Environmental policy (support index)	Weighted average of number of votes for 8 political parties (weights attributed based on their environmental programs in 2023)	Negative	SOSR, Klíma ťa potrebuje
	Local elections participation	Participation rate in municipal elections in 2022	Negative	SOSR
	Waste sorting	The share of municipal waste being sorted for recycling (reference period: 2022)	Negative	IEP (not published)

Source: own

mortality or morbidity, comparable city-level health outcome data for Slovak municipalities were not systematically available and therefore could not be incorporated into the analysis.

The final database includes 15 partial indicators for each of the 141 Slovak cities. The list of indicators and their descriptions is shown in Tab. 3.

2.1 Climate hazard

We included two indicators related to past extreme heat conditions and two indicators reflecting predicted future heat hazards. The first of these shows the average number of tropical days and tropical nights per year measured over the period 1991–2020. Tropical days are defined as days on which the air temperature reached at least 30 °C, while tropical nights are nights on which the temperature did not fall below 20 °C. Future developments were predicted based on the RCP 4.5 scenario, which represents a middle pathway between RCP 2.6 and RCP 8.5. Instead of taking the raw predictions, we applied a transformation that reflects how conditions are expected to change relative to the baseline. This magnitude of change is calculated as the difference between average values for two time periods: 2016–2025 and 2046–2055. The definitions of heat to address both climatological and health-related aspects of this hazard are based on OECD (2023).

2.2 Physical environment

The degree to which climate hazards are manifested in a particular city depends heavily on the characteristics of its physical environment. We selected three indicators that are both easily available and relevant for assessing extreme heat in urban areas. The first of these is tree cover as a percentage of the total area; since green infrastructure contributes to improved microclimatic conditions, cities with a higher proportion of tree-covered land are considered to be less vulnerable to heat. A similar role is played by water bodies, so this second indicator was also measured as a percentage of total area. The third indicator is the share of impermeable surfaces. These surfaces intensify heat accumulation and prevent water absorption, making cities even hotter and more vulnerable to extreme heat.

2.3 Socio-economic context

A fuller understanding of the socio-economic and demographic context is crucial when assessing climate change adaptation (Räsanen, 2019), and the five indicators that we selected for the analysis were intended to capture both sensitivity and adaptive capacity. The first indicator is population density; although this is generally higher in cities than in rural areas, significant differences still exist in the case of Slovak cities. Population density is used here to refer only to inhabited areas (i.e., areas with registered permanent residents) rather than the entire municipal district. Cities with higher population density require more comprehensive protection from the impact of climate change, but initiatives in these areas are also more cost-effective as a greater number of people will benefit from the implemented measures. The second indicator is the proportion of vulnerable population groups. These are primarily judged on the basis of age, with citizens of four years and under and 70 and over being seen as most at risk. The third indicator is the unemployment rate, an indicator that relates to both sensitivity and adaptive capacity. Unemployed individuals may be adversely affected by climate change, if, for example, they rely on seasonal agricultural work, a sector that may become more precarious over time. Low-income households also tend to be less adaptive, as their reduced financial means limit their ability to adopt costly adaptation measures. The fourth indicator is municipal income per capita, a statistic that reflects a city's ability to cope with unexpected crises requiring substantial financial resources, as well as its capacity to engage in long-term planning and the implementation of proactive adaptation measures. The fifth indicator is the travel distance to the nearest hospital. Access to healthcare is essential during heatwaves, especially for the most vulnerable segments of a city's population.

2.4 Governance and civic engagement

The governance dimension in this study is operationalized through indirect proxy indicators reflecting civic participation, environmental behaviour, and climate-related political preferences. These indicators should therefore be interpreted with a degree of caution, as they are more suited for capturing broader socio-political

Tab. 4: Party scores

Party	Score
PS	94.74
Demokrati	90.20
SAS	66.77
KDH	54.48
OĽANO	52.18
Sme rodina	33.02
Smer	32.02
Hlas	NA – 32.02

Source: Klíma ťa potrebuje (2023)

and behavioural orientations rather than providing direct measures of institutional quality, adaptation planning capacity, or policy effectiveness.

Nevertheless, governance remains an important dimension of climate adaptation, as adaptive capacity is closely linked not only to formal institutions, but also to other factors, such as civic engagement, environmental awareness, and public support for climate-related policies. The first variable is the environmental policy support index, which reflects environmental values and climate-policy preferences as expressed through electoral behaviour. The index is calculated as a weighted average of votes cast for eight political parties in the 2023 parliamentary elections. The weights are based on an evaluation of each party's environmental programme conducted by the NGO Klíma ťa potrebuje ("Climate Needs You"). The project titled #VolímKlímu ("I vote for climate") evaluated party platforms related to climate and environmental policy and assigned scores according to the strength of the proposed climate measures (Tab. 4).

The second indicator measures levels of civic engagement within cities by examining the participation rate in the most recent local elections. Participation in local elections can reflect the degree of civic engagement, local political participation, and the willingness of citizens to engage in collective public issues which may indirectly support local adaptive capacity (Hornsey et al., 2016). The third indicator is the share of municipal waste separated for recycling. This variable relates to broader environmental behaviours and civic participation in environmentally oriented practices at the local level. Although not directly related to the topic of heat adaptation, it may serve as an indirect proxy for pro-environmental orientation and collective engagement in sustainability-related activities.

2.5 Creating the index

The general methodological approach used in this study follows the widely accepted approach based on OECD (2008). The specific methodology applied in this case closely mirrors the approach used in the OECD's 2023 study on climate adaptation in Slovakia (OECD, 2023).

Variables for the index were selected based on their relevance and data availability. The number of indicators was set between three and five, a number that allowed for meaningful complexity while remaining clear and concise. In the case of indicators that provided data that were not in a format compatible with the remainder of the dataset, the findings were transformed, reconstructed, or adjusted to a comparable scale; for example, municipal income was converted to per capita terms to ensure compatibility with the other indicators.

In some cases, however, no data were available at the desired scale or at the required level of granularity, and it was necessary to use proxy variables to approximate the original concept. For example, citizen engagement in climate-friendly action is an important component of assessing adaptive capacity, but no direct data exists for Slovak cities, and, therefore, the degree of municipal waste sorting was applied as a proxy indicator. Another example is the use of electoral results combined with an assessment of parties' environmental policy proposals to give an indication of the values held by residents.

Since our indicators use different units and scales, we made them comparable by applying min-max normalization. In the analysis, we applied three methods: simple aggregation with expert weighting, PCA and DEA.

2.6 Simple aggregation with expert weights

In order to gain a fuller understanding of the data, the index was initially constructed using a conventional approach based on expert weighting. Weighting variables in a composite index can be understood as assigning each indicator a certain level of importance; indicators with higher weights contribute more to the overall score, while those with lower weights contribute less. This approach makes it possible to incorporate expert judgement into the index-building process in a process akin to a Delphi evaluation (Räsanen et al., 2019).

We began by calculating a simple average within each of the four dimensions, followed by another simple average across these four components. Equal weighting was applied both within each component and across the four components when producing the final index. Equal weighting represents a transparent and easily interpretable aggregation approach in which all dimensions can contribute equally to the final index. However, the method implicitly assumes an equal level of importance among all dimensions and does not account for correlations between indicators.

Formally, the index *CI* for an entity *e* can be expressed as:

$$
\begin{aligned}
CI_e = {} & 0.25 \cdot climate\ hazard_e + \\
& + 0.25 \cdot socioeconomic\ context_e + \\
& + 0.25 \cdot land\ cover_e + \\
& + 0.25 \cdot governance_e
\end{aligned} \quad (1)
$$

2.7 Principal components analysis

In any assessment of climate change vulnerability, there is a considerable degree of uncertainty regarding the underlying phenomena and their causal relationships, and any attempt to assign expert weights to all variables is a challenging task. Given these inherent difficulties, we opted for a data-driven technique that generates weights endogenously as a second step.

Principal components analysis (PCA) allows the highest possible variance in the data to be integrated into the whole by restructuring the original variables into fewer "components", variables which are essentially the linear combinations of the original indicators. PCA is particularly suitable for datasets where indicators are correlated (Fig. 2). The method assumes the prevalence of linear relationships between variables and places greater emphasis on indicators contributing most strongly to overall variance.

After performing the PCA analysis, the next step was to select the components that best represent the original data. In this task, we were guided by the OECD (2008), which makes several recommendations regarding the retention of components. In this framework, the variables should: i) have eigenvalues greater than one; ii) contribute more than 10% to the explanation of the overall variance individually; and iii) contribute more than 60% to the explanation of the overall variance cumulatively.

Tab. 5 shows the first five components along with the metric values. According to the first rule, four components should be retained; based on the second, only three; and according to the cumulative variance criterion, four again. Nonetheless, it is important to note that these are guidelines rather than strict rules, and their interpretation is thus at the discretion of the researcher. For the purposes of our analysis, we believed that the use of four

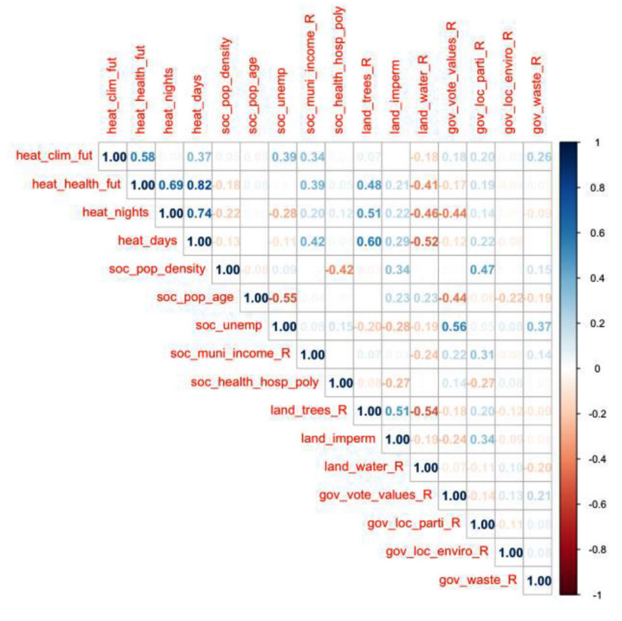

Fig. 2: Correlation matrix

Source: own

Tab. 5: Principal components

Component	Eigenvalue	Variance (%)	Cumulative variance (%)
Component 1	3.94	26.29	26.29
Component 2	2.68	17.86	44.14
Component 3	2.08	13.84	57.98
Component 4	1.34	8.92	66.90
Component 5	0.87	5.82	72.72

Source: own

components offered a reasonable compromise given the results.

In order to construct the index, the individual variance of each component (Tab. 5) was used as its weight, with the weighted sum of the four components then being normalized to produce the final index.

2.8 Data envelopment analysis

The third aggregation method used in the construction of the composite index was data envelopment analysis (DEA), a benefit-of-the-doubt approach that evaluates each city individually by allowing indicator weights to vary according to its specific strengths and characteristics. This approach aligns with the concept of cities as complex systems in which various phenomena interact in a non-linear manner. Since the causal relationships between indicators and vulnerability have not been clearly established and there is uncertainty about how different elements contribute to resilience, DEA would be a suitable tool for synthesizing a complex network of data into a simple metric. DEA also allows for the incorporation of expert judgment, thereby enabling theoretical frameworks or policy priorities to be reflected in the assessment without imposing rigid structures onto the underlying model.

We opted to deviate from the standard DEA model in order to avoid the multiple output variables that this approach typically generates. The model aggregates multiple normalized indicators into a single output measure, with indicator weights determined endogenously for each city. All of the indicators were reversed so that the optimization model (specified as a maximization problem) to adhere to the following logic: 0 represents vulnerability, and 1 represents resilience. Thus, cities in our model aim to maximize resilience.

The resulting composite index (OECD, 2008, 2023) accepts values between zero (representing the worst possible performance) and one (the benchmark value). Rather than limiting the weights directly, the method uses proportion constraints, which restrict the relative flexibility of weights. These constraints are introduced when there are practical considerations regarding the significance assigned to specific indicators.

For the specific constraints, we applied the following rules: i) each variable: maximum 15%; ii) past climate: minimum 15%; iii) future climate: minimum 15%; iv) land cover: minimum 20%; v) socio-economic context: minimum 20%; vi) governance: minimum 20%.

This arrangement leaves a buffer of 10% available for endogenous adjustments within the model, ensuring that cities can compensate for weaker performance in some areas with stronger performance in others.

In general, this methodology allows the four crucial areas of climate, land cover, socio-economic context and governance to be represented almost equally in terms of their overall proportion (though not necessarily according to their individual indicator weights). In order to produce the final values, the results were reversed once again so that the index would be more intuitively interpretable. The final output is presented in the form of a vulnerability index, in which a value of 1 represents high vulnerability and a value of 0 represents low vulnerability.

Each method has distinct strengths and limitations. Equal weighting is transparent but assumes equal importance of all indicators. PCA derives data-driven weights but may be sensitive to the underlying data structure. DEA allows flexible, context-specific weighting but produces less readily interpretable results. By applying all three methods, we were able to assess the robustness of the vulnerability rankings and increase the reliability of the results.

3 Results

The index values for all three indices were grouped into five vulnerability levels, ensuring that each category contained approximately the same number of cities. Level 5 represents high vulnerability, while level 1 represents low vulnerability.

Visually, all three of the indices produced similar results. Cities with higher vulnerability levels tend to be located in the south of the country, largely due to the dominant influence of climate hazard variables, which are not fully offset by the other components. While the PCA-based index appears to display a more spatially continuous pattern, the DEA-based

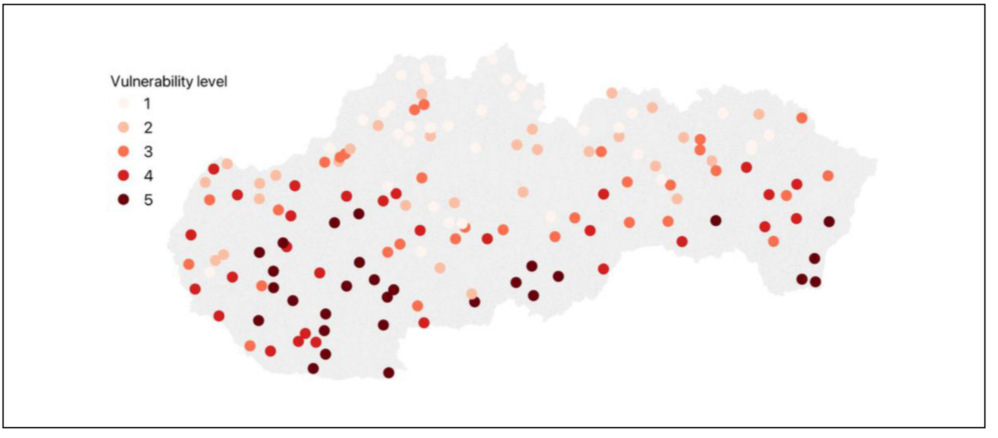

Fig. 3: Simple index

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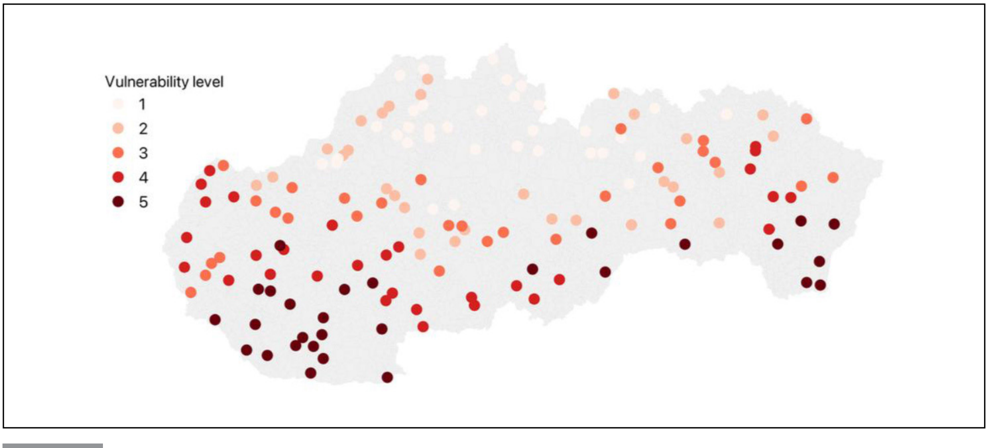

Fig. 4: PCA index

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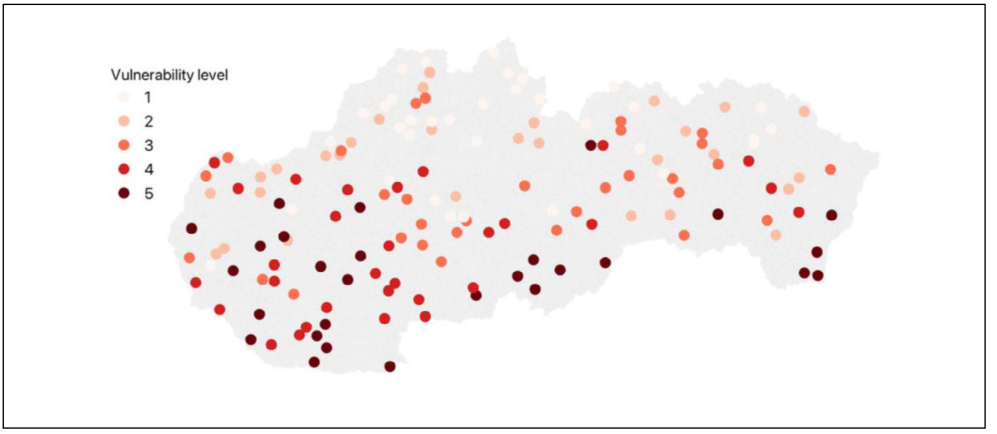

Fig. 5: DEA index

Source: own

index highlights several cities that differ notably from their neighbors. Nonetheless, the visual element of the maps alone cannot capture the full extent of these differences. Therefore, the next section presents a more rigorous method for comparing the three approaches.

3.1 Comparison of the three indices

Three indices were created to maximize the objectivity of the obtained results. The use of multiple aggregation approaches allows the robustness of the vulnerability assessment to be evaluated under different methodological assumptions regarding weighting structures and indicator interactions.

By comparing the results using the method described by Saisana et al. (2005), the two alternative indices were compared to the baseline using an aggregated statistic that measures the mean absolute shift in rank for all evaluated entities relative to the default scenario. Formally, this metric can be expressed as:

$$\bar{R} = \frac{1}{M}\sum_{e=1}^{M}\left[rank_{ref}(Y_E) - rank_S(Y_E)\right] \quad (2)$$

where: R – mean rank shift, which is computed based on the sample of M entities, ranked in a reference scenario and in the scenario S. According to their performance captured in the output variable Y.

We also provided an alternative metric, which, as with the rank metric, compares shifts between the vulnerability levels.

$$\bar{L} = \frac{1}{M}\sum_{e=1}^{M}\left[level_{ref}(Y_E) - level_S(Y_E)\right] \quad (3)$$

The mean level shift between the simple and PCA models was 0.73, and the mean rank shift was 23 positions. Comparing the simple index with the DEA results produced the smallest difference, with only a 0.46 level shift and an average rank change of 15 places. The comparison between the PCA and DEA indices shows that cities would shift by an average of 0.8 levels and 25 ranks, thereby suggesting that the index is relatively robust with respect to methodological changes. The use of a different aggregation method yielded results that were, on average, very similar, suggesting a mean level shift of less than 1. In total, 39 cities experienced no level shift at all. The highest uncertainty regarding the appropriate vulnerability level was observed for Svit, Trebišov and Giraltovce, and additional analyses of the underlying data would be necessary to ensure an accurate vulnerability classification in these cases.

In order to assess the sensitivity of the composite index to governance-related proxy indicators, an additional robustness analysis was conducted, which excluded the governance and civic engagement dimension from the aggregation procedure. The resulting rankings remained broadly consistent with the original simple index. The Spearman rank correlation coefficient between the original and modified rankings reached 0.911, indicating a high degree of consistency between both specifications.

The mean absolute rank shift across cities was 13.4 positions, although several individual cities experienced larger ranking changes. These findings suggest that governance-related proxy indicators influence the classification of certain cities, but the broader spatial distribution of vulnerability remains primarily driven by climatic, environmental and socio-economic factors.

Tab. 6 lists the cities that were judged to be most vulnerable and least vulnerable cities across all three indices. Čierna nad Tisou appears among the most vulnerable cities in both the simple model and the PCA index. With the exception of Trnava, Vrbové and Svit, all of the cities identified as highly vulnerable are located in the south of Slovakia.

The spatial concentration of vulnerability in southern Slovak cities reflects the combined effect of higher climatic exposure, warmer lowland conditions and less favorable environmental characteristics, particularly lower tree cover and a higher potential for heat accumulation. In many cases, these climatic disadvantages are not sufficiently offset by socio-economic or governance-related conditions, resulting in consistently higher vulnerability levels across aggregation methods.

The lists of the least vulnerable cities are also very similar across the three indices, with four cities appearing consistently across all rankings. These more resilient cities are located in the north.

Tab. 6: Top and bottom five cities by methodology

Most vulnerable			Least vulnerable		
Simple model	**PCA**	**DEA**	**Simple model**	**PCA**	**DEA**
Štúrovo	Čierna nad Tisou	Vrbové	Námestovo	Kremnica	Kremnica
Čierna nad Tisou	Veľké Kapušany	Svit	Trstená	Dolný Kubín	Dolný Kubín
Fiľakovo	Gabčíkovo	Trnava	Kremnica	Ružomberok	Ružomberok
Komárno	Nesvady	Lučenec	Ružomberok	Vysoké Tatry	Vysoké Tatry
Želiezovce	Veľký Meder	Leopoldov	Dolný Kubín	Námestovo	Námestovo

Source: own

Five of the cities are located in the south, a region in which climate hazards have the strongest impact (with an average rank of 13.2). These cities are also marked by poor governance, with an average governance-dimension rank of 18.6, and they lag behind in the socio-economic domain, where the mean rank is 27.6. In contrast, there is considerable variability in the land-cover sub-index; Štúrovo ranks 5th, while Čierna nad Tisou ranks 100th. On average, the land-cover rank is 47.6.

When we compare the results for the eight regional capitals (Fig. 7 and Tab. 7), substantial differences can be observed both in the final index values and in several sub-indices. Trnava is clearly the most vulnerable of the regional capitals, partly due to its land-cover characteristics, the weakest result among the eight cities. These disadvantages are further compounded by relatively unfavorable climatic conditions, which are not adequately offset by governance or socio-economic factors.

Banská Bystrica was identified as the most resilient of the capitals, benefiting from highly favorable land-cover conditions, average governance and socio-economic context, and low exposure to climate hazards.

The vulnerability level of Košice was calculated as 5 according to both the simple model and the DEA results, but the PCA metrics gave the city a rating of 2, so the overall assessment for the city is inconclusive. The differing

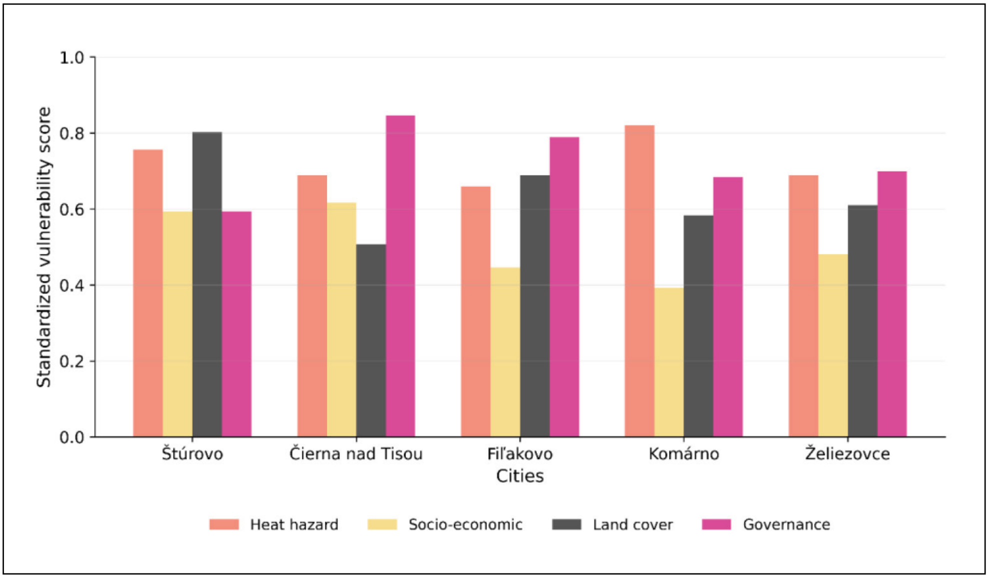

Fig. 6: **Sub-index values in the most vulnerable cities**

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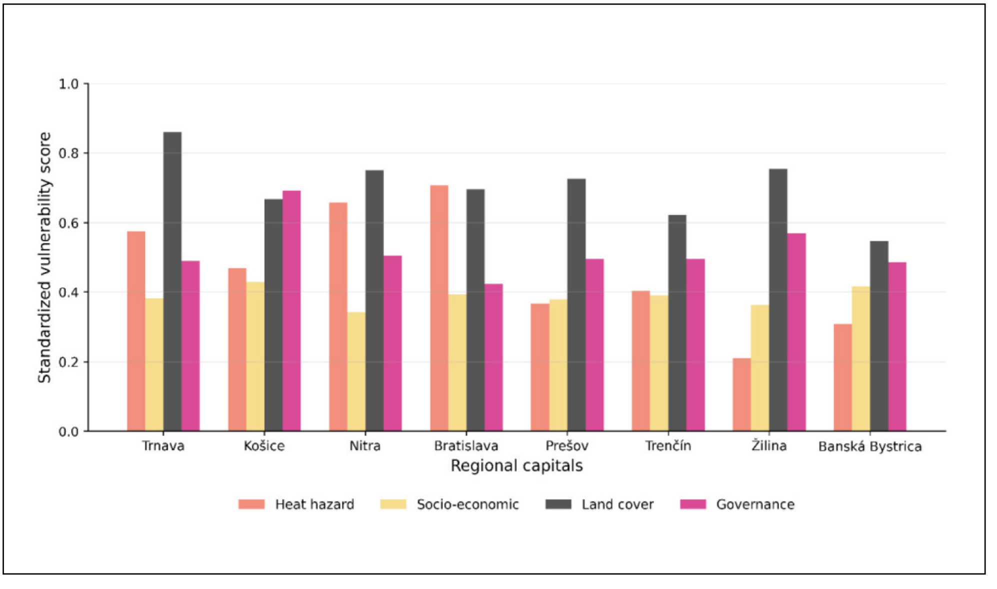

Fig. 7: **Sub-index values in regional centres**

Source: own

Tab. 7: Vulnerability levels of the eight regional capitals

City	Simple index	DEA	PCA
Banská Bystrica	2	2	1
Bratislava	4	4	3
Košice	5	5	2
Nitra	4	5	4
Prešov	3	3	2
Trenčín	3	2	1
Trnava	5	5	4
Žilina	3	3	1

Source: own

classification of Košice across aggregation methods illustrates how sensitive composite indices can be to weighting structures and indicator interactions. While the equal-weighted and DEA approaches assign greater importance to the city's climatic and environmental disadvantages, PCA reduces their influence due to the broader variance structure of the dataset. This example demonstrates how methodological assumptions can have a substantial influence on the interpretation of vulnerability in cities with mixed indicator profiles.

The observed differences between the indices reflect the distinct methodological assumptions underlying each aggregation approach. PCA emphasizes dominant variance structures within the dataset, which may amplify the influence of highly correlated indicators. In contrast, DEA allows cities to perform relatively well through different combinations of strengths, resulting in a greater degree of flexibility and the potential for more heterogeneous rankings. The equal-weighted index provides a more transparent and balanced benchmark but does not account for indicator interdependencies. Rather than identifying a single superior methodology, the comparison highlights the degree of robustness and uncertainty associated with alternative aggregation assumptions.

4 Discussion

The results of the study suggest that urban heat vulnerability in Slovakia is not determined solely by climatic exposure but develops through the interaction between environmental conditions, socio-economic structure and local adaptive characteristics. This highlights the importance of integrated adaptation strategies that simultaneously address the physical form of urban areas, social vulnerability and local governance capacity.

Our findings are consistent with previously published studies of urban vulnerability, the majority of which emphasize the systemic and multidimensional nature of climate risks in cities (e.g., Stolte et al., 2024).

Contribution of this paper lies in the exploratory integration of governance- and values-related proxy indicators into the urban heat vulnerability framework. Previous assessments of heat vulnerability have primarily focused on climatic exposure and socio-economic sensitivity, while governance dimensions have often remained underrepresented due to limited data availability at the urban level. In this study, indicators such as environmental policy support, electoral participation and waste-sorting behaviour are used as indirect proxies reflecting civic engagement, environmental orientation and potential adaptive behaviour. These variables should therefore not be interpreted as direct measures of institutional effectiveness or governance quality, but rather as approximations of broader socio-political and behavioural conditions that might influence local adaptive capacity.

Another methodological contribution is made through the use of three complementary approaches to construct composite indices: a simple expert-weighted model, PCA, and DEA. Each method identifies different aspects of the indicator interactions and weighting assumptions, but the complementary approach allowed a consistent group of cities that are considered highly vulnerable to be determined, as was also the case for the cities that were seen as being among the least vulnerable. This convergence suggests that the three-pronged approach can reveal robust underlying vulnerability patterns despite their methodological differences. The results show a clear spatial trend, with southern Slovak cities generally experiencing higher vulnerability due to the harsher climatic conditions and less favorable environmental characteristics of the region; in contrast, cities in the northern regions of the country showed a tendency to be more resilient to extreme heat.

The use of multiple approaches was intended to evaluate the robustness of the vulnerability assessment under alternative methodological assumptions rather than to identify a single universally superior methodology.

The study contributes to existing literature by providing empirical evidence from a Central and Eastern European context. The study also contributes by focusing on the urban scale. While vulnerability assessments are often conducted at national or regional levels, many adaptation measures are implemented by local governments. While many studies have focused on large Western European or global cities (e.g., Kim et al.; 2017; Macnee & Tokai, 2016; Wang et al., 2021; Wolf & McGregor, 2013), our paper highlights the distinct challenges faced by medium-sized and smaller cities in post-socialist countries, including ageing populations, legacy urban forms and uneven governance capacities, corroborating similar findings by Farkas et al. (2024).

Despite its contributions, the study has several limitations that should be acknowledged. Firstly, the analysis is constrained by the somewhat limited availability of data and indicator selections; this is particularly marked in the case of the governance dimension, where quantitative proxies may be only partially capable of capturing a fuller picture of institutional capacity or policy effectiveness. Secondly, indicator availability, particularly for governance and behavioural dimensions, required the use of proxy variables, and more granular data would further enhance the accuracy of the assessment. In particular, any governance-related indicators should be interpreted cautiously, as they reflect indirect behavioural and socio-political proxies rather than direct measures of institutional adaptation capacity. Another limitation of the study is the lack of external validation using observed heat-related health outcomes such as mortality, morbidity, or hospitalization data (e.g., Wolf et al., 2014). Future research should therefore focus on validating the proposed index against observed heat-related impacts when suitable data becomes available. Finally, although multiple composite index methodologies were applied, all indices involve normative choices regarding weighting, aggregation, and indicator inclusion, which may influence results despite efforts to ensure robustness.

Future research could develop and expand upon the findings outlined in this study in several targeted ways. Firstly, the incorporation of longitudinal data would allow researchers to examine how urban heat vulnerability evolves over time and how cities react to policy interventions. Secondly, extending the framework to include multi-hazard vulnerability would also provide a more comprehensive picture of urban climate risk. Further work could also deepen the governance dimension by integrating qualitative data on local adaptation strategies, planning practices or stakeholder engagement. And lastly, comparative studies featuring countries across Central and Eastern Europe (such as in Farkas et al. 2024) could help distinguish which vulnerability patterns are context-specific and which place-based interventions are needed.

Beyond the Slovak context, the study contributes to broader debates on urban vulnerability by linking empirical analysis to established theoretical frameworks. The paper also reinforces the argument that urban climate adaptation must be place-based, evidence-driven and governance-aware. As cities throughout the world come under increasing risk of extreme heat events, insights such as these are increasingly crucial for shaping effective and equitable urban climate policies.

Conclusions

Climate change is expected to have an extensive impact in the coming decades, resulting in serious threats to human health and economic prosperity, increasing social inequality and the degradation of ecosystems. While Slovak cities are expected to be acutely affected by extreme heat, our research shows that the degree of impact varies considerably across the country. Cities with similar climatic conditions may exhibit markedly different vulnerability levels depending on demographic structure, the availability of green spaces, the quality of housing stock and different levels of institutional flexibility. Our findings highlight the fact that efficient adaptation policies cannot rely on single indicators or hazard exposure factors alone but instead require an integrated assessment that reflects the complex nature of urban systems. Given the complexity of the issue, we propose a composite index that simultaneously captures climatic, land-cover, socio-economic and governance dimensions, providing a comprehensive assessment of urban vulnerability to extreme heat.

Acknowledgments: *This paper was supported by VEGA Research Grant No. 1/0681/22 and No. 1/0702/26.*

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Unlocking the aware citizen: How digital literacy moderates the translation of political awareness into participation

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Abstract: *Political awareness is widely recognized as a foundation for democratic participation, yet the mechanisms through which awareness translates into action remain underspecified, particularly in digitally mediated environments. While prior research has examined political awareness, civic engagement, and digital literacy separately, few studies have tested how these factors interact to shape participation. It has largely overlooked how digital competencies condition the behavioral pathway from awareness to participation. This study integrates these elements within an extended civic voluntarism model and proposing a moderated mediation framework: civic engagement partially mediates the relationship between political awareness and political participation, and critically digital literacy moderates this mediation pathway. Drawing on two-wave survey data collected in Mongolia in October and December 2024 (N = 295), the study finds that civic engagement partially mediates the effect of political awareness on political participation, and that the strength of this pathway depends on individuals' digital literacy levels. Those with higher digital literacy are more likely to translate political awareness into engagement, and civic engagement is, in turn, associated with higher political participation. Whereas low digital literacy weakens this conversion. This conditional indirect effect is statistically significant, indicating that the translation of awareness into action is contingent upon digital competence. The findings refine the classic model of participatory behavior and demonstrate that digital skills are essential for informed citizens to move from awareness to action. The results carry practical implications, suggesting that efforts to increase participation should combine digital literacy training with traditional civic education.*

Keywords: *Political awareness, political participation, civic engagement, digital literacy, civic voluntarism model.*

JEL Classification: *D72, D83, O38.*

APA Style Citation: Zanabazar, G., Mohi Ud Din, Q, & Hong, T. (2026). Unlocking the aware citizen: How digital literacy moderates the translation of political awareness into participation. *E&M Economics and Management*, *29*(3), 184–198. https://doi.org/10.15240/tul/001/2026-3-010

Introduction

The active political participation of its citizens is essential to the survival of a functioning democracy. For decades, scholars have recognized political awareness as a critical foundation for political participation (Delli Carpini, 1996). An informed citizenry forms the cognitive foundation for participation. People who are more politically aware are generally more attuned to how political decisions affect their lives and how they can exert influence. However, the relationship between political awareness and political action is far from perfect. Despite increasing access to information in the digital age, political awareness alone rarely leads to action. It needs an effective channel to become externalized. An important question remains: how does this internal awareness transform into external political action, particularly in the current media landscape?

In today's media environment, social media and internet networks have significantly changed how citizens can participate, resulting in a new ecosystem of political communication (Li & Li, 2022; Lu, 2019). This shift has introduced new opportunities for engagement, such as sharing political content online and organizing communities, but it has also created new challenges, including the proliferation of misinformation and the need for advanced digital skills (Theocharis et al., 2021). This new environment necessitates a re-examination of how citizens become politically engaged, moving beyond traditional models to consider the digital abilities and networked behaviors that now underpin civic life (Boulianne, 2020).

Much of the existing literature has treated civic engagement, the individual and collective efforts to address public concerns, as a parallel outcome or a final destination rather than the essential behavioral pathway that bridges awareness and formal participation (Adler & Goggin, 2005; Lerner et al., 2014; Li & Li, 2022). In reality, by participating in civic activities, individuals build skills, networks, and a sense of efficacy that lower the barriers to more direct political acts. Accordingly, civic engagement is often theorized as an important pathway, yet one of several behavioral pathways through which politically aware citizens become politically active (Oser et al., 2022). At the same time, civic engagement practices evolve, and digital technologies introduce new opportunities and challenges for participation. Digital media have significantly lowered barriers to engagement by providing accessible platforms for discussion, information sharing, and mobilization (Bimber et al., 2015; Boulianne, 2020; Dincecco & Wang, 2021). Citizens increasingly engage through digitally networked forms of participation, including sharing political content online, organizing communities, and taking part in lifestyle-oriented politics (Theocharis et al., 2021). These changing patterns make digital literacy a vital skill for effective civic and political engagement. Digital literacy can be defined as the capacity to locate, interpret, assess, and produce information through the use of digital technologies (Van Deursen, 2011). Individuals with stronger digital literacy skills are able to navigate complex online environments, distinguish credible from misleading information, and participate meaningfully in civic and political discourse (Polizzi, 2023; Willeck & Mendelberg, 2022). Despite extensive research on political awareness, civic engagement, and digital literacy, most prior studies examined these elements separately. Research often focused on discrete relationships such as awareness and participation (Badaru & Adu, 2021), or digital media and engagement (Boulianne, 2020; Polizzi, 2023), while conceptualizing digital literacy mainly as a matter of access, or treating civic engagement as an outcome of individual resources or capacities rather than as a conduit linking awareness to participation (Li & Li, 2022). This leaves a critical gap in existing research, as no integrated framework yet explains how digital competence conditionally enables the translation of political motivation into political action.

This study addresses these limitations by proposing an integrated moderated mediation framework that brings together political awareness, civic engagement, and digital literacy. Drawing on the civic voluntarism model (Verba et al., 1995), which posits that participation results from motivation, resources, and mobilization opportunities. The model is extended to the digital context. Within this framework, political awareness as a form of psychological engagement (motivation), civic engagement as the behavioral channel for mobilization, and digital literacy as a twenty-first-century resource that enables effective political participation in digitally networked environments. This study theorizes a moderated mediation process in which awareness fosters participation through civic engagement, and individuals' levels of digital literacy strengthen this pathway. This research makes significant and targeted contributions to the literature on political communication and participation.

This research extends existing knowledge on digital citizenship by introducing and empirically examining digital literacy as a pivotal moderating resource that amplifies the pathway from political awareness to political participation.

It demonstrates civic engagement as a significant behavioral link between awareness and action, but one that operates in parallel with other important mechanisms and integrates digital literacy into the civic voluntarism model as a vital twenty-first-century resource. In doing so, the research extends the classic model of participatory behavior to the digital context and clarifies how political awareness becomes action across different levels of digital competence. To test this extended framework empirically, this study employs a moderated mediation model to explain how political awareness translates into political participation through the mechanism of civic engagement, and how this pathway is conditioned by an individual's level of digital literacy.

1 Theoretical framework and literature review

1.1 The civic voluntarism model: A foundation for participation

Understanding the drivers of political participation requires a framework that integrates individuals' motivations, capacities, and opportunities. The civic voluntarism model (CVM) (Verba et al., 1995) offers such a comprehensive perspective. CVM posits that participation is a function of three elements: (1) resources (such as time, money, skills) that enable citizens to take action; (2) psychological engagement (interest, knowledge, and efficacy) that motivates action; and (3) mobilization through social networks that recruit individuals into action. Building on this foundation, the present study extends the CVM to the digital context by mapping its core components onto digitally mediated forms of participation. Within this framework, political awareness represents psychological engagement that motivates participation, civic engagement reflects the mobilization processes and opportunities that channel motivation into action, and digital literacy constitutes a modern resource that enables effective participation in a digital environment. This updated framework allows us to preserve the conceptual strengths of the CVM while integrating the digital skills and structures that increasingly shape civic life. Recent studies affirm that the overall logic of the CVM continues to be relevant even as participation shifts toward digital platforms as noted by Alscher et al. (2025) and Theocharis and Van Deth (2017).

1.2 Digital literacy as a conditional resource

The extension of the civic voluntarism model (CVM) is not simply a repetition of earlier work. Instead, it reflects the changing conditions under which participation takes place in digital environments. The digital environment has transformed the public sphere, as discussed by Asimakopoulos et al. (2025), and has introduced new opportunities as well as new limitations for civic action (Hovik & Giannoumis, 2022). These shifts require a reconsideration of what counts as a meaningful participatory resource. In the traditional model, resources were understood as time, money and civic skills and motivation as factors that operate in a simple additive way. Our theoretical argument directly challenges this mechanical assumption. In digital contexts the key enabling resource is digital literacy, which involves the ability to navigate, evaluate, and act within digital spaces according to Asimakopoulos et al. (2025). Recent work on digital participation demonstrates that digital technologies tend to reproduce or even deepen existing inequalities because citizens vary widely in their digital skills (Ahmed et al., 2020). This perspective explains why political awareness is not consistently linked with civic engagement. Awareness becomes behaviorally meaningful only when individuals possess the digital abilities needed to locate, understand, and use information in participatory settings. The civic voluntarism model is therefore extended by showing that psychological engagement in the form of political awareness does not automatically translate into civic engagement. Instead, the influence of awareness depends on digital literacy, which enables citizens to transform their motivations into action in digital contexts. The digital environment thus introduces an important conditional relationship that supports recent calls to refine the civic voluntarism model by examining how resources interact with specific environments and contexts as noted by Alscher et al. (2025).

1.3 Role of political awareness in political participation

Political awareness can be understood as an individual's comprehension of political structures, processes, and current issues, and it serves as a fundamental cognitive precursor to engagement (Delli Carpini, 1996). A large body of research has established that politically aware citizens tend to participate more actively in politics, as awareness offers them the understanding needed to evaluate how political decisions impact their lives and what actions they can take to influence those decisions (Kristensen et al., 2021; Siang Ling & Puyok, 2024). This relationship holds for both traditional and digital forms of participation (Saud et al., 2023). Taken together, these studies suggested that individuals who have greater political understanding are better positioned to transform knowledge into participatory behavior.

H1: Political awareness is positively associated with political participation.

Moreover, political awareness not only predicts participation directly but also encourages involvement in civic and community activities. Being informed about political processes can encourage individuals to feel more responsible toward civic life and more attentive to community challenges (Ekman & Amnå, 2012). Politically aware individuals often show a higher propensity to volunteer, attend community meetings, or otherwise engage in civic life to act on their knowledge. Given that awareness nurtures concern for communal affairs and motivates involvement beyond electoral arenas, individuals are more likely to engage in civic activities. In this sense, political awareness not only motivates formal participation but also nurtures broader civic engagement. This leads us to expect a positive link between awareness and civic engagement:

H2: Political awareness is positively associated with civic engagement.

However, awareness on its own is often insufficient to guarantee action. Scholars caution that even many aware citizens may remain passive unless other factors, such as motivation, efficacy, or opportunity, encourage them to act (Rahman et al., 2025; Zetra et al., 2022). This insight highlights the need for a mediating process that transforms cognitive understanding into behavioral outcomes. Building on this premise, civic engagement can be understood as the behavioral bridge that connects political awareness to formal political action.

1.4 Civic engagement as mediator

Civic engagement can serve as a significant behavioral pathway between political awareness and formal political action. Civic engagement is defined as individual and collective efforts to address public concerns and improve community well-being (Adler & Goggin, 2005; Li & Li, 2022). Civic engagement includes volunteering, community organizing, and issue-based participation. Prior research shows that individuals who participate in civic activities tend to develop communication, organizational, and interpersonal skills, expand their social networks, and cultivate a sense of efficacy, all of which may lower barriers to political involvement (Alscher & Jana, 2025; Serrat et al., 2022). This pattern aligns with the CVM's emphasis on mobilization, as civic and community networks often provide opportunities for recruitment into political action:

H3: Civic engagement is positively associated with political participation.

These insights suggest that civic engagement may operate as a mediating pathway through which political awareness is expressed in more formal political behaviors. Participation in civic activities may offer contexts in which political awareness becomes behaviorally meaningful, helping individuals build experiences and social ties that relate to greater political involvement. Accordingly, the model further proposes that civic engagement mediates the relationship between political awareness and political participation. In other words, becoming civically involved constitutes a significant process through which politically aware individuals translate some of their knowledge and interest into actual participation. Civic engagement provides opportunities and contexts that awareness alone does not offer. It is the process that turns political awareness into visible action (Ekman & Amnå, 2012), providing the "opportunity" that awareness alone lacks. This leads to the following hypotheses:

H4: Civic engagement mediates the relationship between political awareness and political participation.

1.5 Digital literacy as a moderator

In today's digital environment, the transition from political awareness to civic engagement is likely to depend on an individual's digital literacy. Digital literacy is conceptualized as the ability to access, evaluate, and use digital information effectively and critically. People who are more digitally literate are better able to spot reliable information and reject false information (Van Deursen, 2011). Within the civic voluntarism framework, digital literacy functions as a modern resource that enhances citizens' capacity to participate effectively (Goetting & Becker, 2025). Today, political participation is no longer only about access to the internet; it also requires the competencies to navigate complex online environments, identify credible information from misinformation, and engage productively in digital venues (Polizzi, 2023; Willeck & Mendelberg, 2022). For the politically aware individuals, digital literacy empowers action. Those with higher digital skills can more easily find relevant political information and opportunities, connect with networks and communities online, and effectively articulate their views on digital platforms (Boulianne, 2020). In contrast, even highly aware citizens may struggle to turn that awareness into engagement if they lack digital know-how. Without sufficient digital literacy, individuals might be unable to leverage social media or other online tools to mobilize, seek support, or initiate change (Saud et al., 2023). Accordingly, digital literacy is expected to condition the strength of the relationship between political awareness and civic engagement:

H5: Digital literacy moderates the relationship between political awareness and civic engagement.

By moderating the relationship between political awareness and civic engagement, digital literacy may also shape the overall indirect pathway from political awareness to political participation. In other words, if digital literacy amplifies the first-stage awareness effect on civic engagement, and civic engagement in turn leads to participation, then the entire mediated effect of awareness on participation could depend on one's level of digital literacy. This is known as a first-stage moderated mediation (Hayes, 2017). It is anticipated that the indirect effect of awareness on participation through engagement will be more substantial among individuals with higher digital skills. In other words, the effectiveness of the pathway from being informed to being active depends on citizens' digital competencies:

H6: The indirect effect of political awareness on political participation through civic engagement is moderated by digital literacy.

Together, these hypotheses integrate the motivational, mobilizational, and resource dimensions of the civic voluntarism model. Political awareness provides the motivational foundation, civic engagement serves as the mobilization channel, and digital literacy functions as the enabling resource that amplifies this process. Fig. 1 illustrates the proposed moderated mediation model.

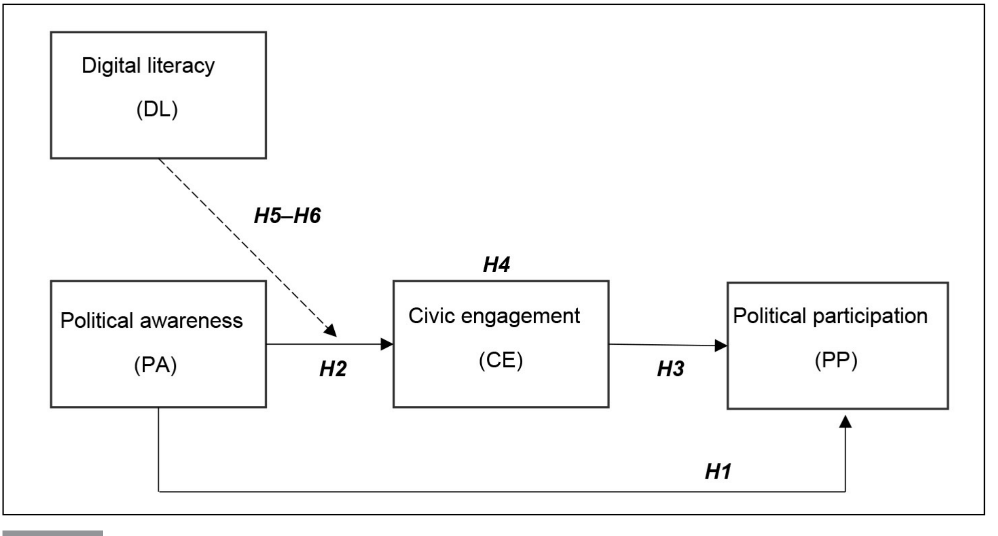

Fig. 1: The hypothesized moderated mediation model

Source: own

2 Research methods

2.1 Sampling and data collection

A two-wave survey design was employed to test the proposed hypotheses and minimize common-method bias. The target population comprised Mongolian adults aged 18 and above. Because Mongolia lacks a unified national sampling frame, a convenience sampling approach was adopted, which is common in emerging democracies where online recruitment remains the most feasible method (Creswell & Plano Clark, 2017). Recruitment used online channels such as social media and university email lists. As a result of this online distribution method, the sample primarily reflects individuals who are relatively active online and comfortable using digital platforms. Citizens with very low digital literacy or limited internet access were therefore less likely to participate, and this underrepresentation should be considered when interpreting results involving digital literacy.

Data were collected in two waves, in October and December 2024, to reduce common-method bias. In the first wave, questionnaires were distributed to 600 potential respondents, and 400 responded. The first survey measured political awareness, digital literacy, and demographic details. In the second wave, the same respondents were contacted, and the questionnaire was distributed to 580 individuals; 370 responses were received. The second survey measured civic engagement and political participation. After matching responses across the two waves and excluding incomplete or inconsistent cases, the final sample comprised 295 participants. The survey was written in English and then translated into Mongolian. In compliance with Brislin (1970) guidelines for cross-cultural research, the back-translation approach was employed to verify translation accuracy. The English questionnaire was translated into Mongolian by a bilingual expert, ensuring its validity for the target population. All procedures involving human participants were reviewed and approved by the Institutional Review Board of the authors' university (Approval No. 2025-43). The data were first coded and analyzed in Mongolia, after which the results were translated into English for reporting and analysis. The demographic characteristics of these participants are presented in Tab. 1.

As shown in participant demographics in Tab. 1, our sample was roughly balanced by gender (54.6% female, n = 161; 45.4% male, n = 134). The participants were between 18 to 54 years old, with the largest age group being 25–34 years (26.4% of the sample). Education levels varied: the most common highest degree was a master's (23.1% of respondents), followed by less than high

Tab. 1: Participant demographics

Demographic variable	Category	Frequency (N)	Percentage (%)
Gender	Male	134	45.4
	Female	161	54.6
Education	Less than high school	67	22.7
	High school	56	19.0
	Bachelor's degree	56	19.0
	Master's degree	68	23.1
	PhD	48	16.3
Age (years)	18–24	72	24.4
	25–34	78	26.4
	35–44	80	27.1
	45–54	65	22.0

Note: N = 295.

Source: own

school (22.7%), bachelor's degree (19.0%), high school diploma (19.0%), and a doctoral degree (16.3%). This demographic diversity reflects Mongolia's digitally active citizenry and provides a robust foundation for analyzing how political awareness and digital literacy jointly shape participation.

2.2 Measures

The survey measured four primary constructs: political awareness, civic engagement, digital literacy, and political participation, aligned with the civic voluntarism model framework (Verba, 1995). All scales were initially developed in English and adapted for the Mongolian context following established cross-cultural procedures (Beaton et al., 2000). Items were rated on a five-point Likert-type scale, typically ranging from 1 (strongly disagree or never) to 5 (strongly agree or always). Higher scores indicate higher levels of each construct. Sample items and reliability information for each scale are presented in Tab. 2. Each measure is described in detail below.

Political awareness was measured using an 11-item scale adapted from Badaru and Adu (2021). Respondents rated their awareness of various political matters on a 5-point scale (1 = not at all aware to 5 = extremely aware). An example item is: "*Are you aware of your rights to vote and be voted for?*". Item scores were averaged to form an overall awareness index. The scale demonstrated excellent reliability in our sample (Cronbach's α = 0.94, M = 3.03, SD = 1.16).

Civic engagement was measured with a 10-item scale adapted from Connolly and Miller (2022). Respondents rated each item on a 5-point scale (1 = strongly disagree to 5 = strongly agree). An example item is: "*I regularly volunteer my time for good causes*". Higher scores reflect greater individual engagement in civic or community activities. This scale was highly reliable (Cronbach's α = 0.94, M = 2.87, SD = 1.18).

Digital literacy was measured with a 19-item scale that was modified from Connolly and Miller (2022) was used to assess digital literacy. Respondents rated their agreement with statements about their digital skills and behaviors (1 = strongly disagree to 5 = strongly agree). An example item is: "*I am confident in my ability to evaluate the credibility of online information*". A mean score was calculated across all digital literacy items, where higher scores reflected stronger digital skills. The scale exhibited excellent internal consistency (Cronbach's α = 0.96, M = 2.95, SD = 1.14).

Political participation was measured with an 18-item scale adapted from Gopal and Verma (2017). Participants reported how often they engaged in various political activities on a 5-point scale (1 = never to 5 = always). An example item is: "*I discuss politics with my friends, relatives, and colleagues*". The 18 items were averaged to create a political participation index, with higher scores indicating more frequent participatory behavior. This scale also showed excellent reliability (Cronbach's α = 0.96, M = 2.86, SD = 1.12). Demographic variables, including age, gender, education, and political orientation, were collected as controls to ensure robustness of the multivariate analyses.

2.3 Data analysis plan

The PROCESS macro for SPSS (Hayes, 2017) was used to analyze the data, which conducts ordinary least squares (OLS) regression-based path analysis and bootstrapping for inferential tests. The analysis proceeded in several steps. First, descriptive statistics and bivariate correlations were computed to examine basic relationships among all variables. Next, direct and mediation hypotheses (*H1*, *H2*, *H3*, *H4*) were examined using PROCESS Model 4 with 5,000 bias-corrected bootstrap samples to ensure robust assessment of mediation effects. Through this analysis, study estimated: (1) the direct effect of political awareness on political participation (testing *H1*); (2) the effect of political awareness on civic engagement (*H2*); (3) the impact of civic engagement on political participation (*H3*); and (4) the indirect effect of political awareness on political participation through civic engagement (mediation, *H4*).

Lastly, the study used PROCESS Model 7 to investigate the moderated mediation hypotheses (*H5* and *H6*). This model assesses whether the mediator path (the a-path, PA → CE) is moderated by a third variable (digital literacy) and whether the overall indirect effect is thus conditional on the level of that moderator. Specifically, the analysis examined the interaction between political awareness and digital literacy in predicting civic engagement (*H5*). The analysis generated an index of moderated mediation to examine whether the mediated pathway from political awareness to participation via civic engagement varies according to digital literacy (*H6*).

3 Results

3.1 Reliability analysis

Reliability testing was carried out by evaluating the internal consistency of all multi-item measures used in the study. Tab. 2 presents the Cronbach's α coefficients for political awareness, civic engagement, digital literacy, and political participation.

Cronbach's α coefficients were computed to assess the internal consistency of the four study scales. Tab. 2 shows all scales demonstrated excellent reliability, with α values ranging from 0.94 to 0.96. Specifically, political awareness (α = 0.94), civic engagement (α = 0.94), digital literacy (α = 0.96), and political participation (α = 0.96) exceeded the recommended threshold of 0.90, indicating excellent reliability for each construct.

Tab. 2: Internal consistency of study scales

Scale	Items	Cronbach's α
Political awareness (PA)	11	0.94
Civic engagement (CE)	10	0.94
Digital literacy (DL)	19	0.96
Political participation (PP)	18	0.96

Note: All items were measured on 5-point Likert scales (1 = strongly disagree to 5 = strongly agree); Cronbach's α values above 0.90 indicate excellent internal consistency.

Source: own

3.2 Descriptive statistics and preliminary analyses

Tab. 3 displays the descriptive statistics and bivariate correlations among the study variables. The means indicated moderate levels of political awareness (M = 3.03, SD = 1.16), digital literacy (M = 2.95, SD = 1.14), civic engagement (M = 2.87, SD = 1.18), and political participation (M = 2.86, SD = 1.12).

As shown in Tab. 3, most correlations were positive and reached statistical significance at the 0.01 level. Political awareness showed strong associations with political participation ($r = 0.76$, $p < 0.01$) and with civic engagement ($r = 0.58$, $p < 0.01$). Civic engagement was also highly correlated with political participation ($r = 0.77$, $p < 0.01$). These strong correlations provide initial support for *H1*, *H2*, and *H3*, suggesting that individuals who are more politically aware, more civically engaged, and more digitally skilled tend to participate in politics at higher rates. Digital literacy, for its part, showed moderate positive correlations with the other constructs (r values ranging from 0.34 to 0.57, all $p < 0.01$), indicating that those with higher digital skills also tended to have greater awareness, engagement, and participation. Overall, the pattern of correlations was consistent with our theoretical

Tab. 3: Descriptive statistics, reliabilities, and correlations among study variables

Variable	M	SD	α	1	2	3	4
1. Political awareness (PA)	3.03	1.16	0.94	–			
2. Digital literacy (DL)	2.95	1.14	0.96	0.34	–		
3. Civic engagement (CE)	2.87	1.18	0.94	0.58	0.57	–	
4. Political participation (PP)	2.86	1.12	0.96	0.76	0.55	0.77	–

Note: $N = 295$; ** $p < 0.01$.

Source: own

model and justified proceeding to the hypothesis tests of mediation and moderation.

3.3 Test of the mediation model

Hypotheses *H1*, *H2*, *H3*, and *H4* were tested using a simple mediation model, Hayes' PROCESS Model 4 (Hayes, 2017) with 5,000 bootstrap samples. The results supported all of the proposed mediation hypotheses, demonstrating partial (complementary) mediation according to the classification system of Zhao and Lynch (2010), as shown in Tab. 4.

Political awareness had a significant positive effect on civic engagement. Specifically, a one-unit increase in awareness was associated with a B = 0.58 unit increase in civic engagement (SE = 0.05), t = 12.07, p < 0.001. This result supports *H2*, showing that politically aware individuals are generally more civically engaged. Civic engagement, in turn, had a significant positive effect on political participation. A one-unit increase in civic engagement corresponded to B = 0.48 higher political participation (SE = 0.03), t = 13.97, p < 0.001. This supports *H3*, indicating that individuals more active in civic life are also more inclined to participate politically.

Even when accounting for the mediator, political awareness continued to exhibit a strong and significant direct effect on political participation. The direct effect was B = 0.46 (SE = 0.03), t = 13.10, p < 0.001. Thus, *H1* was supported independently. Most importantly, a significant indirect effect of political awareness on political participation through civic engagement was observed (B = 0.28), with a 95% confidence interval (based on 5,000 resamples) between 0.22 to 0.35. Because this interval did not include zero, the indirect effect is statistically significant. In accordance with the typology proposed by Zhao and Lynch (2010), these results demonstrate partial (complementary) mediation. Both the direct and indirect effects are significant and operate in the same direction, indicating that civic engagement serves as a significant pathway but not the sole or dominant mechanism linking awareness to participation. The mediation model explained a substantial portion of the variance in the outcome, with political awareness and civic engagement together accounted for about 74.8% of the variance in political participation (model R^2 = 0.748). The strength of the direct effect (B = 0.46) compared to the indirect effect (B = 0.28) suggests that other, unmeasured mechanisms may also contribute to how political awareness into political participation.

Tab. 4: Results of the mediation analysis testing the effect of political awareness on political participation via civic engagement

Path/effect	B	SE	*t*	*p*	95% CI (LL, UL)
Model for mediator (CE)					
PA →CE	0.58	0.05	12.07	<0.001	[0.49, 0.68]
Model summary CE	R^2 = 0.332, F (1, 293) = 145.68, p < 0.001				
Model for outcome (PP)					
PA → PP (direct, c′)	0.46	0.03	13.10	<0.001	[0.39, 0.52]
CE → PP	0.48	0.03	13.97	<0.001	[0.41, 0.55]
Model summary PP	R^2 = 0.748, F (2, 292) = 432.69, p < 0.001				
Total effect (c)	0.74	0.04	20.07	<0.001	[0.66, 0.81]
Indirect effect (a × b)	0.28	0.04	–	–	[0.22, 0.35]

Note: N = 295; PA – political awareness; CE – civic engagement; PP – political participation; bootstrap sample size = 5,000 for the indirect effect confidence interval; all effects are significant at p < 0.001.

Source: own

Tab. 5: Moderated mediation analysis examining the conditional effect of political awareness at levels of digital literacy

DL (moderator)	PA → CE effect	SE	*t*	*p*	95% CI	Indirect effect (PA → CE → PP)	Boot SE	95% CI
Low (−1.14)	0.11	0.06	1.92	0.060	[0.00, 0.22]	0.05	0.03	[0.00, 0.12]
Mean (0)	0.43	0.04	10.47	<0.001	[0.35, 0.51]	0.20	0.03	[0.15, 0.26]
High (+1.14)	0.74	0.06	13.26	<0.001	[0.63, 0.85]	0.36	0.04	[0.29, 0.43]
Model fit (R^2)	$R^2 = 0.584$, F (3, 291) = 136.27, $p < 0.001$.					$R^2 = 0.747$, F (2, 292) = 432.69, $p < 0.001$.		

Note: CI – confidence interval; SE – standard error; R^2 – coefficient of determination; conditional effects are reported at low (−1 SD), mean, and high (+1 SD) levels of the moderator (DL); indirect effects were estimated using bootstrapping (5,000 samples).

Source: own

3.4 Test of the moderated mediation model

Hypothesis 5 posited that digital literacy moderates the relationship between political awareness and civic engagement. Hypothesis 6 posited that the indirect effect of political awareness on political participation through civic engagement is moderated by digital literacy. As a result, the indirect influence of political awareness on political participation through civic engagement would depend on levels of digital literacy, representing a moderated mediation effect. These hypotheses (*H5–H6*) were tested using a moderated mediation model, PROCESS Model 7 (Hayes, 2017), with key results reported in Tab. 5.

The analysis provided strong support for *H5*. There was a significant interaction between political awareness and digital literacy in predicting civic engagement B = 0.32 (SE = 0.05), with t (291) = 6.74, $p < 0.001$. This interaction indicates that the effect of political awareness on civic engagement depends on one's level of digital literacy. To explore this interaction in more detail, simple slopes were analyzed at low (−1 SD), average (0), and high (+1 SD) levels of digital literacy, as shown in Tab. 5. The effect of political awareness on civic engagement was not significant at low levels of digital literacy, B = 0.11, 95% CI = [−0.00, 0.22], $p = 0.06$. Essentially, for individuals with very low digital skills, greater political awareness did not translate into much higher civic engagement. The effect was small and only marginally significant. However, the effect was significant at the mean level, B = 0.43, 95% CI [0.35, 0.51], $p < 0.001$. This suggests that for a person of average digital literacy in our sample, greater political awareness is associated with a notable increase in civic engagement. At high digital literacy, the effect of awareness on engagement was very strong, B = 0.74, 95% CI [0.63, 0.85], $p < 0.001$. In other words, among highly digitally literate individuals, political awareness had a significant positive impact on civic engagement. The difference between low and high digital literacy conditions is that political awareness mattered far more for those who were digitally skilled. These findings support *H5* and show that digital literacy strengthens the link between political awareness and civic engagement. Evidence also supported *H6*, the moderated mediation effect estimated at B = 0.13 (SE = 0.02), 95% CI [0.10, 0.17]. It was statistically significant, indicating that the indirect effect changes with digital literacy. Specifically, the indirect influence of political awareness on participation through civic engagement becomes stronger as digital literacy increases. The conditional indirect effects were examined at specific values of digital literacy, confirming that the mediated pathway from awareness to participation operates primarily among those with moderate to high digital literacy and is minimal among those with low literacy. In short, political awareness leads to action only when individuals possess the digital skills to act on it. The pattern of moderation shows that political awareness becomes behaviorally meaningful only for individuals who possess stronger digital skills. This means that awareness alone is not enough to increase engagement. Citizens must be able to navigate digital spaces in order to use their awareness in ways that support civic involvement.

This interpretation indicates that digital literacy shapes whether political awareness can be expressed in engagement and that the pathway from awareness to participation is conditional on levels of digital competence.

4 Discussion

4.1 Discussion of findings

This study examined how political awareness translates into political participation within a rapidly digitizing environment, using two-wave survey data from Mongolia to extend the civic voluntarism model. The findings reveal a nuanced process in which political awareness promotes political participation both directly and indirectly through civic engagement, but the strength of this pathway depends critically on individuals' digital literacy. Together, the results demonstrate that political awareness is a necessary but insufficient driver of political action; it becomes behaviorally consequential only when citizens possess the digital competencies that enable them to act on their motivation. Political awareness activates behavioral involvement, particularly within digital information environments, and these effects may vary across political and platform contexts.

Political awareness emerged as an important cognitive resource that enables citizens to navigate political life. This aligns with prior research showing that awareness increases attentiveness to political affairs and motivates individuals to participate (Yolmo & Basnett, 2024). Similar to Jamil (2024) findings among university students, political awareness provides the motivational foundation that enables individuals to act when opportunities arise. In Mongolia's emerging democratic context, where political information frequently circulates through social media, awareness enables citizens to perceive politics as relevant and to identify opportunities for action. Importantly, political awareness also predicted higher civic engagement, supporting research suggesting that politically informed citizens often become involved in community issues or expressive civic behaviors as a first step toward more formal political participation (Lee et al., 2022).

Civic engagement functioned as a significant but not exclusive pathway linking awareness to political participation. The mediation was partial rather than dominant, consistent with Zhao and Lynch (2010) classification of complementary mediation. This means that civic engagement is one meaningful route through which awareness becomes action, but other mechanisms such as political efficacy, online expressive behaviors, or interpersonal mobilization likely operate alongside it. The civic pathway identified here reflects Mongolia's mixed environment of offline networks and emerging digital channels, where community involvement still plays an important mobilizing role even as citizens increasingly encounter opportunities through digital platforms.

A major contribution of this study is the strong moderation effect of digital literacy. The simple slopes show that political awareness has minimal influence on civic engagement among individuals with low digital literacy, but a very strong effect among highly digitally literate individuals. This extends earlier work showing that digital competencies enhance citizens' ability to interpret political information and act upon it (Guess & Munger, 2023; Li & Li, 2022). Digital literacy not only amplifies the effect of awareness but fundamentally enables the behavioral conversion of awareness into action. Digitally skilled citizens are better equipped to evaluate information credibility, process complex political cues, navigate online participation opportunities, and mobilize social networks. These mechanisms explain why awareness becomes far more consequential for individuals with higher digital competence.

This has important democratic implications. In Mongolia, awareness may be rising, but digital skill gaps remain uneven across age, education, and rural-urban divides. The large divergence between the behavioral impact of awareness among low- and high-digital-literacy groups indicates a structural inequality: politically aware but digitally disadvantaged citizens may lack the means to act on their motivations. In contrast, digitally skilled citizens can readily transform awareness into engagement, creating a widening participatory gap. This pattern reflects broader concerns that digital transformations empower those with technological resources while leaving behind those without them (Ahmed et al., 2020), producing divides between digitally empowered participants and digitally marginalized observers (Abril, 2023). This pattern helps explain why awareness does not uniformly translate into action: digital literacy determines whether citizens can effectively navigate information landscapes, evaluate competing claims, and identify concrete opportunities for engagement.

These findings extend the civic voluntarism model by incorporating digital literacy as a contemporary political resource and by identifying civic engagement as the mechanism through which awareness shapes political behavior. The moderated mediation framework offers a more accurate understanding of political behavior in digital societies, particularly in countries undergoing rapid technological and institutional change. As recent work suggests, CVM's resource and engagement components may interact in digital contexts, rather than operating additively as originally proposed (Chan & Yi, 2024). The present study supports this view by showing that political awareness becomes actionable only when citizens possess the digital resources needed to engage. Overall, political awareness emerges as an essential but incomplete driver of democratic action. Modern democracies must cultivate not only informed citizens but also digitally capable citizens who can navigate complex information environments and act on their political motivations. If digital skill gaps persist, awareness alone will not ensure equal political voice, and inequalities in participation may deepen despite rising levels of political attention. Variation in effect sizes across individuals may also reflect Mongolia's transitional political environment, where young citizens rely heavily on digital platforms for information but may face barriers to offline participation due to institutional or contextual uncertainty.

Theoretical implications

The present research provides theoretical contributions by updating the civic voluntarism model for the digital era.

First, by establishing a pattern of first-stage moderated mediation, the study provides a more nuanced explanation for the well-documented gap between political awareness and participation. Traditional civic education efforts assume that increasing citizens' political knowledge will automatically lead to greater participation. Our findings refine this by showing that this assumption holds only when citizens possess the necessary digital competencies. This refines the CVM by demonstrating that the resource component is not merely additive but contingent upon the motivational component.

Second, this study contributes to the theoretical understanding of digital inequality. The study demonstrates that gaps in digital literacy create barriers for even politically aware individuals, who may understand politics but lack the skills to act effectively within digital environments. This reframes the digital divide not merely as a matter of internet access, but as a divide in digital competencies that directly affects an individual's ability to convert motivation into action. This integration connects political communication and behavior research, offering a more complete model for the networked democracies.

Third, the finding of partial mediation suggests that the CVM should account for both socially mediated pathways, through civic engagement and direct pathways of individual political action. The strong remaining direct effect of awareness on participation suggests that while civic networks are important, the cognitive foundation provided by awareness also enables direct, individual political acts, such as online political expression or voting, which may not require the intermediary step of community involvement.

Practical implications

Beyond its theoretical relevance, this research carries practical insights for policymakers, educators, and civil society organizations seeking to enhance political participation in Mongolia and similar contexts. The findings provide a clearer framework for integrated approaches to civic education. Empowering citizens requires more than simply increasing their political awareness. It also involves equipping citizens with the critical skills to evaluate digital content, engage in informed digital discourse, and mobilize through digital tools. Civic education programs could teach citizens to spot misinformation and organize initiatives online. The moderation finding suggests that digital literacy interventions should be targeted. For those with limited digital literacy, raising political awareness on its own does not seem to lead very far. People might understand the issues, even care deeply about them, but still find it difficult to act when they lack the digital know-how to participate in online spaces or access civic platforms. Strengthening participation, then, likely depends less on motivational campaigns and more on building the skills that make political action possible in the first place.

Limitations and future research directions

Although the research offers valuable insights into how political awareness, civic engagement, and digital literacy shape political participation, a few limitations should be acknowledged**.** The first concerns the sampling strategy. Because the data were collected through online channels, individuals with very limited internet access or extremely low digital literacy were likely underrepresented. Given this sampling characteristic, it is possible that the moderation effect of digital literacy appeared stronger than it would in a population that includes more digitally excluded citizens. These individuals, who may show weaker translation of political awareness into engagement, were less likely to be captured in the online sample. This may restrict the generalizability of the findings to less-connected segments of the population. Future studies should consider using more diverse or nationally representative samples in order to capture a wider range of digital skills and participation patterns.

A second limitation relates to the timing of the measurements. The two-wave design improves causal inference by separating predictors and outcomes across time. However, both the mediator and the final outcome were measured at the same time point. This limits the ability to establish the full temporal sequence among political awareness, civic engagement and political participation. Future research could employ a three-wave longitudinal design or experimental approaches that separate each stage of the process more clearly.

Despite these limitations, the present study provides meaningful evidence on how citizens move from political awareness to political participation in a digital environment. It highlights the roles of civic engagement and digital literacy in shaping democratic involvement and offers a foundation for future research seeking to understand political behavior in societies undergoing technological change.

Conclusions

The findings suggest that understanding political participation in the digital age requires moving beyond traditional predictors to consider how digital competencies shape the translation of awareness into action. Specifically, the findings from Mongolia show that political awareness increases participation both directly and indirectly through civic engagement. However, this relationship becomes substantially stronger among citizens with higher levels of digital literacy. These results update the civic voluntarism model by showing that digital literacy is a key modern resource enabling citizens to turn awareness into participation. As political life becomes more digital, strengthening citizens' digital skills will be crucial for inclusive participation.

Acknowledgments: *The authors thank all respondents and participating organizations for their valuable support. We are also grateful to Professor Hong Tao for his guidance and feedback throughout the research process. We thank Bat-Ulzii Erdenesuvd for translating the questionnaire into Mongolian, and Batsuren Bat-Otgon for reviewing the translated instrument for clarity, wording, and cultural appropriateness.*

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Journal title: **E+M EKONOMIE A MANAGEMENT**
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Published by: Technical University of Liberec
Studentská 2, 461 17 Liberec 1, Czech Republic, ID no. 46747885

Production: Wolters Kluwer ČR, a. s.
U nákladového nádraží 10, 130 00 Praha 3, Czech Republic, ID no. 63077639

ISSN 1212-3609, ISSN (online) 2336-5064
www.ekonomie-management.cz