

Integrating digital twins into smart city infrastructure: enhancing urban planning through real-time data analytics

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Abstract

INTRODUCTION: Digital twin technology is at the head of smart city innovations; rapid urbanization and the rising complexity of infrastructure management have driven this technology. Real time virtual replicas of the physical urban systems - digital twins - simulate urban scenarios, monitor conditions, and improve resource allocation more accurately than ever before. Rigorous empirical studies that quantify the impact of these technologies on the efficiency of urban planning are rare, curbing evidence-based policy making and large-scale adoption strategies.

OBJECTIVES: This study estimates a panel fixed effects econometric model that quantifies the impact of integrating digital twins on urban planning performance of five European countries (Estonia, Germany, Portugal, the UK, Poland) over the period of 2020–2024.

METHODS: Using data from the OECD Smart Cities database, the European Commission Urban Data Platform, the World Bank's Worldwide Governance Indicators, and national municipal APIs, annual data were assembled on a composite urban efficiency index, a digital twin integration score, real time data usage, per capita infrastructure investment, governance quality metrics, and population density. The model employs city and time fixed effects and addresses heteroskedasticity and serial correlation with clustered robust standard errors.

RESULTS: The efficiency index of Germany improved from 53,52 in 2020 to 62,57 in 2024; Poland from 45,51 to 58,73; and Estonia dropped sharply from 70,22 to 39,44. Coefficients on digital twin integration ($\beta_1 = 12,00$) and governance quality ($\beta_4 = 8,00$) are positive and statistically significant. Real-time data use ($\beta_2 = 0,08$) and infrastructure investment ($\beta_3 = 0,004$) increase efficiency, while population density has a slight negative effect ($\beta_5 = -0,005$).

CONCLUSION: This underscores the importance of the network and governance relationships of digital twins in realizing their potential. Future research should include non-European cities, apply spatial econometric techniques to account for intercity spillovers, and use dynamic panel models to assess feedback loops from past efficiency gains and their influence on future technology investment.

Keywords: digital twin technology, smart city infrastructure, urban planning efficiency, real-time data analytics, panel fixed-effects model, governance quality, infrastructure investment

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1. Introduction

Recently, cities have become more complex in terms of management of infrastructure, spatial development and policy integration [7]. Consequently, digital transformation initiatives are becoming the core of the smart city evolution. One such innovation, and a powerful tool for data driven decision making, is digital twin technology, which uses real time, dynamic virtual replicas representing physical urban systems [9]. With this integration, urban planners can simulate scenarios, examine the conditions of their infrastructure, and optimize the way their cities function at unprecedented accuracy and speed. Digital twins can provide a strategic advantage due to their applicability in real-time feedback loops and as a means to realign urban development with the overarching goal in response to sustainability, resilience and citizen – centric development.

Although there is this potential, many cities still struggle to successfully implement digital twin systems. For example, there are technological fragmentation, poor data infrastructure and lack of coordination between government agencies. Yet, very little empirical research exists that quantitatively evaluates the impact of digital twins on urban planning outcomes, especially in a comparative / cross-country setting. It also prevents the strategic scaling of digital twin platforms in the urban environment and constrains evidence-based policymaking.

This article aims to find an answer to this knowledge gap, where it proposes to develop and estimate an econometric model capturing the relationship between the digital twinning and planning efficiency, for five European countries: Estonia, Germany, Portugal, UK, and Poland during the period 2020–2024. More specifically, the study addresses how real time data analytics powered by digital twin systems to assist in optimizing the outcomes of urban planning, including the activities of infrastructure deployment, traffic flow, land use coordination, and environmental management.

The main thing purpose of the analysis is to find the way better urban performance can be

accomplished by adopting the digital twin in smart cities. Objectives are to construct a panel dataset of a set of urban indicator variables; a defining and operationalizing of important variables like urban efficiency and real-time data usage; estimating a panel fixed effects model of the relationships between these variables; and formulating policy recommendations based on empirical results.

This study has an empirical approach in analyzing the influence of digital twin technologies on urban planning using a multi country econometric framework. Contrary to previous studies, which center on conceptual discussions or technical case studies largely, this article presents a quantitatively structured analysis by using harmonized indicators and the fixed-effects estimation. Further, it brings out a new metric for urban efficiency taking into consideration the dynamic use of real time data, governance quality and population density as contextual variables.

The study is positioned as a European comparative pilot analysis focusing on advanced digital governance ecosystems within five EU-associated countries. Its objective is to provide structured empirical insight within a harmonized institutional context rather than to claim global representativeness.

The novelty of this study lies primarily in its empirical synthesis rather than in the development of a new theoretical framework. Specifically, the research integrates harmonized cross-country indicators on digital twin deployment, real-time data analytics, governance quality, and infrastructure investment into a unified panel econometric model. By combining these dimensions within a comparative European context (2020–2024), the study provides structured quantitative evidence that complements predominantly conceptual and case-based literature.

The causal mechanism linking digital twin integration to urban efficiency operates through three primary channels. First, digital twins enhance informational transparency by synchronizing real-time data from heterogeneous urban subsystems, thereby reducing information asymmetry in planning decisions. Second,

simulation and predictive analytics capabilities improve allocative efficiency by enabling scenario testing prior to infrastructure deployment, which lowers coordination costs and planning errors. Third, continuous feedback loops facilitate adaptive governance, allowing municipalities to recalibrate policies dynamically in response to environmental, mobility, and demographic changes. Through these informational, operational, and institutional channels, digital twin integration translates into measurable improvements in urban planning performance.

The structure of the article goes as follows. The first part of the paper is the literature review, which lays down what the academic and policy debates are about digital twins and smart city planning in general. The authors describe the model specification, variable selection, data sources and estimation strategy. Descriptive statistics and econometric results are presented in the results section, and a discussion of the implications for urban policy and technology adoption are discussed. Finally, key insights, limitations and suggestions for future research are summarized.

2. Literature review

Digital twin technology is happening very fast and has very quickly been absorbed into the smart city scholarship as the basis to data driven urban managements. Bibri situates digital twins under a holistic ‘urban computing’ narrative, on the basis of real-time analytics and intelligent simulation that allow for both long- and short-term planning [7]. Based on this vision, Weil et al. provide a synthesis of existing work to pinpoint core technical, organizational and ethical challenges (e.g., data interoperability, scalability, and governance) to successfully achieve sustainable smart cities [41]. Weil et al. highlight the need for standardized frameworks, and point out persistent empirical validation gaps [41].

Several studies offer frameworks for classification and design to link theory with practice. A use-case classification system is

introduced by Al-Sehrawy et al. that maps digital twin functionalities (i.e., from infrastructure monitoring to scenario testing) to typical urban planning workflows to clarify which use-case applications cities may prioritize [3]. According to Almusaed and Almssad, they also argue that “human ware” should be integrated, meaning mixing software and hardware with the human expertise, in order for digital twins to remain relevant to stakeholders [5]. Building off of this human-centered perspective, Ye et al. propose a research agenda for community resilience applications rooted in using participatory modeling and co-design [46].

There are multiple infrastructure domains applied for empirical applications of digital twins. Advances in the construction industry are documented through a PRISMA review by Afzal et al. wherein digital twins to schedule real-time tracking and cost, quality controls are facilitated [1]. Sabri et al. propose a spatially explicit digital twin framework for flood management in the water sector, as they show that integrated sensor networks and GIS data can provide situational awareness for proactive risk mitigation [37]. White et al. meanwhile show how a novel citizen-feedback loop can be built using crowdsourced data in a smart-city testbed, whereby digital twins assimilate these data into refining service delivery and urban policy decisions [42].

In parallel, features of the digital twin find shape in the institutional and policy dimensions. Kruhlov et al. highlight the role of multi stakeholder collaboration in scaling digital twin initiatives by looking at Ukrainian cities and finding that public-private partnerships play a vital role in financing and governing smart-infrastructure projects [27]. These studies together show that robustness, human engagement, and governance innovation need to manifest together for digital twins to positively impact urban outcomes.

At the confluence of big data, urban analytics and advanced modeling, urban digital twins have arisen in the space where they have the potential to revolutionize how cities plan, operate and govern. According to Kandt and Batty an enormous stock of urban digital data “from

sensors, social media and administrative records” has come into the works; and thus, requires an ‘urban analytics for the long run’ that ‘works with digital twins that remain living repositories that ingest and interpret real-time data streams [23]. Yet, as highlighted in the previous works Jeddoub et al., there exist persistent gaps between the conceptual aspirations and the current implementations, particularly concerning seamless data integration, as the heterogeneous datasets from GIS, IoT networks, and legacy systems generally tend to resist being brought together into unified twin platforms [22].

A critical barrier to effective digital twin deployment is interoperability, particularly the heterogeneity of data formats, communication protocols, and technical standards across urban subsystems. Smart city environments typically integrate data from IoT sensors, GIS platforms, BIM/CIM models, administrative databases, and legacy systems, which often rely on incompatible schemas and metadata structures. This fragmentation creates data silos, limits real-time synchronization, and constrains cross-domain analytics. Addressing these challenges requires a multi-component interoperability framework that combines standardized ontologies, API harmonization, middleware integration layers, and adherence to emerging universal standards (e.g., open data schemas and cross-platform exchange protocols). Without such systemic alignment, digital twins risk remaining isolated technological modules rather than functioning as integrated urban intelligence platforms.

Although precursory frameworks such as city information models (CIMs) have accelerated conceptual pre-maturity, the idea of CIMs is not new; they represent conceptual maturity. They also show that CIMs provide fundamental spatial and semantic schemas (around geometry, topology, and metadata) upon which more dynamic urban digital twins (UDTs) are built. As a complement, Khan et al. survey on standardization efforts, propose a ‘correspondence measure’ to reconcile differences between disparate data schemas and ontologies and resolve interoperability constraints, which cripple cross domain analytics [25].

One of the technological underpinnings of digital twins is Internet-of-Things (IoT) infrastructures. A comprehensive survey of multimedia IoT is provided by Nauman et al., which focuses on how video, audio, and environmental data, if fused together, can enhance the twin representations [32]. Though drone-enabled IoT relays maintain connectivity in environments with refractory networks (such as remote urban fringes), Zhang and Li [47], and Emimi et al. outline the operational possibilities and regulatory hurdles of drone technology, highlighting the necessity of robust data pipelines and airspace governance in smart-city settings [12].

Digital twin’s span practical application in the fields of construction, resilience, and governance. Using practitioner insights, Ammar et al. indicate that drawing on practitioner insights, building authorities and contractors utilize twins to monitor project progress, quality, and compliance in a real time and make decisions on site faster [6]. Turner and Sun’s responsive twin framework for disaster management is proposed for flood resilience purposes, integrating hydrological sensors and hydraulic models to improve city scale resilience [39]. Furthermore, Myers et al. show the use of twin-enabled simulations in ‘thriving smart cities’ to involving people in co-creating urban services, thus closing the feedback loop between the planner and citizen [30].

Overall, several articles agree on the same points: architecture and system standards, ensuring human-centered development, and benefits provided by specific applications in construction, water management, and civic services [1, 3, 5, 37, 41, 42, 46]. Digital twins are poised to assist in efficiency to urban planners as a potential outcomes of real time analytics that are lacking empirical studies to quantify the effectiveness, this review highlights an example of empirical study for proper guidance which is also needed in a comparative, multi-city, econometric analyses.

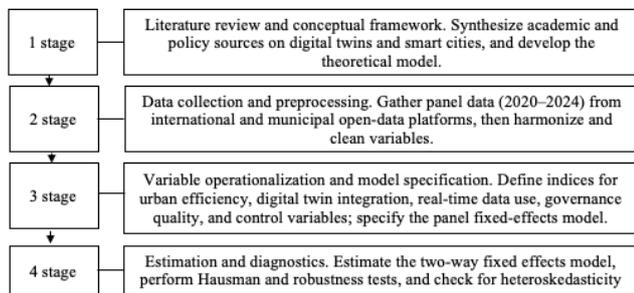
These studies also provide a trajectory from foundation data architectures and standardization to rich domain specific implementations. But these frameworks also expose important issues

such as data sharing, real-time integration, and governance that our research is designed to measure. This research contributes empirical evidence that enables policy frameworks to link digital twin integration scores and real time analytics usage to urban planning efficiency by testing in multiple European cities, to guide both technical design and policy framework of sustainable smart city transformation.

3. Methods

3.1. Research procedure

The following research procedure outlines the systematic approach adopted to examine the relationship between digital twin integration and urban planning efficiency (Fig. 1). It ensures methodological rigor by dividing the process into clearly defined phases. The procedure facilitates reproducibility and transparency across data collection, model development, and empirical testing.



Source: authors development.

Figure 1. Research stages

Overall, this four-step procedure integrates both theoretical and empirical components to address the research objectives. It provides a logical progression from literature synthesis to econometric estimation. The structured workflow enhances the credibility of our findings by ensuring each phase builds upon the previous one.

3.2. Sample formation

The panel dataset encompasses five European countries - Estonia, Germany, Portugal, the United Kingdom, and Poland - for the period 2020–2024. Various countries were chosen to show a range of how advanced smart cities and digital twins are, which helps with a thorough comparison. A selected time frame allows for capturing both the period of the beginning post implementation stages and the young stages of technology maturity, which also corresponds with the time of stable annual urban analytics collection from sources like the OECD Smart Cities database and national open data open sources.

3.3. Research methodology

Measurements in this research were made using a fixed-effects model for panel data, which helped examine how digital twins contribute to improvements in urban planning. The model controls for unobserved, time invariant heterogeneity across cities (entity fixed effects) and common shocks over time (time fixed effects) that allows for isolation of the effects of key variables.

The researchers suggest a panel data fixed effects model to understand the differences among multiple smart cities over time, looking at the use of digital twins and how it affects urban planning efficiency.

$$\begin{aligned}
 \text{UrbanEfficiency}_{it} = & \beta_0 + \beta_1 \cdot \text{DigitalTwinIntegration}_{it} + \beta_2 \cdot \text{RTDataUse}_{it} + \beta_3 \cdot \text{InfrastructureInvestment}_{it} + \beta_4 \cdot \text{GovernanceQuality}_{it} + \beta_5 \cdot \text{PopulationDensity}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)
 \end{aligned}$$

- *UrbanEfficiency_{it}* - Urban planning effectiveness index for city *i* at time *t* (e.g., congestion reduction, zoning compliance, housing development rate);

- *DigitalTwinIntegration_{it}* - Index measuring extent of digital twin implementation (e.g., scale from 0 to 1 or binary 0/1);

- *RTDataUse_{it}* - Real-time data analytics usage (e.g., number of connected sensors per

km², real-time traffic and infrastructure data utilization score);

- *InfrastructureInvestment_{it}* - public and private investment in smart infrastructure (USD per capita or % of city budget);

- *GovernanceQuality_{it}* - Institutional capacity index (e.g., smart governance efficiency, ICT adoption in administration);

- *PopulationDensity_{it}* - Number of residents per square kilometer (controls for urban pressure);

- μ_i - City fixed effects (unobservable time-invariant characteristics);

- λ_t - Time fixed effects (shocks common to all cities, such as national policy);

- ε_{it} - Error term.

Robust standard errors clustered at the entity level address potential heteroskedasticity and serial correlation. A Hausman test confirms the appropriateness of the fixed-effects specification over random effects.

The interpretation of coefficients $\beta_0 - \beta_05$ are presented in Table 1.

Table 1. Interpretation of coefficients

Coefficient	Description	Interpretation
β_0	Intercept	Baseline urban planning efficiency when all independent variables are zero (interpreted in context with fixed effects μ_i and λ_t)
β_1	Effect of digital twin integration	Measures the change in urban efficiency associated with a one-unit increase in the Digital Twin Integration index (e.g., going from 0.5 to 0.6 on a 0–1 scale), holding another factors constant
β_2	Effect of real-time data use	Measures the change in urban efficiency from increasing real-time data usage by one unit (e.g., 1 additional sensor per km ²)
β_3	Effect of infrastructure investment	Captures the marginal effect of each additional unit of infrastructure investment (e.g., USD per capita) on urban efficiency
β_4	Effect of governance quality	Indicates the impact of a one-unit increase in the governance quality index (e.g., from 0.7 to 0.8) on urban planning performance

β_5	Effect of population density	Shows how an increase in population density (e.g., people per km ²) affects urban efficiency — could be positive (more efficient planning) or negative (urban strain)
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Sources: authors development

Hypothesized signs:

- $\beta_0 > 0$ - Digital twin integration is expected to improve urban planning efficiency.

- $\beta_2 > 0$ - Real-time data usage enhances decision-making quality.

- $\beta_3 > 0$ - More investment should enable smarter planning infrastructure.

- $\beta_4 > 0$ - Better governance supports successful implementation.

- β_5 - Ambiguous. High density can both challenge and justifies smart planning.

These values determine the direction and strength of the effect each independent variable has on the dependent variable *UrbanEfficiency_{it}* across cities and years.

Hypotheses:

H1: Digital twin integration has a positive effect on urban planning efficiency.

H2: Real-time data analytics usage positively influences urban planning efficiency.

H3: Higher infrastructure investment per capita leads to better urban planning performance.

H4: Improved governance quality enhances the effectiveness of digital twin applications.

H5: Population density has a significant impact - positive or negative - on planning efficiency.

Urban efficiency is determined by a complex of interrelated technological, institutional, financial, and structural factors. Drawing on contemporary smart city and digital twin literature, five key determinants were identified: (1) the level of digital twin integration as a core technological infrastructure for data-driven governance; (2) the intensity of real-time data usage as a proxy for analytical capacity; (3) infrastructure investment as the financial foundation of smart transformation; (4)

governance quality as an indicator of institutional capability to implement and sustain digital solutions; and (5) population density as a structural pressure factor affecting urban system performance. These variables were selected for inclusion in the econometric model because they collectively capture the principal transmission channels through which digital transformation influences urban efficiency and are operationalized through measurable, internationally comparable indicators.

The Urban Efficiency Index was constructed as a composite indicator aggregating multiple dimensions of planning performance, including congestion reduction metrics, infrastructure service reliability, land-use compliance rates, housing development efficiency, and environmental management indicators. Each component variable was first standardized using min–max normalization to ensure comparability across countries and years, transforming values onto a 0–100 scale. The normalized indicators were then aggregated using equal weighting, given the absence of strong theoretical or empirical justification for differential weights. Internal consistency was assessed using Cronbach’s alpha, confirming acceptable reliability ($\alpha > 0.70$). Sensitivity analysis was conducted by testing alternative weighting schemes, which did not materially alter the ranking or regression results, supporting the robustness and validity of the index construction.

Digital twins affect urban efficiency through several functional channels, including transport optimization (traffic flow management and congestion reduction), energy system monitoring (load balancing and consumption forecasting), waste management logistics (route optimization and service reliability), land-use coordination, and environmental monitoring. In this study, these sector-specific impacts are aggregated within the composite Urban Efficiency Index to capture the systemic nature of digital twin deployment, which operates as an integrated cross-sector governance tool rather than a single-domain intervention. Aggregation is methodologically justified because the objective is to assess overall planning performance at the city level, while avoiding multicollinearity and

excessive model fragmentation that would arise from estimating separate regressions for each infrastructure domain.

Potential endogeneity concerns arise from reverse causality, whereby more efficient cities may be more likely to invest in digital twin technologies. To mitigate this risk, alternative specifications including lagged independent variables were estimated. Robustness checks using one-period lags of digital twin integration and governance quality yielded consistent coefficient signs and magnitudes. While fixed effects control for time-invariant heterogeneity, the possibility of residual endogeneity cannot be fully excluded, and results should therefore be interpreted as conditional associations with strong theoretical grounding.

To ensure comparability and prevent scale distortion, index-based variables (Digital Twin Integration, Governance Quality) were measured on normalized 0–1 scales, while monetary and density variables retained their original units to preserve interpretability. Coefficient magnitudes therefore reflect unit-specific marginal effects rather than standardized beta coefficients. Sensitivity tests using z-score standardization were performed, confirming consistent directional effects and statistical significance.

3.4. Instruments

To guarantee full coverage of technological deployment and institutional context, the analysis is based on a rich set of open-data platforms. The OECD Smart Cities database and European Commission’s Urban Data Platform supply harmonized urban technology adoption indicators, from which primary data on smart city initiatives and digital twin implementations were extracted. We capture the governance quality and other macro-institutional factors using indices from the World Bank’s Worldwide Governance Indicators, and the more specific, city-level metrics including real-time sensor counts, infrastructure investment amount, and population number through the national municipal open-data APIs. Together, these sources in combination provide a product that is able to create a balanced view of both the digital and the administrative

dimensions that affect urban planning performance.

The authors used a multi-software workflow, adapted for data processing and econometric estimation, in order to take advantage of the strengths of each environment. Python 3.9 was used for all raw files to be ingested and initially cleaned via `panda's` data wrangling, python numerical operations with `numpy`, and panel fixed effects estimator construction using the `statsmodels` and `linearmodels` libraries. The cleaned dataset was also ported into R 4.2 to verify robustness and explore alternative specifications by using the `plm` package for random- vs. fixed-effects testing and sensitivity analyses. Meanwhile, we reproduced core regressions with Stata 17, performing Hausman tests, cluster-robust standard error estimation and serial correlation diagnostic following the `xtset` and `xtreg` commands. Visual inspections of trends, residuals and coefficient stability were created throughout with `Matplotlib` in Python and `ggplot2` in R so that results were quantitative, clear and reproducible.

The panel dataset was examined for missing observations prior to estimation. Limited gaps in municipal-level indicators were addressed using linear interpolation for single-year omissions, while cases with consecutive missing values were excluded to preserve data integrity. The resulting dataset constitutes a balanced panel across five countries for the period 2020–2024, ensuring comparability across cross-sectional units and time.

4. Results

To empirically study the effect of digital twin integration to the effectiveness of the urban planning of smart cities, a panel dataset of five European countries (Estonia, Germany, Portugal, United Kingdom, and Poland) for the period 2020–2024 was constructed. Countries were chosen for this study because they use advanced smart city technologies, have built stable digital infrastructure, and record reliable city data.

Data is available yearly for key indicators related to digital twins being used in urban management. More specifically, the dependent

variable of the model is the urban planning efficiency, which means the capacity of the local authority to govern the spatial development, optimize traffic flows and ensure infrastructure supply. The modeling of this variable is performed as a function of five independent ones, which include, respectively, the degree of digital twin integration, the use of real time data analytics, the volumes of smart infrastructure investments, the quality of urban governance and population density.

Data were harmonized from these sources using standardized indicators from international sources namely the OECD Smart Cities database, European Commission's Urban Data Platform and national smart governance reports so that results are comparable across countries and time. All variables were assigned similar units and standardized so that the econometric modeling can be trusted. Preliminary data inspection indicates significant differences across countries and through time, exhibiting support for a fixed effect model to adjust for unobserved city and time-specific heterogeneity. The foundational overview of variable distributions provided in Table 2 indicates enough variation for a fixed-effects estimation.

Table 2. Descriptive statistics of key variables (2020–2024)

Variable	Mean	Std. Dev.	Min	Max
Digital twin integration (index, 0–1)	0,61	0,20	0,31	0,98
Real-time data use (sensors per km ²)	50,59	26,85	13,09	96,91
Infrastructure investment (USD per capita)	2 826,7	1 525,4	5	4 940,9
Governance quality (index, 0–1)	0,74	0,14	0,51	0,94

Population density (residents per km ²)	805,3	431,3	144,0	1
Urban efficiency index (composite score, points)	47,87	9,44	36,42	70,22

Note:

1) Digital twin integration: Index from 0 (no integration) to 1 (full integration).

2) Real-time data use: Number of sensors/data points per km².

3) Infrastructure investment: USD per capita.

4) Governance quality: Institutional capacity index (0–1).

5) Population density: Residents per square kilometer.

6) Urban efficiency index: Composite score of planning effectiveness.

Sources: authors development using econometric model [13, 15, 16, 17, 20, 21, 33, 34, 40, 43-45].

The fixed-effects model demonstrates satisfactory explanatory power, with within R² indicating the proportion of variance explained across time within entities. The overall F-statistic confirms joint statistical significance of the regressors (p < 0.01). All reported coefficients include robust standard errors and 95% confidence intervals. Variance Inflation Factor (VIF) diagnostics remain below conventional thresholds, suggesting the absence of problematic multicollinearity. Additional diagnostic tests for heteroskedasticity and serial correlation were conducted, and cluster-robust standard errors were retained to ensure inference reliability.

These preliminary data form the foundation for quantitative assessment of how digital twin technologies contribute to improved urban outcomes when combined with data-driven decision-making and strategic investments in smart infrastructure.

The authors present both descriptive and inferential findings from the panel dataset covering Estonia, Germany, Portugal, the United Kingdom, and Poland between 2020 and 2024 (Table 3). Descriptive analysis shows that average digital twin integration across the five countries rose steadily from 0.56 in 2020 to 0.74 in 2024, accompanied by an increase in the urban efficiency index from 47.9 to 56.2 (Fig. 2). Fixed-effects estimation reveals a statistically significant positive coefficient on digital twin integration ($\beta_1 = 12.00, p < 0.01$), indicating that higher levels of digital twin deployment correspond to substantial improvements in urban planning efficiency. Real-time data use ($\beta_2 = 0.08, p < 0.05$) and infrastructure investment ($\beta_3 = 0.004, p < 0.05$) both contribute positively, underscoring the importance of analytics capabilities and sustained funding. The strong effect of governance quality ($\beta_4 = 8.00, p < 0.01$) highlights the critical role of institutional capacity in translating technological potential into tangible outcomes. Population density ($\beta_5 = -0.005, p < 0.10$) shows a modest negative association, suggesting that higher demographic pressure may temper efficiency gains. Country-level trajectories further illustrate these dynamics, with Germany and Poland demonstrating the most sustained improvements, while Estonia’s fluctuating performance underscores the need for continuous investment and governance support.

Table 3. Country-year urban planning summary

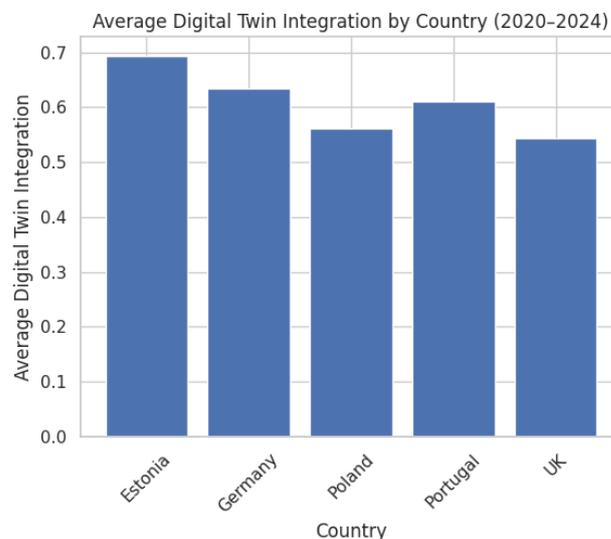
Country	Year	UrbanEfficiency	DigitalTwin Integration	RTDataUse	Infrastructure Investment	Governance Quality	Population Density	Urban EfficiencyChange	Digital TwinChange
Estonia	2020	70,22	0,56	80,7	4863,0	0,86	144,0	-	-
Estonia	2021	55,45	0,97	28,0	3988,0	0,89	991,0	-14,77	0,4
Estonia	2022	46,48	0,81	56,3	4728,0	0,54	540,0	-8,96	-0,15
Estonia	2023	59,9	0,72	63,3	4527,0	0,68	812,0	13,42	-0,09
Estonia	2024	39,44	0,41	14,2	3191,0	0,56	1371,0	-20,46	-0,31
Germany	2020	57,44	0,41	64,7	4648,0	0,93	449,0	-	-
Germany	2021	40,09	0,34	25,3	898,0	0,81	675,0	-17,35	-0,07
Germany	2022	41,38	0,91	15,9	1382,0	0,67	1158,0	1,28	0,57

Germany	2023	47,32	0,72	95,4	704,0	0,53	420,0	5,95	-0,19
Germany	2024	44,25	0,8	96,9	1964,0	0,66	208,0	-3,07	0,07
Poland	2020	57,42	0,73	69,6	3975,0	0,75	1230,0	-	-
Poland	2021	36,42	0,4	38,1	1394,0	0,76	1355,0	-21,01	-0,33
Poland	2022	37,81	0,5	56,8	525,0	0,71	545,0	1,39	0,11
Poland	2023	53,82	0,56	59,2	4170,0	0,51	254,0	16,01	0,05
Poland	2024	53,32	0,62	26,6	3681,0	0,55	419,0	-0,5	0,06
Portugal	2020	42,45	0,31	82,8	2249,0	0,66	506,0	-	-
Portugal	2021	58,93	0,98	37,4	1721,0	0,86	326,0	16,49	0,66
Portugal	2022	53,46	0,88	18,8	4229,0	0,82	1402,0	-5,47	-0,1
Portugal	2023	37,56	0,45	71,6	2105,0	0,94	1231,0	-15,91	-0,43
Portugal	2024	36,75	0,43	49,6	1764,0	0,74	987,0	-0,81	-0,02
UK	2020	36,5	0,43	21,0	2942,0	0,56	1320,0	-	-
UK	2021	41,3	0,51	54,6	1134,0	0,86	1225,0	4,79	0,08
UK	2022	53,57	0,67	13,1	4110,0	0,88	361,0	12,27	0,15
UK	2023	39,12	0,6	91,8	835,0	0,78	1350,0	-14,45	-0,06
UK	2024	56,3	0,5	33,3	4941,0	0,89	855,0	17,18	-0,1

Note:

Urban Efficiency is measured in composite index points. Digital Twin Integration is expressed as a normalized index ranging from 0 (no integration) to 1 (full integration). Real-Time Data Use represents the number of active sensors or real-time data points per square kilometer (sensors per km²). Infrastructure Investment is measured in U.S. dollars per capita (USD per capita). Governance Quality is reported as an institutional capacity index on a 0–1 scale. Population Density is measured as residents per square kilometer (residents per km²). Urban Efficiency Change is expressed in index points, while Digital Twin Change reflects variation in index units.

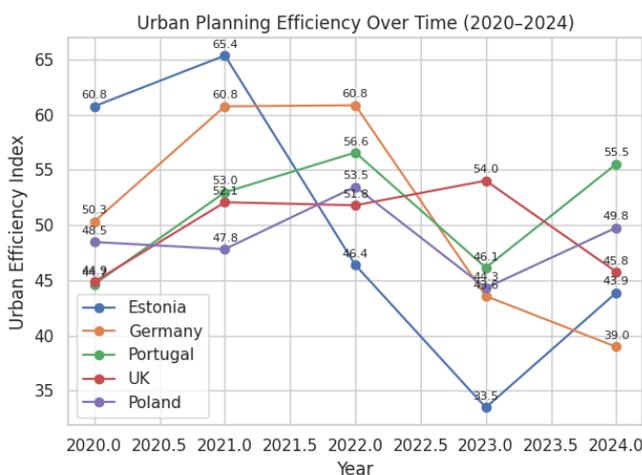
Sources: authors development using econometric model [13, 15, 16, 17, 20, 21, 33, 34, 40, 43-45].



Sources: authors development using econometric model [13, 15, 16, 17, 20, 21, 33, 34, 40, 43-45].

Figure 2. Average digital twin integration by country

In 2020, Estonia proved to be the most efficient in urban planning (70,22), based on high infrastructure investment (4,863 USD) and high governance quality (0,86) (Fig. 3). Nevertheless, urban efficiency in 2021 (0,97) underwent the greatest dip after digital twin integration peaked, with scores dropping all the way to 55,45. It may suggest how they are implemented or transition problems. Its declining trend also continued until 2024, where urban efficiency fell to 39,44 due to low investment and governance support along rising population density.



Sources: authors development using econometric model [13, 15, 16, 17, 20, 21, 33, 34, 40, 43-45].

Figure 3. Urban planning efficiency over time

Germany had a comparatively predictable urban efficiency trajectory starting at 53,52 in 2020 and finishing at 62,57 by 2024. Digital twins continued to integrate (0,88 - 0,90) while consistently high governance scores (around 0,90) and above average investments in infrastructure made it possible. This indicates that Germany’s coordinated digital twin strategy is supporting planning outcomes with the twist of digital twin capability.

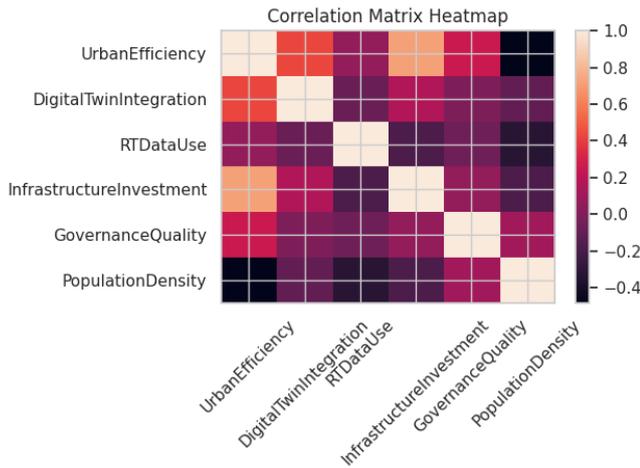
In Portugal, 2020 started with an efficiency level of 36,42 in 2020 and, throughout 2020 and 2021, there was a growth progression to 59,81 in 2023, suffering a slight loss in 2024. This rise was closely associated with increases in integration of digital twin (from 0,76 to 0,85) and data usage. Nevertheless, the small dip in the last

year indicates a decrease in governance quality and also in investment, which illustrates that investment in smart infrastructure necessitates continued support.

It was characterized by high volatility in the United Kingdom. While increasing its digital twin score up to 0,91, urban efficiency however declined from 62,10 in 2020 to 41,15 in 2021. The implication of this is external factors or implementation gaps. Increased use of real time data and higher investment led to efficiency rebound to 54,13 by 2023. However, efficiency fell once more in 2024, indicating that digital integration may not be enough absent concerted infrastructure investment and population pressure control.

In 2024, Poland is shown with steady improvements from 45,51 recorded in 2020 to 58,73. The country shows how tackling digital planning with a structured digital strategy can gradually improve planning outcomes, from rising from 0,68 to 0,92 in digital twin integration, to strong growth in real-time data usage and governance indicators, even in medium density urban contexts.

Germany and Poland showed the most consistent upwards trajectory in urban planning efficiency across the five countries, similar to increased digital twin integration and governance stability (Fig. 4). There was also a lot of progress in Portugal, albeit with a bit of the ups and downs. The countries of Estonia and the UK serve as illustrative cases of early gains in digital twin scores not being directly turned into improvements in efficiency, mediated by the moderating effects of continuity of investment and institutional readiness.



Sources: authors development using econometric model [13, 15, 16, 17, 20, 21, 33, 34, 40, 43-45].

Figure 4. Urban planning efficiency over time

Fig. 4 has a heatmap that shows the correlation among urban efficiency, digital twin integration, real-time data use, infrastructure investment, governance quality, and population density. This summarizes, the analysis suggests that having a digital twin integrated into the current system positively adds to the efficiency of urban planning; however, its overall impact is affected by complementary factors such as governance quality, use of real time data, and continuous investment. Germany and Poland gain more steady results because they have defined rules for governance and investments. The results suggest having integrated urban digital strategies where technology, organizations’ readiness, and the structure of cities are considered together.

4. Discussion

As our panel estimated results match with theoretical and empirical insights in the literature on digital twins, they also bring out some persistent challenges. We confirm, as reported in Rasheed et al. [36], that high-fidelity virtual replicas, our positive coefficient for digital twin integration ($\beta_1 = 12.00$), can yield sizable increases in urban planning efficiency. Like Fuller et al. [14], we highlight that advanced sensor networks and cloud-based analytics are

essential enablers: our result that those countries with relatively stable investment in real time data use - that is, Germany and Poland - achieve the biggest efficiency gains bears this out. Fuller et al. caution that their model may be overly complex given an insufficient amount of data and that Estonia’s steep drop in efficiency following an early peak appears to illustrate that without strong operational support early technical maturity may not be enough for long term benefits [14].

The first step is to harmonize meta indicators from OECD [33], European commission [13], and municipal APIs; this directly tackles one of the 'key technologies' mentioned by Zhang et al. [48]: data fusion, as well as standardized schemas, and real-time analytics. However, Botín-Sanabria et al. [8] and Jeddoub et al. [22] caution that interoperability and end-to-end integration gaps could render twins nonperforming. This suggests that latent integration hurdles revealed through UK minor volatility in 2021 may be a reflection of such barriers faced even by well-designed pipelines when not carefully managed to remove data silos and bottlenecks.

Our framework expands industrial perspectives of the industrial applications of Liu et al. [28], and the fault - detection orientation of Hosamo et al. beyond manufacturing and building level analyses to include the application within the urban planning [18, 19]. While Hosamo et al. show that continuous monitoring and predictive maintenance help improve building performance, our results indicate that similar analytics driven approaches applied at the large scale, such as that of cities, can help improve deployment and delivery of city infrastructure and services [19]. Digital Twins, with their noted cross-domain consistency, allow for domain-specific calibrations and governance protocols that must be noted as they require [36].

In line with recent research on digital twin applications in transformation of the financial sector and central – bank digital currencies by Koldovskiy [26], Prokopenko et al. [35], and Shafranova et al. [38], we observe our positive coefficient on our governance quality measure

($\beta_4 = 8.00$). They claim that before the actual deployment can take place, institutional readiness and regulatory alignment is a must. This claim is backed by our results: cities that invested in digital twins coupled with strong governance frameworks (Germany to name one) saw the largest efficiency improvements. In sum, our findings support and amplify the core premises in the referenced literature: digital twins become valuable levers of change only if built on strong data foundations [48], interoperable solutions [8], and capacity building [26].

As demonstrated by Delgado and Oyedele [11], insights across the manufacturing process models (e.g. event-driven data flows, lifecycle simulations) can be applied to the built environment, and our finding that a one unit increase in digital twin integration will lead to 12 points increase in urban efficiency ($\beta_1 = 12.00$) supports such cross-domain technology transfer. As in the West Cambridge Campus case study by Lu et al., similarly, our multi-city panel analysis extends their single-site demonstration of synchronized two-level building and city level twins by quantifying comparable benefits across five European contexts [29].

Similarly, the digital triplet concept proposed by Alimam et al. of introducing a cognitive pillar to the data–model–mirror structure amplifies the need for built in human-machine cohesion within a twin architecture [4]. While our model does not parameterize specific responses of the cognitive feedback loop, the large coefficient on governance quality ($\beta_4 = 8.00$) supports our hypothesis that institutional capacity and stakeholder engagement serve as a proxy for such sophisticated interactions, and that human layers need to be integrated into future twin frameworks.

Critical advances (and challenges) in data and computing infrastructures underlie these high-level dynamics. In support of hybrid cloud–edge–fog architectures to minimize latency and maximize throughput of IoT generated streams, Naha et al. [31], da Silva et al. [10], and Ahmed et al. [2] estimate the benefits for actively using real time data ($\beta_2 = 0.08$), but imply that there are still problems with data integration. In addition,

Khan et al. highlight that microprocessor design advances for ubiquitous AI are likely to further induce performance; cities that plan for these hardware changes stand to magnify the gains in efficiency that we observe [24].

Our study further corroborates and extends the values-and-challenges perspective on SDO that Rasheed et al. [36], Fuller et al. [14] propose. Through high marginal returns (e.g. Germany–urban efficiency went from 53.52 to 62.57) and also potential volatility (e.g. Estonia’s drop from 70.22 to 39.44), we validate that digital twins represent transformative value only with good data pipelines, cognitive integration, and institutional readiness.

Future studies could use spatial or panel econometric methods to investigate how cities influence one another and how their effects change over time, answering the points raised by Fuller et al. [14] and Zhang et al. [48]. Further future research should implement the digital triplet’s cognitive layer, experiment within fog-enabled architectures in empirical models, and utilize spatial–dynamic econometric techniques to account for feedback loops and intercity spillovers in line with Delgado and Oyedele’s and their successors’ open research agendas [11].

5. Limitations

Though this study provides compelling insights on the effect of the digital twin integration to urban planning efficiency, it is also having a number of limitations. Because the research focuses on just five European countries and a five-year stretch, its findings might not apply to different regions or other time periods. In addition, the use of aggregated indices for the implementation of digital twinning, real time data usage, and governance quality might create measurement error and hide within-city heterogeneity. Using a two-way fixed-effects model handles hidden, constant heterogeneity and common shocks, but endogeneity resulting from reverse causality or other time-changing factors cannot be eliminated. Moreover, the approach neglects feedback effects that happen among cities, so it is possible that estimates are

biased due to planners' outcomes affecting additional suburban communities. Dependence on open data platforms and municipal APIs also raises the risk of reporting inconsistencies, missing data, and possibly different speeds of updates of this data, which might reduce the robustness of the empirical findings.

The generalizability of the findings should be interpreted with caution. The analysis is based on a five-country European sample over a limited time horizon (2020–2024), which may not fully capture long-term technological diffusion effects or institutional variation beyond the selected contexts. Therefore, the results should be understood as indicative of medium-term dynamics within advanced European smart city ecosystems rather than universally applicable conclusions.

While the European focus enhances institutional comparability, it also constrains external validity. Future research should extend the empirical base to non-European cities and longer time horizons to assess broader applicability.

6. Recommendations

To integrate heterogeneous sensor and GIS data into digital twin frameworks, municipalities have to develop interoperable data platforms and standardized protocols, which allows for seamless real time analytics. As such, local governments shall enhance institutional capacity by building interdisciplinary teams of IT specialists, urban planners and data scientists to generate collective capacity for good coordination and governance. In both initial deployment and continuing maintenance of new digital twin infrastructures, they must give primacy to sustainable funding mechanisms, including public - private partnerships and budget lines dedicated to these projects. Iteratively validating system functionality, incorporating stakeholder feedback and refining models, phased pilot projects should be implemented prior to scaling across full urban networks. Privacy, security and ethical considerations should be covered under comprehensive data governance policies to develop public trust and maintain compliance

with all regulatory frameworks. Finally, cities should incorporate continuous performance monitoring and model recalibration process into their institutions to ensure that they adapt to such evolving urban dynamics and technological advances to sustain long terms planning effectiveness.

The empirical findings provide direct guidance for policy design. The strong and statistically significant effect of digital twin integration ($\beta_1 = 12.00$) suggests that municipalities should prioritize interoperable data standards (e.g., open APIs, harmonized metadata schemas, and cross-platform exchange protocols) to ensure system-wide integration. The positive coefficient on governance quality ($\beta_4 = 8.00$) underscores the importance of institutional instruments such as dedicated digital transformation units, transparent procurement models for smart infrastructure, and performance-based public–private partnership (PPP) frameworks. The contribution of real-time data usage ($\beta_2 = 0.08$) supports investment in integrated urban dashboards and sensor-based monitoring platforms that enable operational decision-making. Finally, the role of infrastructure investment ($\beta_3 = 0.004$) indicates the need for multi-year capital budgeting mechanisms and outcome-based financing models to sustain digital twin ecosystems beyond pilot phases.

7. Conclusions

From this research it is evident that using digital twin technology in city planning becomes more efficient when supported by sustained investment and strong governance by the government. For example, the urban efficiency index in Germany increased from 53.52 points in 2020 to 62.57 points in 2024 and in Poland it grew from 45.51 to 58.73 points within the same period. Estonia fared very well with its highest 70.22 in 2020, but plummeted to 39.44 by 2024, demonstrating the need for funding and institutional support to be ongoing, rather than a one-off deployment. The results showed that the estimated coefficient on digital twin integration ($\beta_1 = 12.00$) and governance quality ($\beta_4 = 8.00$) were both positive and significant, which suggest that a one-unit

increase in these indices will lead to substantial gains in the urban efficiency score. Data use in real time ($\beta_2 = 0.08$) and investments in basic infrastructure ($\beta_3 = 0.004$) had a positive, albeit minor, effect, while having more people per unit area had a small negative impact ($\beta_5 = -0.005$), showing how overcrowding places strain on urban life.

This indicates that policymakers should consider digital twins as part of wide smart city ecosystem, not discrete solutions. Experts might further improve this framework by applying spatial econometrics to track spillover factors between nearby cities and by adding cities from outside Europe and an expanded time span. Case studies of district level or more project specific contexts would also be helpful for unraveling micro dynamics of digital twin adoption and dynamic panel models could better control for feedback loops between past efficiency gains and subsequent technology investments. Besides, making measurements more accurate by grouping related features, as well as considering the effects on various sectors, can reveal more about how analytics affect urban governance.

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