



URBAN DIGITAL TWIN GOVERNANCE: THE EFFICIENCY- LEGITIMACY TRADE-OFF

Weibo Zhou¹, Valters Kaze², Anatolijs Krivins³

^{1, 3} Daugavpils University, Daugavpils, Latvia

² RISEBA University of Applied Sciences, Riga, Latvia

¹ jinglinx@foxmail.com; ² valters.kaze@riseba.lv; ³ anatolijs777@gmail.com

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ABSTRACT

With the continuous aggregation of the global urban population and economic activities, the impact of digital technology on public governance has shifted from the tool level to the cognitive and logical levels. In this context, this study explores the evolution path and performance differences of urban digital twin (UDT) as a highly concentrated governance metaphor in different institutional environments.

Objective: This article aims to explain the transnational differences between China and the EU in urban digital twin governance through the analytical perspective embedded in the system. The article examines how different institutional logics shape the allocation of the public sector's dynamic capabilities and explores the resulting trade-off between governance efficiency and legitimacy, particularly to provide strategic guidance for transition economies.

Method: This study adopts the "Most Different Systems Design" (MDSD) method to compare and analyse the governance prototypes of China and the European Union. This study combines the institutional logic perspective (ILP) with the dynamic capabilities framework (DCF) to code policy texts and urban cases (for example, "city brain" and "citizen twins") to describe how system logic is transformed into the operational ability of "Sensing, Seizing, and Transforming".

Results: This study found a structural "efficiency-legitimacy paradox": (1) The Chinese model, characterised by state-led vertical integration, minimises internal coordination costs and performs well in rapid closed-loop implementation ("output efficiency"), but faces challenges in accountability and diversity of innovative ecosystems. (2) The EU model, driven by rights protection and interoperability (for example, a multi-party information management system), ensures stronger "input legitimacy" and institutional resilience, but due to complex multi-stakeholder negotiations, it faces higher coordination friction and results in a slower diffusion rate.

Conclusion: The governance performance of urban digital twin (UDT) depends not only on technical maturity, but also on institutional logic and the adaptability of organisational structure. The study shows that transition economies should avoid simply copying extreme models. On the contrary, they should build a hybrid governance architecture, dynamic balance between development pressure and rights constraints, and maintain a dynamic equilibrium between efficiency and legitimacy through hierarchical governance and interoperability mechanisms.

Keywords: Urban digital twins; institutional logic; dynamic capabilities; EU governance; Chinese model; efficiency-legitimacy trade-off

JEL classification: D73, O33, Q55, H83, L26

Paper type: Research article

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INTRODUCTION

With the increasing concentration of the global population in cities and economic activities, the impact of digital technology on public governance is shifting from the tool level to the method and cognitive level. The urban digital twin (UDT) originated from the concept of full life-cycle mirror modelling of physical assets in aerospace engineering and has now become a highly abstracted technical concept and governance metaphor in the smart city agenda (Zhou et al., 2025a). Under the background of the continuous improvement of the Internet



of Things (IoT), artificial intelligence (AI) and high-performance computing power, the role of UDT has gradually shifted from static expression to dynamic simulation and scene deduction and has been placed as a decision-making support and operation optimisation tool in some urban governance scenarios (Antonova et al., 2024; Beloeva&Venelinova, 2024). It not only improves the city's visibility but also reshapes the government's understanding of urban operational rules, risks, resource scheduling, and action logic.

At the same time, UDT is not a general technical system that can be copied at will. Its data collection, sharing, and algorithmic invocation must be feasible and legitimate under the combined effects of legal boundaries, administrative power and responsibilities (Teivāns-Treinovskis et al., 2022), market structure, and social trust. The study pointed out that although the research on digital twin-related technologies has developed rapidly, the discussion of its governance logic, institutional constraints and social ethical impact is relatively insufficient, resulting in our inability to fully explain the performance differences of digital twin technology (UDT) in different institutional environments (Zhou et al., 2025a). In fact, similar technology visions may yield different promotional speeds and governance effects across cities, and the key differences often stem from how data ownership, usage boundaries, value distribution, and responsibility attribution are institutionalised and incorporated into system rules.

This difference is especially marked when comparing the two main global paradigms. The pathway represented by Chinese practices focuses on top-level design, cross-departmental data centralisation, and platform integration, prioritising efficiency, security, and controllability as core values (Caprotti & Liu, 2022; Atha et al., 2020; Weber, 2023; Yue et al., 2025). Conversely, the pathway represented by EU practices emphasises rights protection, interoperability, and multi-participation, clarifying the boundaries of privacy and accountability through institutional frameworks such as GDPR, and encouraging the diffusion of innovation through standards and open ecosystems (Barcelona City Council, 2018; Borghys et al., 2020; Jørgensen & Ma, 2025; European Commission, 2024; European Commission, 2025b; Open Agile Smart City, 2025; (EU) Regulation 2016/679, 2016; Raes et al., 2025; Wernick et al., 2023).

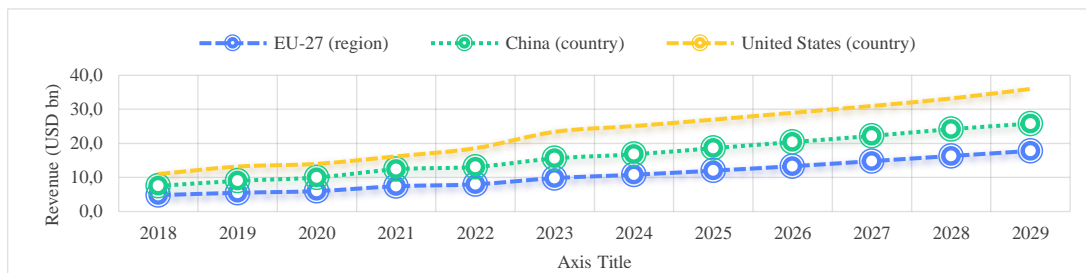
The transition economies of Central and Eastern Europe find themselves at the crossroads of two paradigms. On one side, they must comply with the rules of the European Union, and on the other, they face the pressure of economic catch-up and infrastructure development. Consequently, they need to foster cooperation between green initiatives and digital transformations (Brozkova et al., 2025; Zhou et al., 2025b; Beloeva, Venelinova & Petrova, 2025; Zhelev, 2025). The main governance challenge lies not only in adopting new technologies but also in balancing the urgency of rapid deployment (efficiency) with the requirements of compliance and social acceptance (legitimacy) (Espolov et al., 2023; Steblyakova et al., 2022; Tireuov et al., 2023). Existing research often lacks a clear explanation of how the trade-off between these systems influences UDT's actual governance performance and organisational capabilities. Therefore, this article aims to develop an analytical framework, elucidate the differences in UDT across various situations based on institutional embedding and governance logic, and examine the adaptive strategies necessary to reconcile development pressures with rights constraints within the key context of the transition economy.



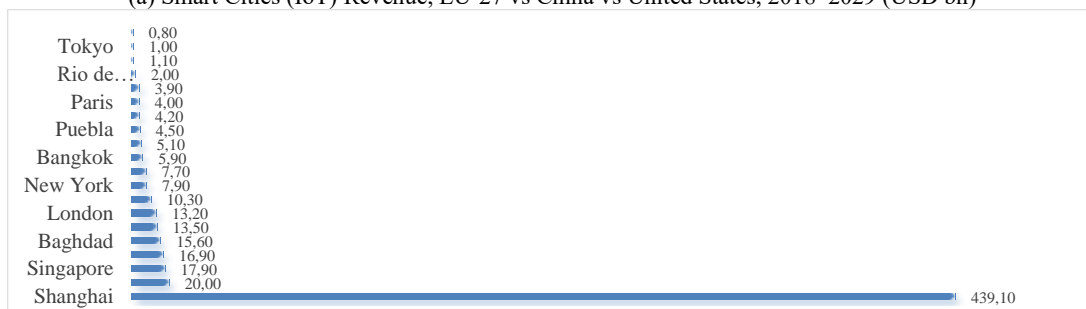
LITERATURE REVIEW

Existing research mostly views urban digital twins (UDT) from a technological perspective, focusing on topics such as 3D modelling, sensor networks, and decision support (Batty, 2018; Shahat et al., 2021; World Economic Forum, 2022; Zhou et al., 2025a). However, the existing literature shows a structural imbalance in the discussion of technology research and governance, leading to a lack of theoretical support for cross-institutional transplantation (Zhou et al., 2025a). Therefore, the academic community is increasingly inclined to regard UDT as a social technology system, emphasising that data legitimacy, cross-departmental collaboration and algorithm accountability are the institutional prerequisites for their effective operation (Floridi, 2020; Gonzalez Otero & Verhulst, 2025; Wernick et al., 2023). Notably, aligning new governance initiatives with regionally dominant human values can significantly improve community acceptance and legitimacy (Kaže et al., 2011).

The market structure also reshapes governance choices: end-to-end solutions for rapid replication are easy to lead to integrated paths, while emphasising interoperability and public value leads to modular paths. Figure 1(a) shows that EU-27, China, and the United States are comparable in market size, implying that the difference in governance models is more due to institutional logic than technical prospects.



(a) Smart Cities (IoT) Revenue, EU-27 vs China vs United States, 2018–2029 (USD bn)



(b) CCTV Cameras Per 1,000 Inhabitants in Selected Global Cities (Latest Available Year Reported)

Figure 1. Smart City Market Scale and Surveillance Proxy.

Source(s): Statista Market Insights

Figure 1(b) further shows that high-intensity perception facilities in some megacities increase privacy risks while improving efficiency, providing empirical background for discussing the tension between output and input legitimacy later.

In terms of global paradigm differentiation, China's path is described as a state-led integration model, which realises algorithmic scheduling and efficiency improvement through the "city brain" (Atha et al., 2020; Caprotti & Liu, 2022; Weber, 2023; Jurgelāne-Kaldava et al., 2024; Yue et al., 2025). The EU path focusses



on rights and interoperability, establishes boundaries based on regulations such as GDPR and Data Act, and promotes ecological innovation through practises in Barcelona and other places (Barcelona City Council, 2018; Calzada & Almirall, 2020; Celeste, 2024; European Commission, 2024; European Commission, 2025b; Open & Agile Smart Cities, 2025; Regulation (EU) 2016/679, 2016; Raes et al., 2025; Wernick et al., 2023). Although the integration path can quickly mobilise resources, it is easy to provoke legitimacy disputes; the interoperability path reduces the risk of locking, but it is accompanied by higher coordination costs (Jørgensen & Ma, 2025; Wernick et al., 2023).

Institutional logic theory provides a perspective for explaining this difference. Society is composed of a competitive institutional order, in which national logic emphasises security and performance, while democratic logic emphasises rights and participation, which directly determine the organisational boundaries and risk tolerance of UDT (Friedland & Alford, 1991; Thornton et al., 2012; Floridi, 2020). To analyse this process, this study introduces a dynamic capability framework to concretise government governance into a continuous process of "perception, acquisition and reconstruction" (Teece et al., 1997; Teece, 2018; Kattel & Mazzucato, 2018; Teece, 2023; Mehmeti et al., 2024). This perspective reveals how the institutional environment shapes the government's resource-allocation preferences in addressing information gaps and implementing strategies (Zhou et al., 2025b).

This is particularly critical for the transitional economies in the "institutional mezzanine". Central and Eastern European countries face double pressure to transform while embedding EU rules. Although mechanisms of institutional and technological interaction (Brozkova et al., 2025; Zhelev, 2025). Therefore, by building an integrated analytical framework, this article aims to clarify the governance mechanism of the China-EU paradigm and to provide a theoretical basis for transition economies to find a suitable mixed governance structure within the constraints of rights and development.

METHODS AND DATA

This study adopts Most Different Systems Design (MDSD), which uses China and the European Union as extreme governance prototypes across two institutional environments to maximise logical differences, thereby enabling clearer identification of its impact on urban digital twin (UDT) governance architecture, data mechanisms, and capacity configuration. Comparative analysis takes the institutional logic perspective (ILP) and the dynamic capability framework (DCF) as the core analysis lens: ILP is used to identify the dominance of institutional orders such as the state, market and civil rights in different systems and their conflict structure (Friedland & Alford, 1991), and DCF is used to explain how institutional logic is transformed into operational governance performance through the combination of capabilities at the organisational and platform level (Teece et al., 1997).

Empirical materials take typical urban and national or regional policy practises as embedded cases. China focusses on the practical context of "city brain" and platform integration path (Atha et al., 2020; Caprotti & Liu, 2022; Weber, 2023; Yue et al., 2025), and the European Union focusses on multi-centre practice oriented



by digital sovereignty, open data and interoperability governance (Barcelona City Council, 2018; European Commission, 2024; European Commission, 2025b; Open & Agile Smart Cities, 2025; Regulation (EU) 2016/679, 2016). The data sources mainly include policy and legal texts, standards and technical framework documents, and second-hand evaluation materials around Hangzhou, Xiong'an, Barcelona, Helsinki and other cities to extract institutionalised constraints, identify cross-domain collaboration interface rules, and supplement the implementation details through triangular mutual evidence (Open & Agile Smart Cities, 2025; Atha et al., 2020; Barcelona City Council, 2018; Caprotti & Liu, 2022; Jørgensen & Ma, 2025; Weber, 2023). In the analysis process, this article thematically codes the text and the case, and summarises the logic of the dominant system and its constraints on the dimensions of data centralisation or decentralisation, platform opening or closure, and accountability and participation mechanisms (Friedland & Alford, 1991).

At the macro-narrative level, this article further concretises the dynamic capabilities into an operational governance mechanism chain and serves as a micro-coding framework for case analysis. Based on the classic division of dynamic capabilities, this study summarises the governance operation of UDT as a closed loop of "Sense/Sensing, Capture/Seizing and Reconstruct/Transforming": perceive the collection breadth and social penetration of multi-source heterogeneous data; capture corresponding to the algorithmic logic that converts data into model assets and supports decision-making; and reconstructs the execution mode of digital insights back to physical systems and social processes (Teece et al., 1997; Zhou et al., 2025b).

This micro framework provides a unified analysis benchmark for comparing UDT models across different systems. Under this framework, we not only pay attention to technical indicators, but also pay attention to how the institutional logic reshapes the configuration of the above-mentioned chain: for example, examining whether the state-led logic tends to strengthen order and efficiency through "high-frequency perception and rapid capture", and whether the rights-oriented logic tends to balance the power of the algorithm through "negotiated reconstruction" and data sovereign constraints (Weber, 2023; Zhou et al., 2025b). At the same time, in order to reduce the subjective risk of qualitative interpretation, this article supplements the use of open market and governance capacity indicators as a background reference, such as the smart city (IoT) market scale and urban perception intensity agent index based on Statista Market Insights to show the pace of technological expansion, and characterise the structural environment of digital public capacity with the long-term sequence of EU DESI and the difference between the supply and use of e-government, to assist in judging the representativeness of the case conclusion (European Commission, 2024; European Commission, 2025b; Eurostat, 2024).

RESULTS

The Chinese Mode

The evolution of China's urban digital twin (UDT) is not a simple technological change, but a systematic reshaping of national governance capabilities in the digital space. In the process, the "city brain" rose from the concept of enterprise to an institutionalised governance paradigm and was deeply integrated into the policy framework of the new smart city (Caprotti & Liu, 2022; Zhang et al., 2019). Therefore, it is necessary to



understand that China's UDT needs to go beyond technical parameters and examine how it transforms urban operations into a computable object to pursue rapid response in public safety and management. This article follows the thematic coding framework (Friedland & Alford, 1991), focusing on analysing the data form, platform structure and accountability mechanism under the leadership of national logic.

From a mechanistic perspective, China's UDT exhibits significant "cycle compression" characteristics, and its governance process closely resembles the OODA cycle in the military domain (Weber, 2023). In the perception stage, the Chinese model emphasises the construction of "visible cities" through high-density sensor networks and cross-departmental data aggregation to eliminate "data islands". For example, the Hangzhou city brain realises multi-departmental linkage disposal by real-time perception of key scenes (Di, 2024). Although this article measures infrastructure coverage as the number of cameras per thousand people, this indicator only reflects perceived density and is not directly equivalent to the level of compliance with data privacy.

In the "understanding the city" adjustment stage, the CIM platform realises the deep integration of space-time data. Qingdao's practice shows that the three-dimensional fusion of "space-time big data" provides a context for simulation deduction, shifting governance from status quo record to law prediction (Wu, 2025). This ecological structure, with the base platform as the core, supports rapid access and collaboration among upper-level applications (Yu et al., 2025). The subsequent decision-making link reflects the technocratic logic. For example, Hangzhou uses AI algorithms to dynamically regulate traffic, which significantly improves traffic efficiency while significantly reducing labour costs in coordination (Weber, 2023).

In the execution process, the Chinese model shows the efficient mapping of digital decision-making to physical execution. The "one-network unified management" in Huangpu District of Shanghai has greatly compressed the governance chain (Cui et al., 2023; Han et al., 2023), while the Xiong'an New Area has pushed this to the extreme of "digital real synchronisation", realising the unified scheduling of cloud brain for automatic driving and other systems (Guo et al., 2025). From the perspective of political economy, Xiong'an is more like the experimental field of "national entrepreneurship". As a system integrator, the government enhances cross-departmental execution by pre-dissolving and coordinating costs (Wang et al., 2024) and by using the BIM platform to implement the process constraints across the whole life cycle (World Economic Forum, 2022).

From the perspective of transaction costs, the Chinese model significantly reduces collaboration costs through the hierarchical system's unified platform (Jantschgi et al., 2022). The strategic alliance between the government and technology giants is conducive to rapid infrastructure replication, but it may also lead to market concentration and curb marginal innovation (Atha et al., 2020; Chen, 2024). This governance trade-off of centralised mobilisation for performance constitutes the core feature of China's UDT. To deepen the research, this paper will test the constraints imposed by different institutional logics on the platform structure using the same coding dimension, thereby enabling a leap from phenomenon description to mechanism comparison (Friedland & Alford, 1991; Teece et al., 1997).

The EU Mode



Unlike China's centralised and integrated "city brain" approach, the European Union Urban Digital Twin (UDT) features a rights-oriented federalisation. In terms of power structure, it emphasises multi-level division of labour and local autonomy and gives priority to procedural justice and social consultation. The European Commission tends to guide the digital transformation of member countries through rules and incentives such as the General Group Exemption Regulation (GBER) rather than forcing technology convergence (Bulfone et al., 2026). Under this framework, the "Digital Decade" strategy positions UDT as a tool to serve public value and digital sovereignty and is deeply nested with the European digital constitutional agenda (Calzada, 2022; Celeste, 2024; Floridi, 2020). This article adopts the same thematic coding dimension (Friedland & Alford, 1991; Celeste, 2024; Wernick et al., 2023; Jørgensen & Ma, 2025), aiming to test how this rights-oriented environment constrains data boundaries and platform structures.

To provide a macro foundation, this article introduces the Digital Economy and Social Index (DESI). As shown in Figure 2, although the EU's "digital public service" has improved significantly, improvements in human capital and enterprise application capacity have lagged behind. This imbalance shows that institutional progress on the supply side has not automatically translated into synchronous absorption on the social side, and the implementation of UDT still faces multiple constraints.

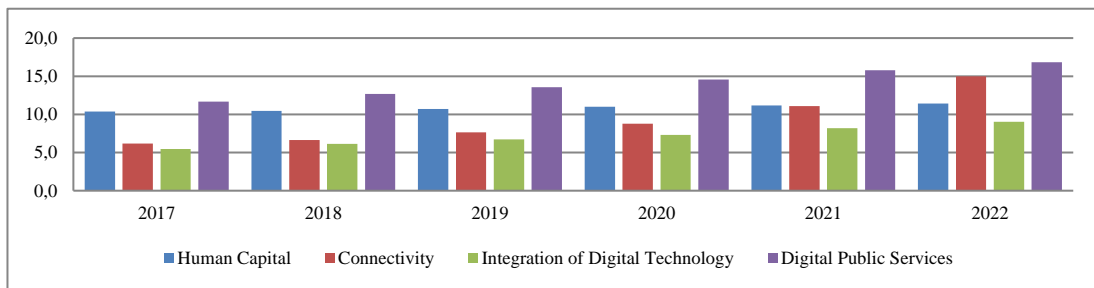


Figure 2. Progress of EU DESI in Four Dimensions (2017–2022).
Source(s): European Commission

In other words, although the EU is good at establishing systems and norms, it still faces multiple constraints in the application of these norms. This imbalance determines that EU UDT must rely on a combination of governance tools. Figure 3 further shows that the slope of digital public service capacity is significantly higher than the actual growth in residents' interactions. This gap reveals the core challenge facing EU UDT: how to embed the system within the social collaboration network and lower the threshold of use.

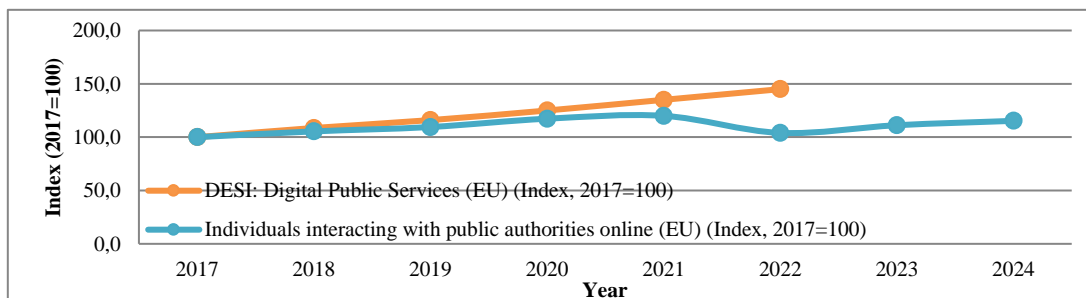
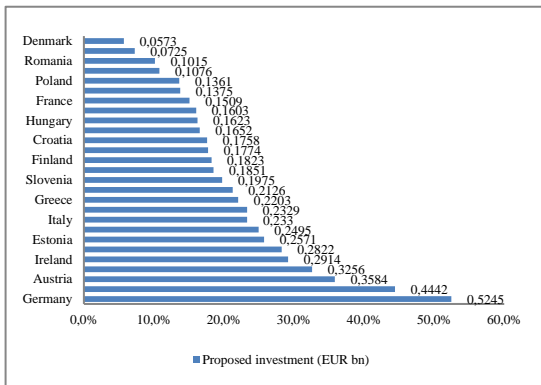


Figure 3. EU E-Government Progress and Uptake (Index, 2017=100).
 Notes: DESI Series Available through 2022; Eurostat Series Extends through 2024.
Source(s): European Commission; Eurostat

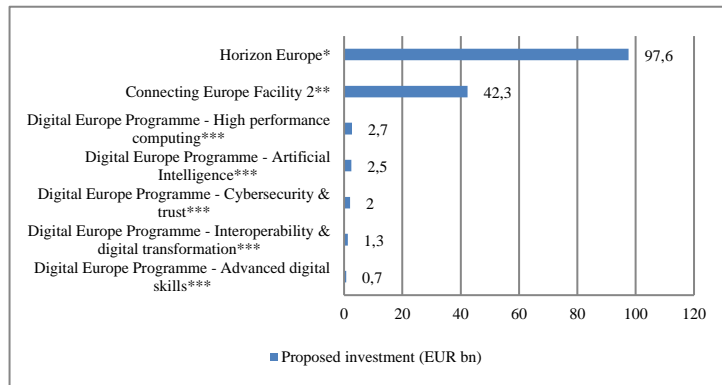


In the rights-oriented governance structure, this phenomenon of "ability progress is not synchronised with use growth" is not surprising. The complexity of the identity authentication system, the demarcation of cross-departmental data sharing, differences in platform availability and accessibility, and procedural friction arising from the compliance process may raise the threshold and amplify differences in experience in the short term. Therefore, the advantage of the EU model lies in the accumulation of trust and legitimacy through privacy protection and procedural justice, but its cost is often reflected in higher early coordination costs and slower large-scale diffusion speed; this also echoes the statistical evidence below about "technical problems, difficult to use, electronic signatures or identification problems" in the use of e-government obstacles (see Figure 5).

Due to the lack of mandatory integration conditions, the European Union chose standardisation and interoperability as its guiding principles. The "minimum interoperability mechanism (MIMs)" promoted by the Open and Agile Smart City Network (OASC) constitutes the governance base (Pourcin, 2025; Raes et al., 2025; Open & Agile Smart Cities, 2025). This practice is closely coupled with legal frameworks (Krivins, 2019) such as GDPR and the Data Act, aiming to expand data availability without sacrificing rights (Regulation (EU) 2016/679, 2016; Celeste, 2024; European Commission, 2024; European Commission, 2025b; Jørgensen & Ma, 2025; Wernick et al., 2023).



(a) Share of NextGenerationEU Funds Allocated to Digitalisation (% , 2021–2026)



(b) Proposed EU-Level Investments in Key Digital Programmes (EUR bn, 2021–2027)

Figure 4. EU Policy Toolkit for Digitalisation.

Source(s): Bruegel; European Commission

Combined with the differences in the allocation of financial funds shown in Figure 4, the European Union uses funds and rules to shape the ecology through projects such as Digital Europe, and is committed to reducing locking risks and cultivating innovation in small and medium-sized enterprises through common standards (Teece et al., 1997; Celeste, 2024; Open & Agile Smart Cities, 2025; European Commission, 2025a; Publications Office of the European Union, 2024; Espelt et al., 2019).

This kind of "citizen-oriented" approach is concretised in many forms in urban practice. Barcelona has reshaped data into public infrastructure through the "Technological Sovereignty" policy, uses distributed tools to protect citizens' data rights, and builds the vCity platform into a "sandbox" for policy negotiations (Barcelona City Council, 2018; Calzada & Almirall, 2020; Monge et al., 2022; Espelt et al., 2019; Raes et al.,



2025; Borghys et al., 2020). Bologna proposed "Citizen Digital Twin (CDT)", extending analogue objects to social behaviour and making the technical system a carrier of consultative democracy (Luca et al., 2024; Roversi, 2024; Radtke & Renn, 2024). Helsinki opened access to high-precision models through "Helsinki 3D+" to reduce barriers to innovation and build an "Energy and Climate Atlas" to support the carbon-neutral vision (Hämäläinen, 2021; Raes et al., 2025; Gonzalez Otero & Verhulst, 2025). To sum up, the "federal resilience" of the EU model does not come from centralised control, but from a set of institutionalised capabilities that can achieve interoperability under the constraints of rights and form cooperation in multi-subject participation.

Comparative and comprehensive

Based on the comparative dimension, this article summarises the core differences between the two governance prototypes in Table 1, supplemented by the e-government data in Figure 5 as empirical evidence (Wernick et al., 2023; Jørgensen & Ma, 2025). The comparison shows that the Chinese model is manifested as a governance combination with hierarchical system and integrated platform as the core, focussing on forming a closed loop with strong constraints and high speed through data aggregation and linkage, while the EU model is presented as a rights-oriented federal project, emphasising multi-level division of labour, procedural justice and cross-domain cooperation promoted through rules and funds.

Table 1. Comparison of China-style integrated platform vs EU-style rights-based federation (key dimensions)

Dimensions	The Chinese Model (City Brain)	EU Model (Citizen Twin)
Core Institutional Logic	State-led development, authoritarian efficiency	Digital sovereignty, deliberative democracy
Primary Objectives	Order, growth, security, speed	Sustainability, rights, inclusivity, consensus
Governance Architecture	Centralised, vertically integrated (government + conglomerates)	Federal structure, horizontal collaboration (MIMs standard)
Data Philosophy	Data as national resource (centralised management)	Data as a civic right (data commons/GDPR)
Decision-Making Cycle	OODA loop (automation/dehumanisation)	Sensing-Deliberation-Action (human-in-the-loop)
Market Structure	Winner-takes-all (state-backed entities dominate)	SME ecosystem (open-source/interoperability)
Transaction Costs	Low internal coordination costs, high asset specialisation risks	High internal coordination costs, strong adaptability and resilience
Key Dynamic Capabilities	Seizing: Rapid execution and mobilisation	Sensing: Multi-stakeholder input

Source(s): Authors' comparison

This difference is essentially an institutionalised response to data legitimacy and cross-subject collaboration, leading to significant differences between the two in capacity structure and risk exposure (Celeste, 2024; Floridi, 2020; Jørgensen & Ma, 2025).

On this basis, this article puts forward the "paradox of governance efficiency". In engineering tasks such as transportation governance, China UDT can efficiently generate output legitimacy by converting complex objects into computable indicators and organising rapid closed loops. However, efficiency is not the same as adaptability. Due to excessive reliance on internal feedback, when faced with value conflicts or high uncertainty, the system is prone to blind spots because of a lack of external calibration (Barsekh-Onji et al.,



2025). This structure strengthens the ability to "capture and execution", but weakens the correction mechanism through multi-subject negotiation (Teece et al., 1997).

On the contrary, the EU model has an institutional advantage in input legitimacy. By proactively addressing privacy and accountability issues, EU UDT has built a stronger foundation of trust (Celeste, 2024; Wernick et al., 2023; Jørgensen & Ma, 2025). However, this advantage comes at the cost of high coordination costs, and complex compliance processes may delay decision-making (Radtke & Renn, 2024; Radtke, 2025). The EU exchanged early institutional frictions for long-term accountability, focusing on interoperability and scalable reconstruction under the constraints of rights, rather than pursuing short-term diffusion speed (Open & Agile Smart Cities, 2025; European Commission, 2025a).

For transition economies, simple replication of any extreme is not sustainable. A reasonable strategy is to gradually expand the external calibration capacity to achieve a dynamic balance between efficiency and legitimacy while establishing a closed loop of minimum execution (Teece et al., 1997; Jørgensen & Ma, 2025).

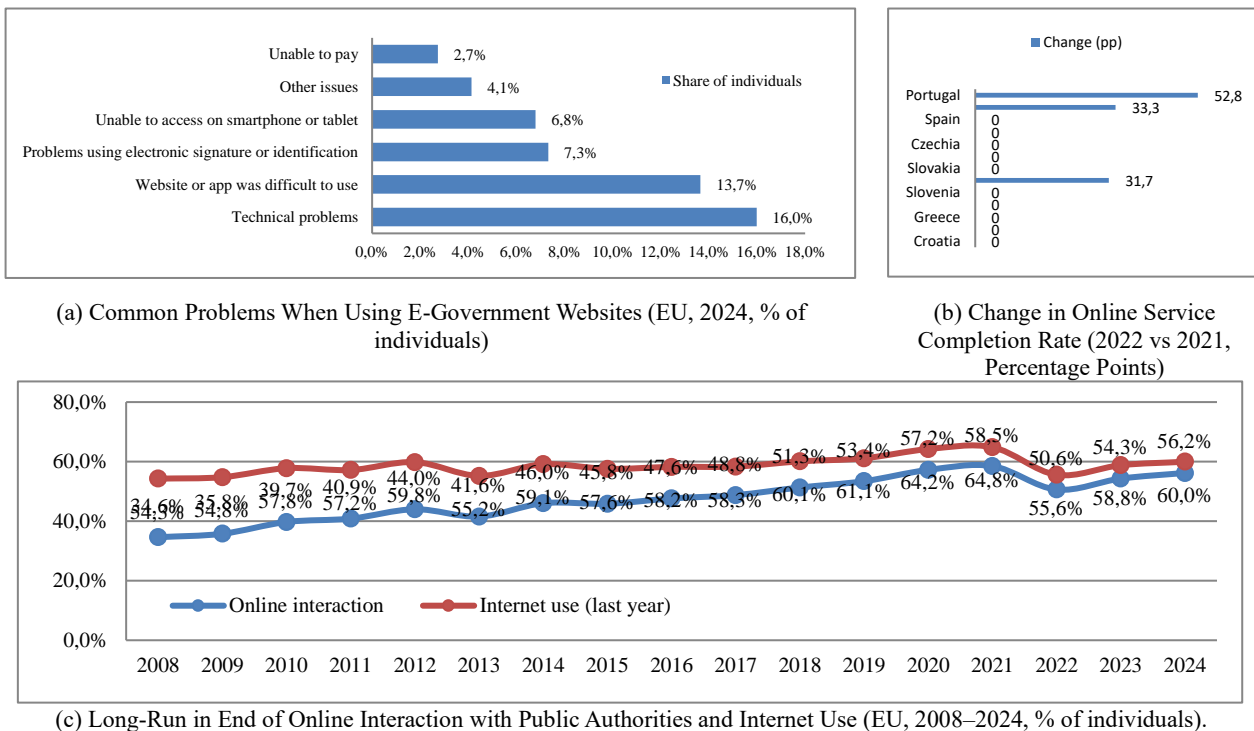


Figure 5. EU E-Government Friction and Service Delivery.
 Source(s): Eurostat; European Commission

This trade-off is specifically reflected in the empirical data in Figure 5. Figure 5(a) shows that technical and identity authentication issues constitute the main obstacles to EU e-government. These superficial experience problems actually reflect deep institutional requirements: the service process must meet strict safety and auditing standards, so experience improvement requires long-term coordination between the system and engineering (Wernick et al., 2023; Jørgensen & Ma, 2025). At the same time, Figures 5(b) and 5(c) show that improvements in supply-side capacity do not necessarily translate into linear growth or synchronous reductions



in friction at the user end. This means that there is a structural gap between "capacity-building" and "wide adoption" in the EU, and it must continue to invest resources to solve the problems of "good use" and "trust" in order to translate institutional progress into governance performance (Jørgensen & Ma, 2025; Wernick et al., 2023; Radtke & Renn, 2024). The problems of the "good use" and "trust" are associated with the enduring beliefs of the social groups in the preferred mode of conduct or choices – in other words, social values. Indeed, societal value orientations can directly impact public trust and compliance: in Latvia, individuals driven by self-centred values showed higher acceptance of tax evasion, whereas those with traditionalist and community-oriented values were more likely to pay taxes properly (Kaže et al., 2011). This finding illustrates how aligning digital governance efforts with prevailing social values can improve legitimacy and citizen cooperation.

To sum up, the Chinese model exchanges low coordination costs for visible performance but needs to be wary of accountability risks; the EU model establishes long-term legitimacy with the right boundaries but faces the challenge of compliance friction and a slow diffusion rate. The core issue in the future is how to build an intermediate path that can act quickly and continuously correct deviations under different institutional conditions.

DISCUSSION

Technical Deep Dive: "Perception-Capture-Reconstruction" Framework

The previous section reveals the structural tension in the China-Europe model between efficiency and legitimacy. To overcome this binary opposition, the governance performance of UDT should not be limited to visual fidelity or computing power, but to building a sustainable "perception, capture and reconstruction" closed loop. Combined with Singapore's practice, the framework aims to achieve an effective governance response without panoramic surveillance and facing value constraints (Zhou et al., 2025b).

In the "perception" link, given common data fragmentation and insufficient coverage in transition economies, the physics-informed neural network (PINN) offers an efficient compromise. Compared with pure data-driven methods that rely on massive samples, PINN achieves robust estimation with small samples by embedding physical laws and using engineering laws to address data shortcomings, thereby finding a technical balance between "perceptual depth" and "privacy boundary" (Zhou et al., 2025b).

The "capture" link determines whether the system can move from static display to dynamic decision-making. Deep Reinforcement Learning (DRL) transforms UDT into a "policy sandbox" and learns the output strategy rules through the trial-and-error of AI agents, yielding insights beyond intuition. For example, it is recognised that reducing heat gain under specific conditions is marginally more beneficial than improving equipment efficiency, thereby enhancing the technical value for structural decision support (Zhou et al., 2025b).

The "reconstruction" link concerns the embedding and social recognition of the governance process. The key is to quantify indicators such as finance, emission reduction and comfort into interpretable policy options (Zhou et al., 2025b). In a rights-oriented environment, this transparent trade-off can provide a basis for public deliberation, reduce the legitimacy dispute caused by technocratic decision-making (Radtke & Renn, 2024;



Radtke, 2025; Wernick et al., 2023; Jørgensen & Ma, 2025), and finally realise the dynamic coupling of the technical system and the social system (Teece et al., 1997). Moreover, emerging research even proposes novel methods to gauge individual human values for better policy alignment, reflecting an increased focus on integrating citizen motivations into digital governance (Kaže et al., 2022).

Strategic Enlightenment for Transitional Economies

For transition economies, strategic choices should not be reduced to a choice between Chinese-style integration and EU-style rights governance. The former is efficient but can expose vulnerabilities when feedback is insufficient (Barsekh-Onji et al., 2025); the latter has strong legitimacy but faces compliance friction and diffusion tension (Wernick et al., 2023; Jørgensen & Ma, 2025; Radtke & Renn, 2024; Radtke, 2025). The more pragmatic direction is to build a "mixed architecture" for situational adaptation.

First, interoperability should be regarded as the core "sovereign capacity". Transition economies should adopt open standards, represented by MIMs, to avoid falling into supplier lock-in from closed solutions. Through API openness and model standardisation, local small and medium-sized enterprises (SMEs) can participate in the ecological division of labour, thus enhancing path reversibility and governance autonomy (Publications Office of the European Union, 2024; Raes et al., 2025; Open & Agile Smart Cities, 2025; Floridi, 2020; Celeste, 2024). However, the success of such digital reforms also depends on stakeholder readiness – in Latvia, many SMEs were found to be at an initial stage of mastering e-environment tools (Ščeulovs et al., 2011), highlighting the need for improved digital literacy and inclusion to realize sustainable governance benefits.

Secondly, the "rebound effect" needs to be included in the policy design. In respect to the computationally intensive characteristics of UDT, which may bring additional emissions, the policy should introduce green IT indicators (Miszczak et al., 2024), requiring the system to have carbon perception and include energy consumption in the audit to avoid the legitimacy crisis caused by "digital emission increase".

Finally, "layered governance" should be implemented, and the principle of intelligent specialisation should be followed. The infrastructure layer should be centralised to ensure data continuity, while the application layer should be open to society to improve the iteration speed (Wernick et al., 2023; Jørgensen & Ma, 2025). At the same time, investment should prioritise advantageous scenarios for coupling with local industries, such as ports or manufacturing, to quickly form a closed loop of performance under resource constraints.

CONCLUSION

This study redefines urban digital twins (UDT) as governance infrastructure embedded within institutional boundaries, thereby making two complementary academic contributions. First, combined with the institutional logic and dynamic capability framework, this article demonstrates that the performance difference of UDT not only comes from computing power or data accuracy, but also depends on the institutionalised configuration of data rights, collaborative forms and accountability mechanisms. These factors reshape the public sector's ability in the "perception-acquisition-reconstruction" chain.



Secondly, by comparing China's integrated platform with the rights-oriented path of the European Union, the research reveals that "efficiency-legitimacy" is a trade-off structure shaped by institutional tools. The integrated platform achieves an efficient closed loop by compressing the OODA cycle, but it faces pressure to account for algorithmic decisions and limited innovation. Although the rights framework is accompanied by coordination friction and expansion delays, it establishes greater institutional robustness through procedural justice. The key insight of this article is that this trade-off is not a simple normative choice but must be internalised in the cost structure of system design, especially in response to crises and long-term development goals.

For transition economies, the way out is not to replicate the extreme model, but to build a mixed architecture that adapts to the situation. For economies that lack a large-scale market, interoperability is a strategic asset to maintain sovereignty and path reversibility. Effective strategies should use open standards, such as MIMs, at the infrastructure level to reduce locking risks, encourage multi-ecology at the application layer, and release innovation vitality while ensuring security through "layered governance", thereby achieving a dynamic balance between efficiency and legitimacy.

Future research can be expanded from three directions: first, introduce fine granularity indicators to distinguish the weight changes of output and input legitimacy; second, test the specific impact of interoperability process on cross-domain synergy; third, include green computing into the evaluation system to respond to the "digital rebound effect", providing theoretical support for the governance plan that takes into account efficiency, legitimacy and low-carbon goals.

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Conflict of interests

The authors declare no conflict of interest.

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About the authors



Weibo ZHOU

PhD candidate, Faculty of Humanities and Social Science, Daugavpils University, Daugavpils, Latvia.

Research interests: SDG management, green innovation, ESG, digital twins, circular economy.

ORCID ID: 0009-0009-3475-1092



Valters KAZE

Professor, Dr.oec., RISEBA University of Applied Sciences, Riga, Latvia.

Research interests: digital transformation, artificial intelligence, consumer behaviour and motivation.

ORCID ID: 0000-0003-1502-6994



Anatolijs KRIVINS

Associate Professor, Dr.iur., Faculty of Humanities and Social Science, Daugavpils University, Daugavpils, Latvia.

Research interests: business law, corruption, criminology, criminal law, public service, municipalities.

ORCID ID: 0000-0003-1764-4091

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