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Digital Twins for Climate and Air Quality Policy: A Decision Tool for Smart Cities or Technocratic Illusion?

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Abstract: Digital twins are increasingly promoted as advanced decision-support tools for climate change mitigation and air-quality management. By creating data-driven virtual replicas of cities, infrastructures, and environmental systems, digital twins promise improved forecasting, scenario testing, and evidence-based policymaking. Governments and international organizations often frame these technologies as objective and neutral solutions capable of improving policy decisions and environmental outcomes. Despite their rapid adoption, there is limited critical evaluation of whether digital twins genuinely enhance climate and air-quality decision-making or whether they reinforce technocratic forms of governance that marginalize political accountability, human judgment, and local knowledge.

This research will critically examine the role of digital twins in climate and air-quality policy from a governance and decision-quality perspective. Touching interdisciplinary literature from environmental policy, science and technology studies, and AI governance, the study will analyze how digital twins frame environmental problems, define "optimal" outcomes, and represent uncertainty. Using comparative case studies of digital twin initiatives in selected smart cities and climate policy programs, the research will evaluate whether these systems improve transparency, inclusiveness, and accountability in policymaking or instead function as technocratic instruments that obscure value judgments and concentrate decision-making power.

This study contributes to debates on smart cities, algorithmic governance, and public-sector innovation by challenging techno-solutionist assumptions in environmental governance. It aims to inform policymakers and researchers about the conditions under which digital twins can serve as meaningful decision-support tools rather than technocratic illusions in climate and air-quality policymaking.

Keywords: *Digital Twins; Smart Cities; Urban Digital Twin; Environmental Governance; Air Quality Management; Policy Decision-Making.*

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I. INTRODUCTION

➢ *Context and Background*

Two of the gravest public and environmental health threats of the twenty-first century are air pollution and climate change (Al-Thani & Isaifan, 2024; Isaifan & Al-Thani, 2024). According to the State of Global Air (2024), approximately 8.1 million deaths in 2021 were caused by air pollution, making it one of the leading causes of death worldwide (Brauer, 2024). The exposure is the greatest among low and middle-income countries, as most of them have lower regulatory potential. Urban pollution and climate change are associated with rising temperatures, changes in weather, and extreme events (Al-Thani & Isaifan, 2025). Given this, cities are the most vulnerable in this context due to population density, transport systems, and great energy consumption, making them the center of emission generation and exposure risks.

In response to the worsening air quality and climate change worldwide, in 2021, the WHO narrowed its Global Air Quality Guidelines (2024). The new requirements set significantly lower particulate matter thresholds than those observed in several cities. They underscore that even minimal

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changes in exposure can bring about major health improvements. Thus, these stricter standards point to gaps between scientific evidence and existing policy practices. They also emphasize the sense of urgency in the process of enhancing urban management of air quality and embedding climate and health agendas.

➢ *Agendas of Smart Cities and Digitalization*

A major response to these pressures has been the fast digitalization of urban governance under the umbrella of smart cities. Tech firms and municipalities impose data-oriented, sensor-based, and algorithmically optimized methods to handle mobility, infrastructure, and environmental risks. Due to this, smart city projects are usually motivated by promises of providing better service and more efficient use of public resources. They also contend to aid more prompt and precise actions through the near-real-time data. This shift has resulted in expanded monitoring networks and increased sophisticated analytics.

A combination of regulatory monitoring locations, low-cost sensors, and satellite data within the cities generates dense spatial coverage. Short-term pollution predictions and source allocation are enhanced with the help of machine learning and associated models (Topping et al., 2021). Urban authorities now use sensor networks, data platforms, and predictive systems to monitor environmental threats and assist in response. In such a landscape, digital twins have become a commendable and often celebrated tool in smart city agendas.

➢ *Digital Twins: Definition and Applications*

The digital twin idea started in the engineering field (Fuller et al., 2020). It is a virtual symbol of a dynamically related physical object or system that is in constant interaction through data exchange. However, with time, the concept has extended beyond product life cycle management to more complicated systems, such as infrastructure, cities, and environmental processes. Experts agree that a digital twin is a virtual representation of a real-world object or system that is controlled by real-time data to reflect and predict the behavior of its real-world counterpart (Fuller et al., 2020).

According to field surveys, they have many similar features. For instance, they consist of two-way data change between virtual and physical places, dynamic modeling, and twins' usage to assist tracking, diagnostics, optimization, and scenario examination (Rasheed et al., 2020). The idea has been transferred to cities, not just on individual assets, but also to districts and whole urban systems. Batty defines urban digital twins as digital copies of the city systems that are closely intertwined with the physical presence and may serve as sensors, controllers, monitors, predictors, and design aids (Batty, 2018).

Notably, various urban-based projects make use of three-dimensional geospatial and building information models along with information on traffic, energy consumption, and environmental factors (Al-Mohannadi et al., 2023). They also provide this data on interactive systems that can be questioned and edited by officials. The applications here are widespread, such as using simulation digital twins in transportation to model traffic flows, test route techniques, and understand how new infrastructure impacts congestion and emissions (Lis & Mądziel, 2026; Wu et al., 2025).

Furthermore, digital twin modeling in infrastructure and energy provides performance and utility networks to enable efficiency metrics and predictive maintenance across various applications (Prasath & Vishnupriya.T, 2025). On a considerably greater scale, the Destination Earth program by the European Commission is an attempt to create a very detailed digital twin of the Earth (*Destination Earth*, 2026). It aims to model climatic processes, catastrophic weather, and human-ecosystem interactions, helping to support the European Green Deal (Bauer et al., 2021). These examples demonstrate how digital twins can bridge complex information and tangible policy decisions.

In addition, digital twins are advanced in the sphere of air quality as they can combine heterogeneous data streams and provide granular, adaptive governance. Topping et al. (2021) postulated that an urban air quality digital twin can consume real-time data on monitoring networks, cheap sensors, satellite data, traffic, and meteorological data to present an end-to-end decision system that encodes local dependencies (Topping et al., 2021). IoT sensors, weather stations, and open data are incorporated into prototypes that are developed on top of platforms like FIWARE to monitor pollutant concentrations within the city, predict changes based on prevailing weather conditions, and issue alerts when these thresholds are surpassed.

Conceptual work defines air quality digital twins as a dynamic virtual reflection of atmospheric pollution (Air Quality Digital Twins, Sustainability Directory). Such systems enable the visualization of pollution patterns and the exploration of what would happen in a situation, such as traffic restrictions or industrial controls (Bauer et al., 2021). Besides this, they can also aid in basic reasoning about health consequences in various interventions. This yields three main benefits: digital twins enhance efficiency as they make it possible to test the policies and infrastructure virtually; they have a higher predictive capacity due to their advanced models; and they can provide insight into potentially objective data to decision makers (Bauer et al., 2021).

➢ *Problem Statement and Research Gap*

Despite their potential, the rapid deployment of digital twins in smart cities and environmental agendas has generated notable concerns regarding their implications and governance. According to critical scholarship, dominant narratives focus on the technical sophistication and objectivity, instead of the normative and political nature of designing and using digital twins (Batty, 2018). On the contrary, they believe these factors are being downplayed. Like any other model, digital twins are based on assumptions, selective data inputs, and certain algorithmic decisions. These factors shape their representation and neglect mechanisms. Therefore, climate digital twin commentators warn that large-scale simulations risk personifying nature as a machine. They diminish complexity and uncertainty, and, particularly, social processes, when considering social processes. It has been noted that reliable twins need close consideration of the measurement of errors, bias in low-cost sensor networks, and the development of atmospheric science in urban air quality (Topping et al., 2021). In a scenario where attention is not given, there is a possibility that seemingly accurate output will conceal constraints and foster overconfident judgments about health and environmental dangers.

Moreover, the conceptualization of digital twins as governance-enhancing tools may signal an underlying reliance on technological solutionism in addressing complex systemic challenges. Morozov applies this term to solve complicated social and political problems with technical solutions as the main approach (Morozov, 2013). Opponents of the smart city projects claim that such projects can give preference to efficiency and optimization rather than justice, participation, and pluralism. They can remove issues about the governance of cities. Based on empirical research of urbanized digital twins, it has been found that such systems can also lead to concentrating power in technical communities and their vendors, while citizens are provided with simplified interfaces and few places of influence over models.

While the technical literature on digital twins in urban contexts is expanding, it is largely confined to definitions, architectural design, data integration, and performance evaluation, with a primary focus on engineering and computer science disciplines. There is limited research on how digital twins can transform the framing of environmental problems, decentralize power, or manage uncertainty and contest in policymaking. Science and Technology Studies offer ample ideas in examining the relationship between knowledge, technology, and social order in terms of how it is shaped by one another (Jasanoff, 2004). But these lessons are just starting to be used in the environmental governance of digital twins. This introduces a definite gap in research at the point of the intersection of digital twin technologies, air quality management, and critical governance analysis.

- *Objective and Significance of Research*

The overarching aim of this study is to provide a critical analysis of the role and implications of digital twin technologies in shaping urban air quality governance (Figure 1).

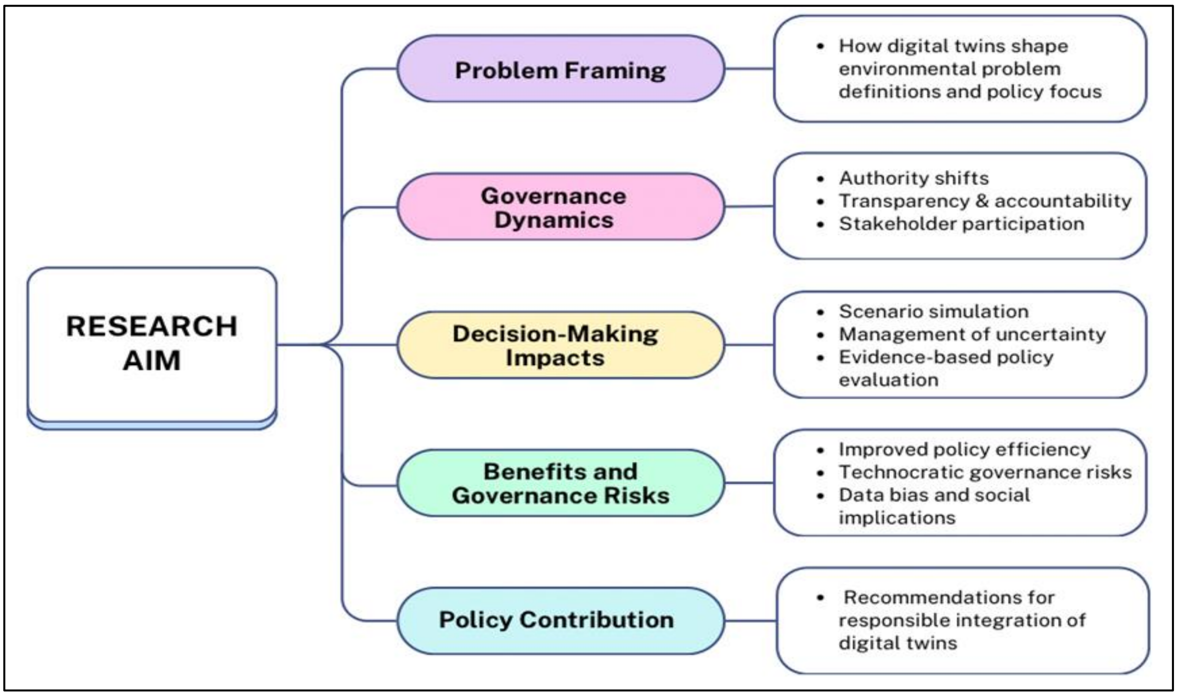

Fig 1 Analytical Framework of the Research Objective
Source: the Authors.

This study is grounded in the theoretical foundations of Science and Technology Studies (STS), technocracy, and technological solutionism, as reflected in the environmental governance literature. It moves beyond purely technical or celebratory accounts to develop a contextualized understanding of how digital twins interact with institutional structures, power dynamics, and public participation. More specifically, the paper critically examines how digital twin discourse is constructed and embedded within smart city agendas and environmental policy frameworks. It analyzes their implications for air quality governance, including shifts in authority, decision-making processes, and the management of uncertainty. Furthermore, the study evaluates both the opportunities and limitations of air-quality-focused digital twin applications through selected case studies. Building on this analysis, it proposes policy-relevant recommendations

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for integrating digital twins into air quality governance in ways that complement, rather than substitute, human judgment, political oversight, and stakeholder deliberation.

Theoretically, this research aims to contribute to the emerging body of literature that assumes that digital twins are sociotechnical assemblages that promote the emergence of specific imaginaries of environmental control and urban futures. In practice, it covers an area of policy where the stakes are great. The quality of air has a direct effect on human health and, in many cases, disproportionately affects already vulnerable groups, such as the residents of low-income neighborhoods and areas in the Global South.

The decisions about the design, governance, and interpretation of digital twins will determine what interests are privileged and which knowledge is counted as the cities and the national governments continue their extensive investment in digital infrastructure and projects like Destination Earth. These decisions will also influence the tradeoffs between health, climate mitigation, and economic development. By defining these problems, the paper would help justify more transparent, inclusive, and reflective applications of digital twins in air quality governance.

II. METHODOLOGICAL APPROACH

➢ *Research Design and Literature Selection*

This study adopts a qualitative critical review design to examine the role of digital twins in air quality management and climate governance (Fuller et al., 2020). Rather than aiming for exhaustive coverage, the review seeks to provide an analytically grounded synthesis of current scholarship and policy discourse, with a focus on the governance implications of emerging digital technologies. The approach is interdisciplinary, drawing on insights from environmental policy, Science and Technology Studies, and digital governance literature.

A targeted and iterative literature identification strategy was employed to capture relevant academic and policy sources (Azadi et al., 2025). Searches were conducted across major databases, including Scopus, Web of Science, and Google Scholar, using combinations of keywords such as "digital twins," "air quality management," "climate governance," "AI in environmental policy," and "urban digitalization." Sources were selected based on their conceptual relevance, contribution to the field, and recency, with priority given to peer-reviewed journal articles, high-impact reports, and influential policy documents. Additional sources were identified through backward and forward citation tracking to ensure adequate coverage of foundational and emerging contributions.

The analysis was conducted using a qualitative thematic synthesis approach. Selected sources were iteratively reviewed to identify recurring patterns, conceptual tensions, and governance challenges associated with the deployment of digital twins (Figure 2). The interpretation was guided by theoretical lenses from STS, particularly concepts related to technocracy, data-driven governance, and techno-solutionism. This framework enabled a critical examination of how digital twins are positioned as decision-support tools, and the extent to which they reshape authority, accountability, and epistemic practices in environmental governance.

To contextualize the discussion, selected real-world applications of digital twins in urban and environmental management are used as illustrative examples. These cases are not treated as formal comparative case studies, but rather as empirical anchors that demonstrate how digital twin technologies are being implemented across different governance contexts. Case selection was based on their relevance to air quality and climate-related applications, as well as their representation in the existing literature.

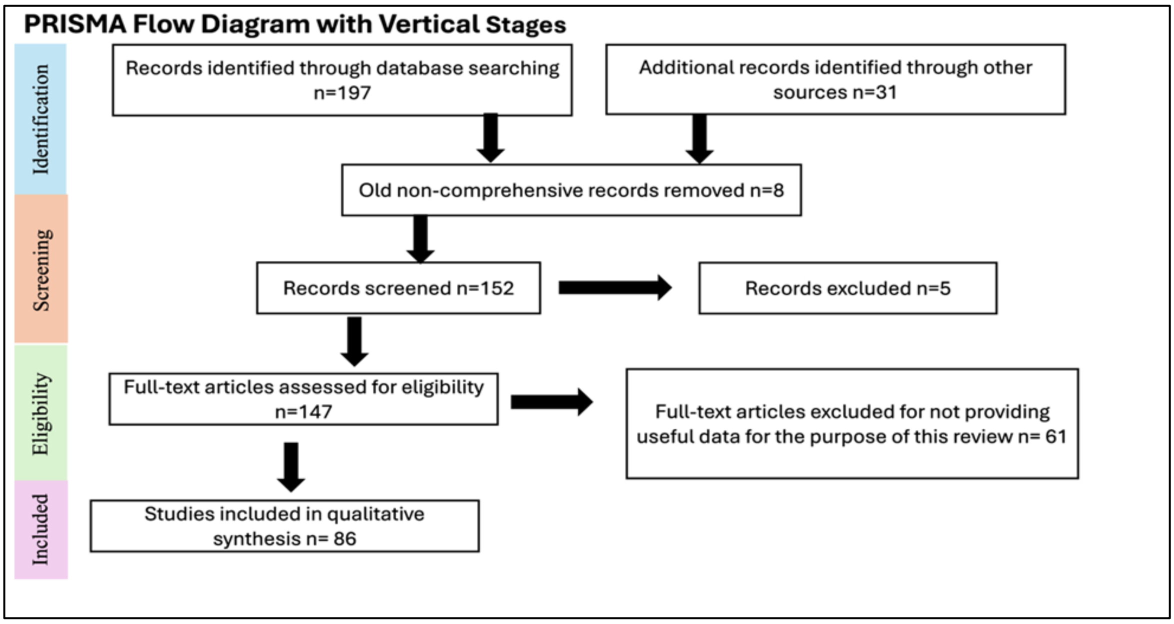

Fig 2 Literature Review Selection Process
Source: the Authors.

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➢ *Analytical Approach*

- *Qualitative Document Analysis*

The study adopts qualitative document analysis as its principal methodological approach, undertaking a systematic and structured review of the selected literature and platforms to elucidate recurring themes related to authority, legitimacy, and governance dynamics (Knopf, Macq & Wentland, 2025). This methodological approach is essential as it enables the systematic tracing of how digital twin systems are framed, justified, and operationalized within policy and scholarly discourse. Through thematic analysis, the study examines how narratives of efficiency, optimization, and performance frequently displace considerations of democratic accountability and public participation in official policy frameworks. Moreover, qualitative document analysis ensures that the analytical focus remains on institutional practices, governance logics, and discursive constructions, rather than on the technical specifications of the underlying technologies.

- *Comparative Case Study Analysis*

This project uses a comparative approach to look at different scales of digital twin implementation. By comparing a local city-scale project to an international effort like Destination Earth, the research can identify universal patterns in how these technologies are deployed (Steiner, 2025). This comparison reveals that there is no single objective way to build a digital twin. Instead, the design of each system reflects the specific political and institutional environment where it was created. And it highlights the diversity of approaches and the subjective nature of what counts as a successful simulation.

- *Critical Discourse Analysis*

This research also relies heavily on Critical Discourse Analysis (CDA) to reveal the power dynamics hidden within policy language (Jasanoff, 2004). CDA focuses on how words are used to establish authority and minimize public disagreement. When a government report describes a digital twin as precision-based or real-time, it is making a specific rhetorical move because it is structuring the narrative to suggest complete scientific certainty. This language treats simulation as the ultimate authority.

With CDA, this research shows that the language of total certainty is a way of bypassing democratic consideration. By telling the public that the machine has given the precise answer, governments imply there is nothing left to debate. This makes the resulting policy feel like a certainty rather than a political choice. It frames technology as an authority rather than a tool for discussion.

➢ *Conceptual Framework*

- *Science and Technology Studies*

Science and Technology Studies (STS) serve as the main theoretical framework for this study. This field is significant because it challenges the popular belief that computer programs are neutral or objective. Technologies are never simply tools, according to STS. These are social constructs that take into account the assumptions of their creators (Jasanoff, 2021). A digital twin is more than just a neutral representation of reality. Based on algorithmic decisions and specific data inputs, it actively creates a version of reality (Batty, 2024).. Every piece of code that determines which pollutants to monitor and which to disregard, for instance, is a value judgment.

A model will produce a biased policy if it prioritizes traffic emissions but lacks structural knowledge about industrial factory output. STS enables this study to break down the digital twin and uncovers hidden political choices. Because the maker has the last say over what is not displayed on the map, the map is not fair. Digital twins create the world they are measuring, according to STS's central claim.

- *Technocracy*

Additionally, the study makes significant use of the concept of technocracy. And this refers to a form of government in which technical experts and specialized systems take over decision-making authority from elected officials (Morozov, 2013). Technocracy poses a serious threat to democratic discourse in the context of climate policy.

By reframing inherently political challenges as technical problems, digital twins can function as instruments of depoliticization (Knopf, Macq & Wentland, 2025). When policy decisions are presented through simulation outputs portrayed as objective or mathematically definitive, the scope for public contestation may be significantly reduced. This dynamic can create epistemic barriers, where meaningful participation appears contingent upon specialized technical expertise, thereby discouraging broader civic engagement. Accordingly, this study examines how digital twins may operate as exclusionary governance spaces that limit public access and deliberation. It critically interrogates the risk of enclosing political decision-making within technocratic frameworks, where debates are constrained by technical narratives and the capacity of the public to question, interpret, or challenge policy choices is diminished.

- *Techno-Solutionism*

Techno-solutionism is a key part of this structure. It describes the deeply flawed but popular belief that big social and political challenges can be solved primarily through technological innovation (Morozov, 2013) (Morozov & Bria, 2016). In urban air quality management, this mindset frames environmental degradation as just a data optimization problem (Bollano, 2025) (Azadi et al., 2025).

This research highlights the trap of viewing the city as a giant machine that just needs to be adjusted. Techno-solutionism often serves as a convenient distraction for politicians. If a mayor can point to a new 3D map as a solution for climate change, it takes the pressure off the administration to perform unpopular work. This might include confronting major corporate polluters or addressing historical urban planning decisions where low-income neighborhoods were intentionally placed next to highways. This study argues that you cannot solve these structural realities simply by improving traffic light patterns with a simulation.

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➢ *Data Sources and Case Selection*

To establish the conceptual framework, this research draws on a diverse set of qualitative data sources that reflect both governmental and industry perspectives on digital twin development and deployment. Governmental white papers produced by municipal planning offices are analyzed to identify the official objectives associated with digital twin initiatives, as well as the policy narratives and justifications used to support large-scale public investments. In parallel, municipal air quality platforms are examined as public-facing digital interfaces through which environmental data is visualized and communicated, enabling analysis of how information is framed for public consumption and which indicators are prioritized in decision-making contexts.

In addition, communications from technology vendors, including marketing materials and promotional reports, are reviewed to understand how digital twin technologies and smart city solutions are presented to policymakers and urban authorities. These sources are particularly valuable for identifying the underlying techno-solutionist narratives that shape expectations around technological intervention in complex environmental challenges. Finally, the European Union's Destination Earth (DestinE) initiative is used as a primary case study. As a large-scale digital twin project aimed at creating a high-resolution virtual model of the Earth, DestinE provides critical insight into how climate governance is increasingly mediated through advanced simulation systems and centralized data infrastructures (Bauer, Stevens & Hazeleger, 2021) (Destination Earth, 2026).

➢ *Rationale and Evaluative Criteria*

The rationale for this specific mix of methods is to ensure the research captures the human element of urban infrastructure. Because you cannot understand the political impact of a digital twin by looking at a server rack, instead, you must look at how technology changes the way we talk about our communities. To evaluate these systems, the research establishes four specific governance criteria (Table 1). First, does the tool improve transparency by showing what data was excluded? Second, does it clarify uncertainty rather than hiding it behind graphics? Third, does it strengthen institutional accountability by making it easier to trace why a policy was chosen? Fourth, does it expand stakeholder participation by giving the community a greater voice?

Table 1 Governance Evaluation Criteria

Governance Criterion	Evaluation Question	Purpose
Transparency	Does the tool show what data was excluded?	Promotes openness in the modeling process
Uncertainty Communication	Does the system clarify uncertainty instead of hiding behind graphics?	Prevents misleading representations
Institutional Accountability	Can the decision-making process be traced?	Ensures responsibility in governance
Stakeholder Participation	Does the system allow community involvement?	Encourages democratic engagement

This qualitative and interdisciplinary approach provides a robust analytical foundation for critically assessing the accountability of emerging digital systems. It shifts the evaluative focus toward determining whether such tools genuinely enhance human decision-making or instead reproduce new forms of digital exclusion. In doing so, it reorients the inquiry beyond technocratic concerns of computational accuracy toward fundamentally normative questions of governance, specifically, whether policy processes remain transparent, inclusive, and democratically grounded.

To place these criteria in a wider context, Figure 3 shows the main pillars of good governance and the role of Information and Communication Technology (ICT) in supporting them. This helps connect the evaluation criteria to broader ideas about how governance should work in practice. It also shows that digital twins should not only be judged by how well they function technically, but by whether they support more transparent, inclusive, and accountable decision-making.

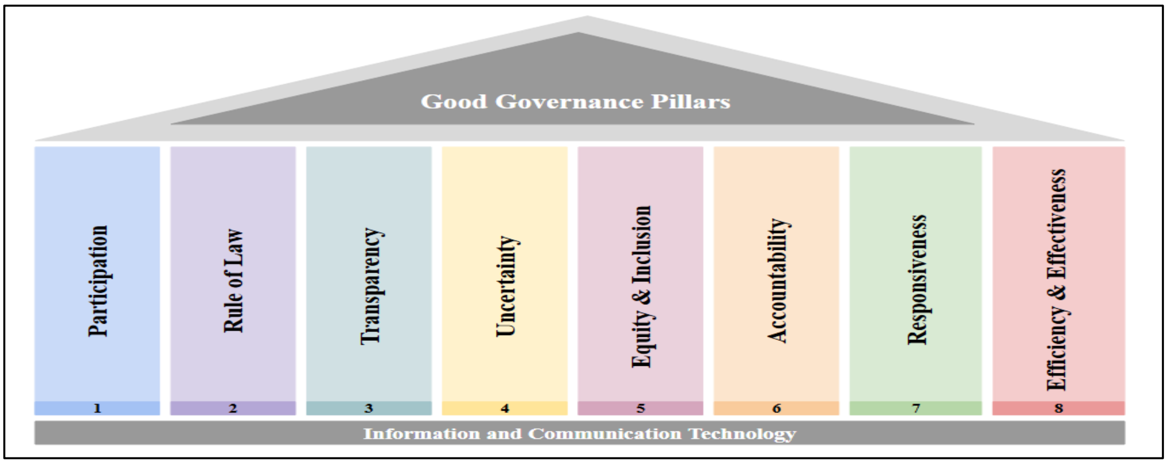

Fig 3 Governance Evaluation Framework Applied in this Study
Source: the Authors.

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III. THEMATIC ANALYSIS OF DIGITAL TWINS IN ENVIRONMENTAL GOVERNANCE

➤ *Digital Twins and the Reconfiguration of Policy Decision-Making*

Digital twins are often presented as tools that can make environmental policymaking more precise, efficient, and responsive (Batty, 2018) (Fuller et al., 2020). The idea sounds appealing: if governments can create a digital replica of a city and simulate environmental changes in real time, policymakers can test decisions before implementing them in (Rasheed et al., 2020). Traffic restrictions, emission policies, or infrastructure investments can be modeled and adjusted within the digital environment before they affect actual communities (Azadi et al., 2025) In theory, this kind of simulation reduces uncertainty and allows governments to make better-informed decisions (Knopf, Macq & Wentland, 2025).

However, the relationship between digital twins and policymaking is not quite as straightforward as it sometimes appears. While these systems provide new analytical capabilities, they also influence how environmental problems are understood and framed (Batty, 2024). A digital twin does not simply display reality. It represents reality through a specific set of data inputs, modeling assumptions, and design choices (Batty, 2024). These choices shape what policymakers can see and what they may overlook (Saltelli et al., 2024).

For example, digital twins are particularly effective at analyzing measurable environmental variables such as emissions levels, traffic flows, temperature changes, or pollution concentrations (Fuller et al., 2020). These types of data can be collected through sensors, satellites, and monitoring stations, and then integrated into computational models (Azadi et al., 2025). When policymakers interact with a digital twin, they often see visualizations and simulations based on these measurable indicators (Knopf, Macq & Wentland, 2025). As a result, policy discussions may begin to focus more strongly on problems that can be quantified and modeled. Environmental challenges that are harder to measure, such as long-term social vulnerability or unequal exposure to pollution, may receive less attention simply because they are more difficult to represent within a simulation (Azadi et al., 2025).

Another important aspect of digital twins is their ability to support scenario planning. Policymakers can explore multiple “what-if” scenarios before implementing environmental policies (Bauer, Stevens & Hazeleger, 2021). For instance, a city might use a digital twin to test how introducing a low-emission zone would affect air quality across different neighborhoods (Topping et al., 2021). Another scenario might simulate the environmental effects of expanding public transportation networks or changing traffic flows (Azadi et al., 2025). These simulations allow governments to compare outcomes and identify policies that appear more effective according to the model (Knopf, Macq & Wentland, 2025)

At the same time, scenario simulations can create the impression that policy decisions are primarily technical exercises rather than political ones (Morozov & Bria, 2016). If a digital twin suggests that one option produces slightly lower emissions than another, it may appear to be the objectively “correct” choice. But environmental policy rarely depends on a single variable. Decisions often involve trade-offs between economic costs, social impacts, and long-term sustainability (Azadi et al., 2025). A simulation may highlight one dimension of the problem while leaving others less visible (Batty, 2024).

Digital twins can also change the tempo of policymaking. Because they provide real-time or near-real-time data, they encourage a style of governance that prioritizes continuous monitoring and rapid response (Fuller et al., 2020) (Rasheed et al., 2020). In some situations, this can be beneficial, particularly when dealing with environmental emergencies such as pollution spikes or extreme weather events (Bauer, Stevens & Hazeleger, 2021). Governments can identify risks earlier and respond more quickly.(Knopf, Macq & Wentland, 2025), however, a stronger focus on real-time management may also shift attention away from slower structural solutions that require long-term planning and political negotiation (Topping et al., 2021).

These observations do not suggest that digital twins are inherently problematic. In many cases, they genuinely improve the ability of governments to understand environmental systems and evaluate potential interventions (Batty, 2018) (Knopf, Macq & Wentland, 2025). What they do show is that digital twins do more than provide technical information. They shape the context in which policy decisions are made. By emphasizing certain forms of data, encouraging simulation-based planning, and promoting real-time monitoring, they influence how environmental governance operates in practice (Batty, 2024).

For this reason, digital twins should be understood not only as technological tools but also as political instruments embedded within governance systems (Jasanoff, 2004). Their value depends not only on technical accuracy but also on how their insights are interpreted, debated, and integrated into broader decision-making processes (Knopf, Macq & Wentland, 2025).

➤ *Technocracy, Expertise, and Authority*

A technocratic framework helps explain how digital twins are reshaping authority in policymaking. Digital twins are not just neutral tools; they influence who holds power, how decisions are justified, and what is considered reliable knowledge. This influence is particularly visible with Local Digital Twins (LDTs) in smart city governance.

First, digital twins increase reliance on technical experts. Both the urban freight study and the LDT chapter show that these systems depend on data, simulation models, and assumptions about human behaviour (Marcucci, 2020) (Raes et al., 2025). Their complexity means that only specialists can fully understand how they operate and

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interpret the results. Experts, therefore, play a central role in explaining the outputs. Policymakers still have the final decision-making authority, but they often depend on expert interpretation. In this way, technical knowledge becomes a significant source of influence within the policy process.

Second, policymakers may become increasingly dependent on model outputs. LDTs support decision-making across the entire policy cycle, including design, implementation, and evaluation, through descriptive, diagnostic, predictive, and prescriptive analysis (Raes et al., 2025). This broad capacity makes them influential in practice. When a model can show what is happening, why it is happening, and what might happen next, it can make certain policy options appear more effective or rational than others. Policymakers may therefore feel pressure to follow the options indicated by the model, especially when these outputs are presented as evidence-based. This demonstrates a technocratic approach in which technical results begin to guide political choices. This effect is reinforced because LDTs connect long-term planning with everyday decision-making. By helping to "close the gap" between policy design and implementation, they embed model-based analysis throughout the process (Raes et al., 2025). While this improves coordination and responsiveness, it also increases reliance on the models and the experts who manage them over time.

Third, there is a risk that decision-making authority shifts from elected officials to technical specialists. This shift is often indirect. Experts influence how models are built, what data is included, and how results are interpreted. Policymakers who act against a model's recommendation may appear to disregard evidence. Over time, this can reduce the scope for political judgment. Both sources note that models cannot fully capture the complexity of reality and depend on assumptions that are not always transparent to non-experts (Marcucci, 2020) (Raes et al., 2025), which makes critical evaluation difficult and limits debate.

At the same time, LDTs are designed to involve different stakeholders, including citizens, in interpreting the data (Raes et al., 2025). This promotes a more inclusive approach to decision-making. However, those with greater technical knowledge are still likely to have more influence, particularly when managing complex simulations. Therefore, digital twins, especially LDTs, have the potential to restructure authority in governance systems. They increase reliance on experts, encourage policymakers to depend on model outputs, and can shift influence away from elected officials. While they improve the use of evidence in policymaking, they also raise important questions about accountability, transparency, and the balance between technical expertise and democratic decision-making.

➢ *Digital Twins and Techno-Solutionism*

Digital twins are often known for their powerful technological tools and their ability to solve complex environmental challenges in modern cities. This perspective strongly connects with what Evgeny Morozov & Bria (2016) describes as technological solutions; the belief is that technological innovations can provide efficient answers to social and political problems (Morozov & Bria, 2016). In the field of environmental governance, policymakers are already touting digital twins as tools to optimise urban systems and simulate policy impacts on climate and air quality. These technologies are often embraced by policy-makers, governments, and smart-city initiatives as objective, apolitical, technical systems that will identify the most efficient environmental policies. Scholars have similarly warned that smart-city technologies can oversimplify urban challenges by prioritising technological optimisation over broader governance considerations (Kitchin, 2014). These assumptions flatten multifaceted, entangled environmental problems, reducing them to inputs for narrow calculations, rather than questions of social behaviour, political priorities, and economic organization.

Digital twins align closely with techno-solutionist narratives, drawing on big data and predictive modeling to inform policy prescriptions. By enabling policymakers to simulate alternative scenarios, such as traffic restrictions, emission controls, or energy transitions, these systems generate virtual representations of urban environments and offer projections of potential outcomes. On one level, such a model dependency helps distill the complexity of otherwise highly dynamic and opaque ecological systems, where air pollution is intrinsically linked to the design and regulation of urban spaces. However, while these tools provide valuable analytical support for decision-making, they also risk abstracting environmental governance from its broader social and political dimensions. In doing so, they may privilege technical optimization over considerations of equity, accountability, and public deliberation. Figure 4 is a representation of the core components of a digital twin, illustrating how a physical object is represented, monitored, and linked to its virtual counterpart. These components form the foundation of a DT-DSS system, enabling simulation, visualisation, and predictive analysis.

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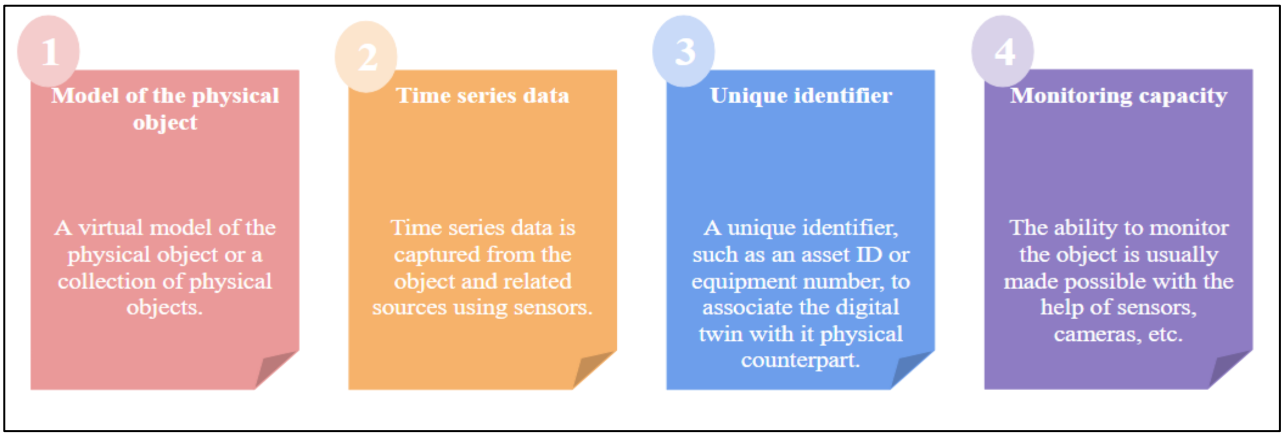

Fig 4 Core Components of a Digital Twin
Source: the Authors.

Effective solutions to environmental threats (such as air pollution and climate change) require more than sophisticated modelling tools. Designing effective policy responses often involves much more than just running a digital simulation. For example, city governments adopt policies to reduce urban air pollution. Nonetheless, these are controversial choices that involve tricky trade-offs between economic growth and public health, as well as political viability. Digital twins can simulate possible results of those policies, although, of course, they cannot say whether they would be socially or politically acceptable. As scholars in science and technology studies argue, technological systems cannot be separated from the political and social contexts in which they operate (Jasanoff, 2016). However, leaving everything to technical systems risks missing an important truth: environmental governance is always a question of values and political negotiation.

Digital twins can certainly strengthen the hand of data and analytics in environmental policy-making. To view digital twins through the lens of technological solutionism would be to lack a critical perspective on the role technology can and should play in policy processes. They should present digital twins as decision-support systems for augmenting, rather than replacing, political judgment. The expansion of their use risks entrenching a technocratic mode of policymaking, in which decisions appear to be determined by technical systems. Critics have therefore questioned whether digital twins improve environmental governance or simply shift it toward technocratic governance.

Digital twins (DTs) combined with decision support systems (DSS) are changing how cities plan and manage urban renewal projects. Instead of just tracking data, DT-DSS systems let planners see how different risks-structural, environmental, and social-interact. This turns digital twins from simple models into active tools that guide decisions (Raes et al., 2025).

One big advantage is the ability to run "what-if" scenarios across different areas at once. Urban renewal is complex: building decay, environmental risks, and social displacement often happen together. Traditional methods, relying on past data or expert judgment, often miss these cascading effects. DT-DSS systems let planners test strategies and see possible knock-on effects before taking action, making planning more proactive (Raes et al., 2025).

Visualization is also important. Showing data on buildings, the environment, and social factors in one interface makes it easier to understand trade-offs. Planners don't have to switch between dashboards for cost, safety, or compliance; integrated systems provide a clear view of how decisions affect multiple areas. Predictive forecasting is another key benefit. Continuous sensor data allows models to update in real time, helping managers spot problems before they happen and turning risk management into an ongoing process rather than a series of reactions. (Raes et al., 2025).

There are limits, though. Models depend on assumptions, data quality, and how well systems work together. City data is often incomplete, and overreliance on models can give a false sense of certainty. Dashboards and metrics provide clarity but cannot fully capture social dynamics, politics, or community input. If predictions are treated as fact, human judgment can be pushed aside, and measurable outcomes may be prioritized over ethical considerations like fairness or long-term social impacts (Raes et al., 2025).

In short, DT-DSS tools give cities powerful ways to plan and manage complex urban projects, but their value depends on oversight, critical thinking, and integrating human expertise alongside model outputs.

➢ *Ethical Limits of Digital Twins in System Management*

Digital twins offer unprecedented levels of insight and control over infrastructure, production, and environmental systems; however, their capabilities remain inherently limited. Regardless of their sophistication, digital twins cannot autonomously adjudicate questions of fairness, access, or social equity (Raes et al., 2025). In infrastructure contexts, their effectiveness stems from the relative stability and measurability of physical assets such as roads, bridges, and buildings. While these models can optimize traffic flows or resource allocation, they cannot determine the distributional consequences of such optimizations, potentially leaving marginalized groups excluded.

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In production systems, digital twins frequently reduce complex social and environmental challenges to simplified metrics, prioritizing efficiency or profitability over equity considerations (Raes et al., 2025). These limitations are further amplified in environmental and social domains, where climate dynamics, ecosystems, and human behavior are highly complex and interdependent. Although digital twins can inform decision-making, they cannot ensure desirable or equitable outcomes. Overreliance on such models risks privileging technical outputs over ethical and social considerations, thereby obscuring trade-offs and potentially exacerbating existing inequalities.

➢ *Transparency, Uncertainty, and Data Bias*

While digital twins provide new opportunities for environmental monitoring and analysis, they also raise governance challenges related to transparency and data control. These potential benefits and concerns are summarized in Table 2.

Table 2 Benefits and Governance Challenges of Digital Twin Technologies

Aspect	Potential Benefits	Governance Challenges
Data Analysis	Improved understanding of environmental systems	Data privacy concerns
Decision Support	Ability to simulate policy outcomes	Over-reliance on technical models
Urban Management	Better coordination between city departments	Unequal access to data
Environmental Policy	More precise monitoring of pollution	Risk of techno-solutionism

Digital twins are believed to be instruments for minimizing uncertainty in designing environmental policy. However, it should not be ignored that their models are still constructed on assumptions, faulty scientific research, and selective information. Various experts, such as (Topping et al., 2021) caution that urban air-quality twins have the potential to conceal faulty measurements and sensor bias using seemingly accurate outputs as long as an uncertainty is not explicitly addressed. This gives the impression of the model appearing more accurate than it is in reality. As a result, this can lead policymakers to be highly dependent on making use of simulation results as fact but not as situated judgments. If cautious use is not encouraged, this can diminish critical thinking in policymaking, with a potential impact on millions of people. Since digital twins, like any other technology, have a high likelihood of uncertainty, their use in governance shouldn't be holistic and absent from checks and measures. It is significant as they move uncertainty from the political to the technical realm.

This argument is supported by the widespread presence of data bias. According to STS work by (Jasanoff, 2021), scientific tools introduce a code of how to view the world that favors certain risks and communities over others. In cases where network monitoring is more intense in richer neighborhoods than in informal settlements or in cases where emissions inventories do not capture the informal economy, a digital twin can generate an objective pollution map. It can systematically overrepresent the rich. When these kinds of maps are applied to defend climate interventions, they end up providing biased data. If proper measures are not taken, this data is later used to formulate 'evidence-based decisions' that replicate, instead of remediating, existing inequalities.

In addition, algorithmic opacity raises another governance issue. According to (Fuller et al., 2020), digital twins incorporate intricate modeling, data assimilation, and feedback schemes that are not easily accessible to non-experts. It creates a clear divide and leads to the concentration of information. In other projects, cities trial an open documentation system and are exposed in dashboards. Others have the piping up to the modeling stanzas closed and beyond inspection. As a result, this creates a clear political divide. Simply put, open designs allow citizens, NGOs, or local professionals and leaders to challenge assumptions and outputs. Whereas closed design concentrates enlightenment in technical communities and vendors. Even though both structures share the same underlying technology, they manifestly differ in how power and accountability are shared.

Lastly, when policy decisions are presented by model outputs, accountability becomes difficult. According to (Saltelli et al., 2024), massive climate and environmental models often diffuse responsibility among experts, institutions, and algorithms. When a digital-twin-supported policy of traffic or zoning goes wrong, decision-makers can quickly find ways to blame the model for what it indicated, instead of themselves for their own normative preferences in respect to risk-acceptance or distributional effectiveness. Unless there are explicit rules of governance that record uncertainty, such as in the existence of data bias, and final responsibility resides with identifiable institutions, it is more probable that digital twins can strengthen technocratic rather than democratize environmental policymaking. Nevertheless, under these protections, they can be re-focused to favor the principles of co-production and accountability identified in the conceptual framework, transforming them into instruments that help increase, as well as make power and judgment increasingly visible.

Environmental digital twins face major uncertainty. Even advanced climate or urban models can only provide probabilities, not certainty. Treating outputs as facts can lead to policies that do not match reality. Human oversight is essential to interpret results, consider limitations, and include social values. For instance, urban models that track health, mobility, or environmental conditions can improve services, but they could also enable surveillance, discrimination, or unequal access (*AI-Generated Digital Twins for Science (HORIZON-INFRA-2025-01-TECH-04)*, 2025).

Ethical issues in environmental modeling are not technical problems; they are questions of power, consent, and

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community priorities. Decision-makers must balance predictive insights with fairness and long-term sustainability.

➢ *Limits of Control and System Complexity*

The idea that digital twins can give complete control is misleading. Complex systems-cities, industries, or ecosystems-are inherently unpredictable. Pushing for total optimization can create instability or unintended effects. Goals like improving environmental outcomes can lead to technocratic overreach without proper checks.

Digital twins work best when matched to the system. Infrastructure is stable and measurable; production systems have clear goals but need value considerations, and environmental systems are unpredictable. Each system requires different approaches to modeling, governance, and interpretation (Raes et al., 2025).

Digital twins are powerful tools for exploring options and making more informed decisions, but they can't settle moral questions. Ethics isn't something a model can calculate. We need institutions that question assumptions, make trade-offs clear, and make sure the tech serves people, not the other way around. In infrastructure, digital twins work in fairly stable, easy-to-measure settings. Roads, buildings, and maps don't change overnight, and most things can be seen or measured directly. That makes predictions more reliable. The main ethical concerns are about access, privacy, and inclusion, not about whether the system will suddenly fail. Production systems are more active but still manageable. Industrial digital twins usually focus on clear goals like efficiency or profit. The problem here is not that tech cannot predict results; it is that it reduces complicated social and environmental issues into a single number. Things like work conditions, environmental effects, or supply-chain risks can be ignored unless we try to include them. So, the challenge is less about technology and more about the narrow goals it is given.

Environmental and social systems are the most complicated. Climate, ecosystems, and other natural systems are unpredictable, with feedback loops, random events, and surprising behavior. Digital twins can give useful insight, but they cannot be perfectly accurate. Unlike factories or roads, these systems cannot be controlled precisely. Using these models to make decisions carries a bigger risk of overconfidence and giving too much power to technical outputs. These domains can be understood along a spectrum: relatively stable and predictable systems such as infrastructure; goal-oriented yet value-sensitive systems such as production; and highly complex, dynamic systems such as the environment. Effective governance of digital twins should therefore be calibrated to their position along this continuum, reflecting varying degrees of uncertainty, value contestation, and societal impact.

Empirically, cities such as Amsterdam and Singapore deploy digital twins to manage infrastructure, including roads, bridges, and utilities, enabling early detection of maintenance needs and improved operational efficiency. In industrial contexts, digital twins enhance productivity and resource efficiency within manufacturing systems. By contrast, environmental applications, such as Copenhagen's flood management digital twins, are primarily used to inform planning and risk mitigation under conditions of high uncertainty (Raes et al., 2025).

Despite success, challenges remain. Models rely on assumptions and incomplete data. Overreliance can shift authority from humans to technical systems. Real-time monitoring may favor what can be measured, like traffic or energy use, over social goals like equity. Ethical and social concerns must be actively considered to ensure digital twins contribute to fair and inclusive decision-making.

In production, factories like some car plants in Germany use industrial digital twins to improve efficiency and output. That sounds good, but there are tradeoffs. Worker conditions, environmental effects, and supply chain risks can be simplified or ignored. If these factors are not actively included, the system can favor management over workers or communities, showing how tech can reinforce existing inequalities. Environmental and social systems are more challenging. Cities experimenting with climate models, like Copenhagen for flood planning, can simulate rainfall and drainage to prevent disasters. These insights are valuable, but the real world is messy. Extreme weather, politics, or community pushbacks can disrupt even the best predictions. These digital twins guide decisions; they do not guarantee outcomes.

Relying too heavily on digital twins can make people think the models are 100% accurate. All models depend on assumptions, incomplete data, and simplifications. If decision makers take outputs as gospel, authority can shift from elected officials to technical systems without anyone noticing. Real-time data can speed up city responses, but it can also favor things that are easy to measure, such as traffic flow, emissions, or energy use, over social goals like fairness or long-term well-being. Ethical challenges crop up when decisions affect people who don't understand the models. A zoning change or urban renewal plan guided by a simulation might hurt vulnerable communities, and if citizens can not question the model, those with technical knowledge end up having more influence.

Digital twins give cities, factories, and environmental managers tools they did not have before. They let people see risks ahead of time, test "what-if" scenarios, and make connections across complex systems. But their value depends on how they are used. Transparency, accountability, and oversight are key. Without them, models can take too much authority, hide ethical tradeoffs, and leave non-experts out of the conversation.

IV. GOVERNANCE IMPLICATIONS AND POLICY CONSIDERATIONS

Building on the thematic findings presented in Section 3, this section translates these analytical insights into governance and policy implications.

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The analysis demonstrates that digital twins are increasingly positioned at the intersection of climate governance and urban air quality management, where complex environmental systems require integrated, data-driven approaches. By combining emissions inventories, atmospheric models, and real-time monitoring systems, digital twins expand the analytical capacity of policymakers to simulate environmental scenarios and evaluate intervention strategies (Dembski et al., 2020)(Pinho-Gomes et al., 2023). However, their growing role introduces important governance implications that extend beyond technical performance to issues of accountability, uncertainty, and equity.

➢ *Digital Twins as Decision-Support Tools*

When incorporated into environmental governance, digital twins generate several important policy implications. First, digital twins must function as decision-support tools rather than decision-replacement mechanisms. Climate mitigation and air-quality regulation rely on normative judgments concerning economic restructuring, public health priorities, intergenerational equity, and social justice (Jasanoff, 2021). Although digital twins can model projected reductions in greenhouse gas emissions under renewable energy scenarios, they cannot determine how transitional costs should be allocated across sectors or communities. Similarly, air-quality simulations may indicate that transportation restrictions reduce nitrogen oxide concentrations and secondary ozone formation; however, the socioeconomic consequences of such measures require political deliberation. Democratic accountability remains essential in interpreting and applying digital outputs.

➢ *Managing Scientific Uncertainty in Policy*

Second, policymakers must incorporate recognition of scientific uncertainty into institutional frameworks. Climate change is increasing the frequency and intensity of extreme weather events, introducing atmospheric conditions that challenge existing modeling assumptions (IPCC, 2023). High-resolution models depend on assumptions embedded in emissions inventories, meteorological forecasts, and calibration parameters, and they may not fully capture real-world variability. Digital twins rely on scenario-based projections rather than deterministic predictions. Policy decisions must therefore consider confidence intervals, scenario variability, and sensitivity analyses (Saltelli et al., 2024). Transparent acknowledgment of uncertainty strengthens adaptive governance and reduces overreliance on apparent model precision.

➢ *Ensuring Transparency in Digital Twin Systems*

Organizations must also establish governance structures that embed transparency in the use of digital twins. These platforms depend on complex data infrastructures incorporating satellite observations, local monitoring stations, industry emissions disclosures, and algorithmic modeling systems. Without clear documentation of data sources, calibration methods, and modeling assumptions, digital twins risk becoming opaque decision-making tools (Kitchin, 2021). Transparency through open data standards and independent peer review is essential for scientific legitimacy and public trust.

➢ *Strengthening Accountability in Governance*

Accountability mechanisms must accompany digital twin implementation. Public-private partnerships frequently support the deployment of smart city technologies, yet such collaborations can obscure responsibility for policy outcomes. While digital twin outputs may inform policy recommendations, public agencies should retain final decision-making authority. Multidisciplinary oversight committees can help ensure democratic legitimacy and institutional responsibility.

➢ *Prioritizing Environmental Justice*

Environmental justice must remain central to the governance, design, and oversight of digital twins. Low-income and marginalized communities living near highways, industrial corridors, and ports often experience disproportionate exposure to air pollution. Digital twins can map pollutant concentrations at fine spatial resolution, revealing disparities in exposure. Community participation is essential to contextualize model outputs with lived experiences and structural vulnerability. Integrating community-based monitoring and citizen science data can enhance equity and responsiveness. Incorporating epidemiological exposure-response models into digital twin platforms further strengthens the connection between atmospheric concentrations and measurable public health impacts.

➢ *Adaptive Governance and Continuous Updating*

Digital twin governance should incorporate adaptive management techniques. As technologies evolve and socio-economic conditions shift, climate mitigation strategies must also adapt. Digital twins should be periodically recalibrated using updated emissions of inventories and atmospheric observations. Embedding digital twins within iterative policy cycles allows flexibility and ensures integration of emerging scientific evidence.

➢ *Aligning Digital Twins with Global Climate Goals*

Digital twins must also align with global climate frameworks. The Paris Agreement relies on nationally determined contributions as the primary mechanism for global decarbonization (UNFCCC, 2015) (IPCC, 2023). Urban digital twins can assist in monitoring sector-specific mitigation efforts by integrating greenhouse gas inventories with real-time energy use, transportation emissions, and industrial production data. Policymakers require reliable data to assess progress toward climate targets.

By modeling decarbonization pathways across energy, transportation, buildings, and industrial systems, digital twins can illustrate mitigation progress at the local level. Many mitigation measures, including renewable energy transitions, electrification of transportation, and building efficiency improvements, simultaneously reduce greenhouse gas emissions and decrease concentrations of particulate matter, sulfur dioxide, and nitrogen oxides (Shindell et al., 2018). Quantifying climate and health co-benefits within a unified

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modeling framework strengthens policy evaluation. Life-cycle emissions analysis should also be incorporated to account for emissions generated during material extraction, manufacturing, and disposal associated with renewable infrastructure.

➢ *Supporting Climate Adaptation Planning*

Digital twins can additionally support climate adaptation planning. Urban heat island simulations under varying land-use, vegetation, and surface reflectivity scenarios enable assessment of localized temperature differentials. Such modeling can identify communities at elevated risk of heat-related illness and inform equitable infrastructure investment. Integration of long-term climate projections into digital twin systems also supports planning for sea-level rise, flooding, and extreme precipitation. These tools must remain transparent and publicly accountable to ensure equitable adaptation strategies.

The governance implications discussed above can be conceptually integrated into a unified framework linking digital twin systems with governance outcomes, as illustrated in Figure 5.

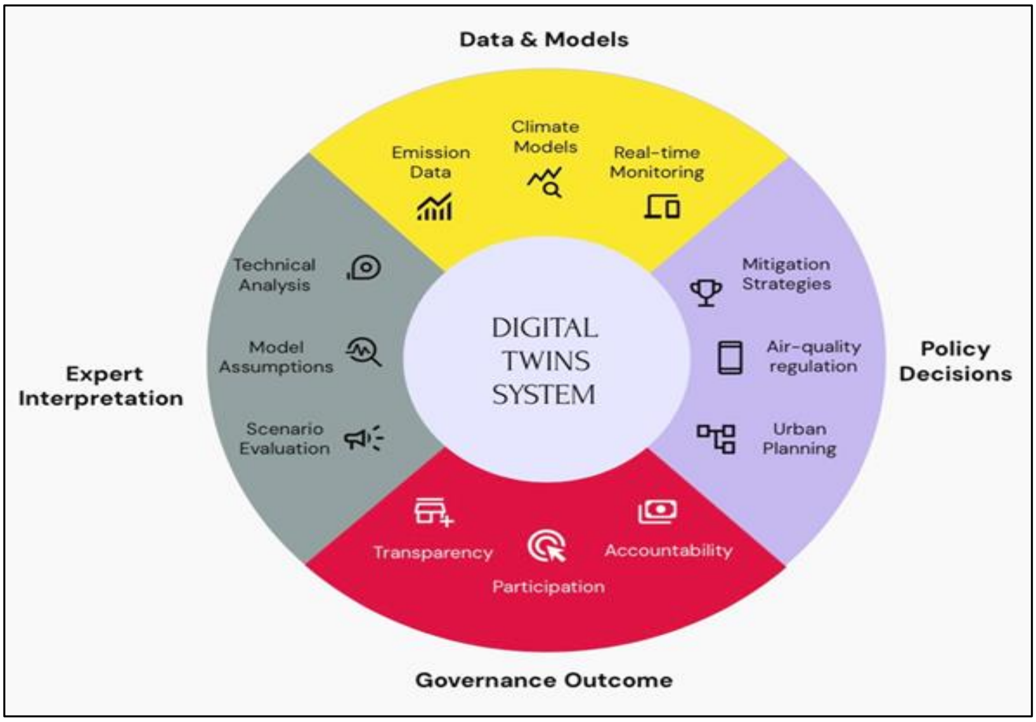

Fig 5 Conceptual Framework Linking Digital Twin Systems to Governance Outcomes in Environmental Policy, Highlighting the Balance Between Technical Modeling Capacity and Democratic Oversight
Source: the Authors.

V. CONCLUSION

This study critically examined the role of digital twins in shaping climate change mitigation and urban air quality governance, positioning them not merely as technical tools but as socio-political instruments embedded within decision-making systems. The findings demonstrate that digital twins significantly enhance the analytical capacity of environmental governance by integrating emissions data, atmospheric modeling, and real-time monitoring into coherent decision-support structures. These capabilities enable policymakers to simulate interventions, anticipate risks, and design more responsive strategies in increasingly complex urban environments.

However, the analysis also highlights that digital twins fundamentally reshape how environmental problems are framed and governed. By privileging quantifiable indicators, simulation outputs, and model-based reasoning, they risk narrowing the scope of policy deliberation and marginalizing social, ethical, and political considerations that are less amenable to computational representation. This dynamic may contribute to the consolidation of technocratic authority, where decision-making increasingly depends on expert interpretation and algorithmic outputs, raising critical concerns regarding transparency, accountability, and democratic legitimacy.

Accordingly, the study argues that the value of digital twins lies not in their capacity to replace human judgment, but in their potential to augment it within robust governance frameworks. Effective integration requires explicit recognition of uncertainty, transparent documentation of data and modeling assumptions, and institutional mechanisms that ensure accountability and stakeholder participation. Embedding environmental justice considerations and community-based knowledge into digital twin systems is particularly essential to avoid reproducing existing inequalities and to support more inclusive policymaking processes.

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From a broader perspective, this research contributes to the literature by reframing digital twins within a governance-centered paradigm that bridges environmental policy, Science and Technology Studies, and digital governance. It advances the argument that environmental decision-making in the era of digitalization must balance computational sophistication with normative and democratic oversight. Without such a balance, digital twins risk reinforcing techno-solutionist approaches that obscure trade-offs and limit public engagement.

Despite these contributions, the study is subject to some limitations. First, it relies on qualitative document analysis and selected illustrative cases, which, while appropriate for conceptual and critical inquiry, limit the generalizability of findings across diverse governance contexts. Second, the analysis focuses primarily on discourse, policy framing, and institutional dynamics, without incorporating empirical evaluation of specific digital twin implementations or their measurable policy outcomes. Third, the rapidly evolving nature of digital twin technologies and governance practices means that some insights may require continuous updating as new applications and regulatory frameworks emerge.

Future research should therefore complement this work with empirical, data-driven assessments of digital twin performance in real-world policy settings, as well as comparative analyses across different institutional and geographical contexts. Investigating how participatory mechanisms and co-production approaches can be effectively integrated into digital twin systems also represents a critical avenue for advancing more democratic and accountable forms of environmental governance.

Ultimately, as climate change intensifies and urban air pollution continues to pose significant health risks, digital twins offer valuable opportunities to enhance evidence-based policymaking. Their long-term impact, however, will depend not only on technological advancement but on the strength of the governance structures within which they operate. Ensuring that these systems remain transparent, accountable, and inclusive is essential for aligning digital innovation with the broader goals of sustainable and democratic environmental governance.

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The authors declare no conflict of interest.

➢ *Funding:*
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➢ *Data Availability:*
This study draws on published literature, policy documents, and publicly accessible institutional sources cited in the reference list.

➢ *Table of Abbreviations*

Abbreviation	**Meaning**
STS	Science and Technology Studies
QDA	Qualitative Document Analysis
CDA	Critical Discourse Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
DestinE	Destination Earth
EU	European Union

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