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RESEARCH ARTICLE

Lost in translation: why digital twins thrive in research but falter in politics and public administration

Friederike Richter, Kirsty Campbell and Jasmin Riedl

Fakultät für Staats- und Sozialwissenschaften, Institut für Politikwissenschaft, Universität der Bundeswehr München, Neubiberg, Germany
Corresponding author: Friederike Richter; Email: friederike.richter@unibw.de

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Abstract

Since 2017, Digital Twins (DTs) have gained prominence in academic research, with researchers actively conceptualising, prototyping, and implementing DT applications across disciplines. The transformative potential of DTs has also attracted significant private sector investment, leading to substantial advancements in their development. However, their adoption in politics and public administration remains limited. While governments fund extensive DT research, their application in governance is often seen as a long-term prospect rather than an immediate priority, hindering their integration into decision-making and policy implementation. This study bridges the gap between theoretical discussions and practical adoption of DTs in governance. Using the Technology Readiness Level (TRL) and Technology Acceptance Model (TAM) frameworks, we analyse key barriers to adoption, including technological immaturity, limited institutional readiness, and scepticism regarding practical utility. Our research combines a systematic literature review of DT use cases with a case study of Germany, a country characterised by its federal governance structure, strict data privacy regulations, and strong digital innovation agenda. Our findings show that while DTs are widely conceptualised and prototyped in research, their use in governance remains scarce, particularly within federal ministries. Institutional inertia, data privacy concerns, and fragmented governance structures further constrain adoption. We conclude by emphasising the need for targeted pilot projects, clearer governance frameworks, and improved knowledge transfer to integrate DTs into policy planning, crisis management, and data-driven decision-making.

Policy Significance Statement

This article highlights the need for political and administrative actors to recognise the potential of Digital Twins (DTs)—virtual replicas of physical systems that enhance decision-making. Despite academic and private sector investment, DTs remain underutilised in governance, often perceived as future-oriented rather than immediately applicable. Through a systematic literature review and a case study of Germany, this study identifies a gap between academic developments and public sector engagement with DTs, hindered by institutional inertia, fragmented governance, and data privacy concerns. Public administration and policymakers must better understand the capabilities and risks of DTs, particularly their potential for real-time, data-driven governance. Strengthening pilot projects, regulatory frameworks, and cross-sector collaboration is essential for integrating DTs into policy planning, crisis management, and administrative decision-making.

1. Introduction

The concept of Digital Twins (DTs) has gained significant prominence since 2017, becoming a focal point in both academic research and applied sciences. These virtual replications of physical systems have attracted researchers across various disciplines, including agricultural science, biomedical engineering, civil engineering, computer science, and systems engineering, due to their ability to enhance our understanding of complex systems—from production processes to supply chains—and to provide innovative solutions to real-world challenges like water resource management, infrastructure resilience, and environmental sustainability.

Within academia, DTs have evolved beyond mere theoretical constructs, with researchers developing high-level concepts (e.g., Di Filippo et al., 2020; Ford and Wolf, 2020; Zlatev and Dimov, 2022), functional prototypes (e.g., Kaewunruen and Lian, 2019; Conejos Fuertes et al., 2020; Pilati et al., 2021), and even fully operational DTs (e.g., Johannsen et al., 2021; Papyshev and Yarime, 2021; Ricci et al., 2021) across diverse fields. The private sector has embraced DTs, leveraging them to improve productivity, efficiency, and innovation. According to Research Nester, the DT market size exceeded USD 15 billion in 2022 and is projected to reach USD 100 billion by 2035, with key players including Accenture plc, IBM Corporation, GE Group, Microsoft Corporation, among others.

In response to growing academic and industrial interest, governments have allocated substantial funding to support DT research and development. In the United States, federal agencies such as the Department of Energy and the National Science Foundation have supported DT applications in energy systems and environmental monitoring. The UK government has invested in the development of a national DT ecosystem, integrating DTs through securely shared data to enhance infrastructure planning, design, and management. Singapore, known for its smart city initiatives, has funded projects that integrate the Internet of Things (IoT) and DTs to optimise city management and sustainability efforts. Meanwhile, the German government has primarily focused on funding DT research to support industrial processes and digital integration. These investments reflect the growing recognition of DTs' real-world applicability.

Despite these investments, a stark divergence emerges when examining politics and public administration. Although governments fund extensive DT research, DTs remain largely absent from administrative workflows and policymaking. Their potential for addressing pressing societal challenges is frequently overlooked, reflecting broader trends in emerging technology adoption in governance. Prior research highlights similar patterns in the limited uptake of big data and artificial intelligence in public administration (Guenduez et al., 2020).

This study bridges the gap between DT advancements in academia and their limited adoption in politics and public administration, using Germany as a case study. Guided by the Technology Readiness Level (TRL) and the Technology Acceptance Model (TAM) frameworks, we examine key barriers to adoption, including technological immaturity, limited institutional readiness, and scepticism regarding practical utility. Our methodology combines a systematic literature review of DT use cases with an analysis of German politicians' and public servants' perceptions of DTs. Germany's federal governance structure, strong data privacy regulations, and commitment to digital innovation make it an ideal case study for assessing (barriers to) DT adoption.

This article is structured as follows: First, we outline the history of DTs and define the term "Digital Twin." Next, we introduce the TRL and the TAM frameworks, which provide the analytic foundation for our study. We then detail the research design, including the systematic literature review and case study methodology. The results section presents insights from our literature review and case study analysis, examining DT applications, perceived benefits, and engagement within the German public sector. Finally, we discuss the barriers and opportunities for DT adoption in politics and public administration before concluding with key takeaways and pathways for integrating DTs into governance structures.

2. Introducing Digital Twins

Although the term "Digital Twin" (DT) is relatively new, the concept of using a digital copy to study a physical object dates back to the 1960s, when the National Aeronautics and Space Administration

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(NASA) employed basic twinning ideas during its space exploration missions. Specifically, NASA created ground-based duplicates of onboard systems to simulate and analyse conditions during the Apollo 13 mission (Marcucci et al., 2020, 3). These digital counterparts were crucial, as Boschert and Rosen (2016, 63–64) highlight, in mirroring flight conditions and assisting astronauts in critical situations. The first documented use case of DTs was therefore likely within a US federal agency.

The 1990s saw the conceptualisation of DT technology take shape, notably through David Gelernter (1991), who envisioned digital representations of cities or corporations as transformative tools. In the early 2000s, Michael Grieves (2011, 2014, 2) further developed DTs in the context of product lifecycle management (PLM) at the University of Michigan. While manufacturing remains the primary domain for DT research (Grieves, 2014; Grieves and Vickers, 2017; Tao and Zhang, 2017), the technology is increasingly applied in other fields, including agriculture (Johannsen et al., 2021; Pylianidis et al., 2021; Verdouw et al., 2021), energy and utilities (Kaewunruen et al., 2019; Francisco et al., 2020; Borowski, 2021), healthcare (Bruynseels et al., 2018; Björnsson et al., 2019; Ricci et al., 2021), and urban planning (Nochta et al., 2019; Marcucci et al., 2020; Nochta et al., 2021; Papyshev and Yarime, 2021). These advancements underscore the perceived benefits of DTs, particularly real-time monitoring, predictive analytics, and scenario modelling, which have driven their expanding adoption.

Despite the growing recognition in academia and the private sector, DTs remain largely absent from public administration and policymaking. While some government agencies and ministries fund research on DTs, few have incorporated them into internal administrative processes or policymaking. This gap is also reflected in the limited scholarly focus on DT applications for governance. Existing studies highlight both the potential and challenges of DTs in public sector contexts, particularly in urban planning and infrastructure management. Nochta et al. (2019), for instance, describe city-level DTs as next-generation urban modelling tools, capable of addressing complex urban challenges. However, they also identify systemic barriers such as interoperability constraints, data privacy concerns, and the need for robust governance frameworks. Dani et al. (2023) discuss smart city platforms based on DT technology as decision-support systems, allowing real-time monitoring and simulation of urban conditions. Wan et al. (2019) similarly stress the importance of governance frameworks, cross-disciplinary collaboration, and realistic expectations for DT deployment, noting that DTs are not universal solutions and must be adapted to sector-specific needs.

More targeted use cases further illustrate both the promise and limitations of DTs in policymaking. Marcucci et al. (2020) explore DT applications in urban freight policymaking, demonstrating how DTs facilitate policy experimentation and participatory planning. However, they also highlight challenges related to data availability and the complexity of urban freight systems. Papyshev and Yarime (2021) propose a task-based approach to urban mobility data generation, where city authorities create synthetic datasets by asking participants to perform specific activities in urban environments. This method helps address data scarcity and privacy concerns, as the generated data does not represent real individuals. By enabling predictive simulations for previously unobservable scenarios, this approach showcases the potential of city-level DTs to inform urban policymaking.

Collectively, these studies demonstrate both the opportunities and challenges of integrating DTs into politics and public administration. While DTs could enhance data-driven decision-making and policy-making, their practical adoption remains hindered by technological, organisational, and regulatory barriers. Addressing these barriers requires a structured analytical approach. The following section introduces the Technology Readiness Level (TRL) and Technology Acceptance Model (TAM) frameworks, which provide a foundation for analysing DT maturity and user acceptance in politics and public administration.

3. Frameworks for understanding Digital Twin adoption in politics and public administration

To analyse the adoption of DTs in politics and public administration, this study employs two complementary frameworks: the Technology Readiness Level (TRL) framework and the Technology Acceptance

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Model (TAM). Together, these frameworks provide a structured lens for assessing both the technological maturity of DTs and the factors influencing their acceptance by political and administrative actors.

3.1. Technology readiness level (TRL)

Originally developed by NASA, the TRL framework is a widely used tool for assessing the maturity of technologies, from initial conceptualisation (TRL 1) to full operational deployment (TRL 9) (Mankins, 1995). It provides a systematic scale for evaluating whether a technology is ready for practical application and for identifying gaps that must be addressed prior to adoption.

In academic research, the TRL framework has been widely adopted to assess the development trajectory of emerging technologies across diverse sectors. In the field of artificial intelligence, for example, it has been applied to evaluate the maturity of innovations ranging from self-driving cars to virtual assistants (Martínez-Plumed et al., 2021). In the health sector, TRL has been adapted to support the development and regulatory assessment of pharmaceutical products (Arnouts et al., 2022). Similarly, in the context of sustainable construction, it has been used to assess the readiness of digital technologies aimed at improving building energy efficiency (Wijaya and Asif, 2025).

These examples demonstrate TRL's growing importance as a cross-disciplinary tool for mapping innovation maturity. In this study, we apply the TRL framework to systematically assess the technological maturity of DT applications identified in our literature review. Each use case is classified along the TRL scale, allowing us to evaluate where DT technology stands across various sectors and how its maturity may influence its readiness for adoption in public administration.

3.2. Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM) examines the factors influencing user acceptance of technology, focusing on two primary factors: perceived usefulness (PU)—the extent to which a user believes the technology will enhance performance—and perceived ease of use (PEOU)—the degree to which the technology is considered easy to understand and implement (Davis, 1989). Initially developed for information systems, TAM has been widely applied in healthcare, education, and public sector innovations to predict and explain technology adoption. Studies on e-government portals highlight the role of trust and user-friendly interfaces in fostering adoption (Cegarra et al., 2014; ELKheshin and Saleeb, 2020). In education, TAM has helped assess the acceptance of learning management systems and e-learning platforms, demonstrating that user perceptions are critical in technology-supported environments (Granić and Marangunić, 2019). In healthcare, TAM has been used to analyse the adoption of telemedicine and electronic medical records, showing that perceived ease of use and perceived usefulness influence both patient and provider acceptance (Yarbrough and Smith, 2007; Holden and Karsh, 2010).

These studies consistently underscore the importance of PU and PEOU in shaping technology adoption, particularly in organisation settings where digital transformation intersects with governance challenges. This study applies TAM to assess the attitudes of political and administrative actors towards DTs, particularly their perceived value in decision-making, crisis management, and policymaking. By identifying perceptual and organisational barriers, TAM provides insights into why DTs are often viewed as futuristic rather than practical tools for governance.

3.3. Integrating TRL and TAM

While TRL assesses the technological maturity of DTs, TAM focuses on the organisational and behavioural factors influencing adoption. Together, these frameworks provide a comprehensive understanding of the challenges preventing DT adoption in politics and public administration. TRL determines whether DT technology is ready for real-world use, while TAM examines whether users—politicians and public administrators—are prepared to adopt and integrate it into their workflows. By integrating these frameworks, this study highlights the dual challenge of DT adoption: technological readiness alone is insufficient if political and administrative actors lack trust in DTs or perceive them as difficult to

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implement. Addressing both technological and institutional barriers will be critical for facilitating the broader adoption of DTs in governance.

4. Research design

This study employs two primary research methods: a structured literature review of DT use cases and a case study analysis of Germany, incorporating document analysis and semi-structured interviews (Richter et al., 2025). Together, these methods provide a comprehensive understanding of DT development, adoption, and engagement within politics and public administration.

Our analytical approach is guided by the TRL and TAM frameworks introduced in the previous section. We apply TRL to assess the technological maturity of DT applications, based on the literature review. Each use case is categorised using TRL stages 1–9, providing a systematic view of where DT technologies currently stand. In parallel, we use TAM to interpret qualitative interview data from German policymakers and public servants, focusing on three core dimensions of user acceptance: perceived usefulness, perceived ease of use, and organisational readiness. This dual framework allows us to link the technological readiness of DTs with the institutional and perceptual barriers that shape their adoption. By combining these perspectives, we offer a more holistic understanding of the gap between DT development and its limited implementation in political and administrative practice.

4.1. Structured literature review of DT use cases

To assess the expansion of DT applications across industries, we conducted a structured literature review of DT use cases. A DT use case refers to a practical example in which DT technology is applied to create a dynamic simulation of a physical system.

Our primary sources were SCOPUS, Google Scholar, and the Digital Government Reference Library, ensuring a comprehensive coverage of academic and government-related research. To expand our dataset, we employed a snowball sampling approach, leveraging references from identified publications. Additionally, we cross-checked publication records of scholars specialising in DTs.

The review included English-language studies published between 2017 and 2022, reflecting the period of significant growth in DT research. A preliminary search showed only 17 articles published on DT use cases between 2011 and 2016, and none prior to 2011. Only studies explicitly mentioning "digital twin" or "digital twins" in their titles were considered. Theoretical overviews and literature reviews were excluded but used to verify the completeness of our dataset, with data collection being concluded on 7 April 2023.

Ultimately, we identified 348 publications, including conference papers, peer-reviewed articles, and research reports on DTs, from which we extracted key details such as objectives, benefits, application sectors, and technological maturity. The TRL framework was applied to classify use cases based on their stage of development, ranging from conceptualisation (TRL 1–3) to operational implementation (TRL 8–9). For an overview of the coding scheme, consult Supplementary Table A1.

4.2. Digital Twins in Germany: a case study of public sector engagement

To complement the literature review, we conducted a case study analysis of Germany, examining how DTs are perceived and addressed in politics and public administration. Germany provides an ideal context for studying DT adoption due to its emphasis on technological innovation, federal governance structure, and robust data privacy regulations. The case study explores both the opportunities and barriers to DT adoption, with a focus on political discourse and administrative engagement.

4.2.1. Case selection

Germany was selected for this case study due to its federal governance structure, which presents both challenges and opportunities for technology adoption, as decision-making and political action are often decentralised and divided across federal, state, and local levels. This structure offers a valuable lens to

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examine how institutional dynamics influence DT adoption. Germany's strict data privacy regulations further complicate adoption, highlighting the challenge of balancing technological innovation with regulatory compliance. Finally, DTs have gained growing political attention, as reflected in federal funding programmes and parliamentary discussions, making Germany a relevant case for assessing political and administrative engagement with DTs.

4.2.2. Document analysis of parliamentary discussions on Digital Twins

To analyse political discourse surrounding DTs, we examined parliamentary records using the Documentation and Information System for Parliamentary Materials (DIP) database. The DIP database is a collaborative information system operated jointly by the German Bundestag (Federal Parliament) and Bundesrat (Federal Council). It serves as a repository for documenting parliamentary activities, encompassing official documents and verbatim reports such as stenographic records (plenary protocols), and provides a comprehensive overview of parliamentary deliberations within both constitutional bodies. Within this database, we identified 42 relevant documents through a keyword search for "digital twin," "digital twins," "digitaler Zwilling" or "digitale Zwillinge." Each document was manually coded and analysed to extract insights on the frequency and trajectory of DT discussions in parliament, the political parties driving these discussions, and the framing of DTs in political debates. This analysis provided a timeline of DT engagement in German politics and insights into how DTs are positioned within broader policy narratives.

4.2.3. Semi-structured interviews with politicians and public servants

In addition to document analysis, we conducted semi-structured interviews with two key groups: politicians in the Bundestag who had previously engaged with DT-related topics, and public servants in German federal ministries, offering insights into administrative perspectives on DT adoption.

To select interviewees, we identified politicians based on their involvement in DT-related discussions in parliament (e.g., politicians who had participated in plenary debates, co-signed motions, or expressed their views on DTs in parliamentary activities; cf. Supplementary Table A2). Of the eight politicians contacted, two agreed to participate. The interviews explored their understanding of DTs, political priorities for DT adoption, and challenges in integrating DTs into policymaking. These discussions provided insights into how DTs are framed in political discourse and the divergence between political priorities and technological advancements.

To assess DT engagement across policy sectors, we also contacted all 16 German federal ministries in September 2024 through two approaches. First, we sent email inquiries via general ministry addresses, requesting that our questions be forwarded to relevant units, such as digitalisation, technology, or innovation departments. Second, we used publicly available organisational charts to directly contact specialised departments.

Out of the 16 ministries contacted, two confirmed that DTs were actively relevant to their work and agreed to participate in interviews. Seven ministries responded that DTs were not on their agenda. Six ministries indicated some relevance; three of which provided written responses, while efforts to schedule interviews with the remaining three were unsuccessful. One ministry did not respond. The interviews covered current DT engagement, barriers to adoption, and the strategic significance of DTs in public sector decision-making.

4.3. Limitations of the study

While this study provides valuable insights into DT research and its adoption in governance, several limitations should be acknowledged. The reliance on SCOPUS, Google Scholar, and the Digital Government Reference Library may introduce selection bias, as these databases do not capture all grey literature or non-English publications on DT use cases. Additionally, the structured literature review was confined to English-language publications, reflecting the dominance of English in academic research but potentially excluding key regional insights.

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The case study approach, focusing exclusively on Germany, limits the generalisability of the findings to other political contexts. Future research should explore comparative analyses across governance systems to assess how institutional and regulatory factors shape DT adoption globally. The small interview sample (two politicians, two public servants) reflects both the nascent stage of DTs in governance and policymakers' reluctance to engage with the topic, a tendency heightened by the upcoming federal elections in February 2025. Expanding the study to include survey-based research or a broader range of administrative actors could offer a more comprehensive perspective on DT adoption.

Despite these limitations, this study makes a significant contribution by identifying barriers to DT adoption in governance and highlighting the divergent engagement across policy sectors. It provides a foundation for future research on how DTs can be leveraged to enhance policymaking and administrative processes.

5. Results

This section presents the findings of our investigation into DT adoption, focusing on their growth and application in academic research and their reception in politics and public administration. The results are structured into two main parts. The first examines the expansion of DT research, highlighting sectoral applications, perceived benefits, and technological maturity using the TRL framework. The second explores how DTs are discussed and perceived in the German political and administrative landscape, drawing on parliamentary records and interviews with politicians and public servants, analysed through the TAM to assess the barriers and opportunities for adoption.

5.1. DTs, a thriving topic in research: insights from a structured literature review and TRL analysis

Our analysis of 348 publications on DT use cases from 2017 to 2022 reveals a significant increase in research, following a bell curve pattern rather than continuous or exponential growth (Figure 1). Publications peaked at 84 in 2020, before declining to 70 in 2021 and 44 in 2022. This decline may indicate a slowdown in practical DT implementations, but a more plausible explanation is that COVID-19 disrupted research activities, particularly those requiring laboratory development and large-scale testing environments. Additionally, delays in the peer-review process likely contributed to the lower output in 2021 and 2022.

This interpretation is further supported by our TRL analysis (Figure 2), which shows that most DT use cases remain in early technological stages. Of the 348 publications, 183 describe conceptual frameworks (TRL 1–2), where researchers propose DT models for specific applications. A smaller subset of 21 studies presents detailed models (TRL 2–3) that bridge the gap between conceptualisation and prototyping. Additionally, 133 publications explore DT prototypes (TRL 4–7), demonstrating their functionality in test-bed scenarios. In contrast, only 11 studies examine fully operational DTs (TRL 8–9), where DTs are actively used in real-world scenarios. This confirms that DTs are still largely a high-level concept, requiring further research, refinement, and implementation before achieving technological maturity.

Our data confirms that manufacturing remains the dominant sector for DT research, with 167 publications on specific use cases (Figure 3). This aligns with previous studies identifying manufacturing as the foundational sector for DT development (Grieves, 2014; Grieves and Vickers, 2017; Tao and Zhang, 2017). However, interest in DT applications across other sectors is growing. The second most explored sector is urban logistics and planning, with 54 publications, reflecting the strong alignment between digital urban twins and smart cities (Gracias et al., 2023).

Our findings also indicate that while the term "DT" is gaining traction across diverse fields, practical applications remain limited in some sectors. Sectors such as energy and utilities (29 publications), automotive and transportation (23), healthcare (21), and agriculture and farming (17) show increasing interest in DT-related research. However, DT research is scarce in aerospace and defence (10 publications), telecommunications (3), home and commercial (2), and oil and gas (1). This variation

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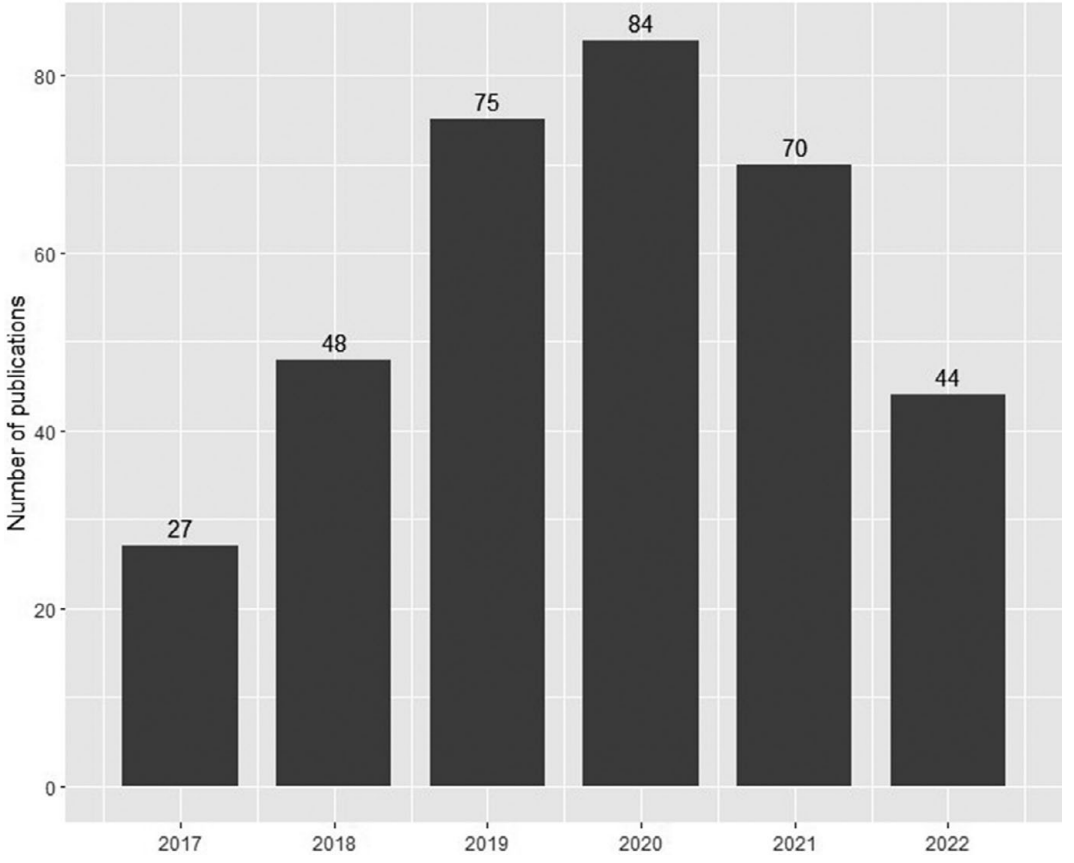

Figure 1. *Number of publications on DT use cases (n = 348), 2017–2022.*

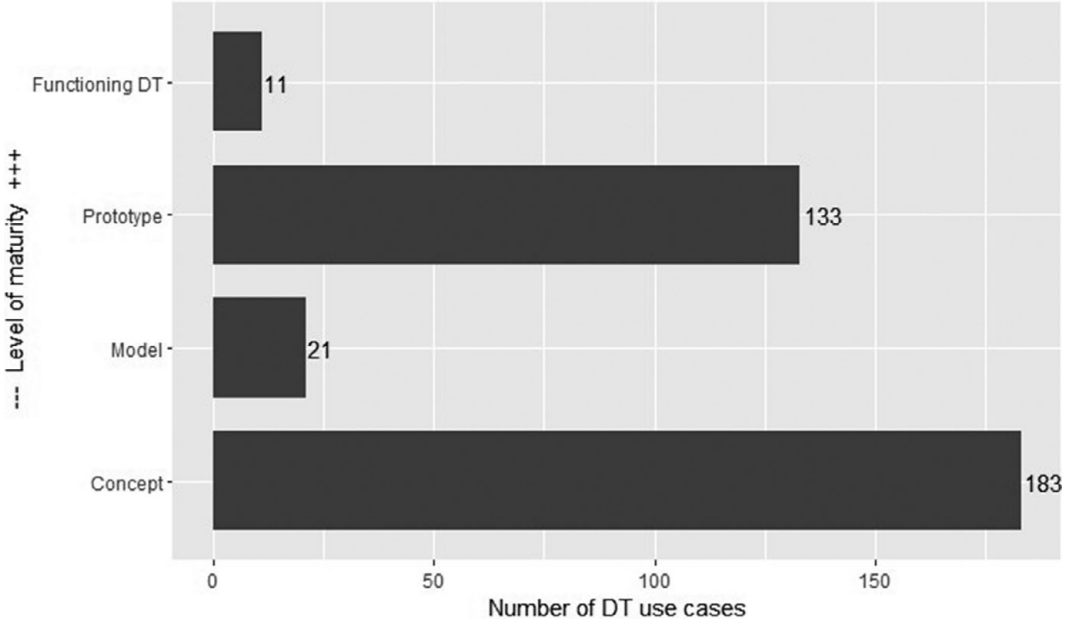

Figure 2. *Maturity of DT use cases (n = 348), 2017–2022.*

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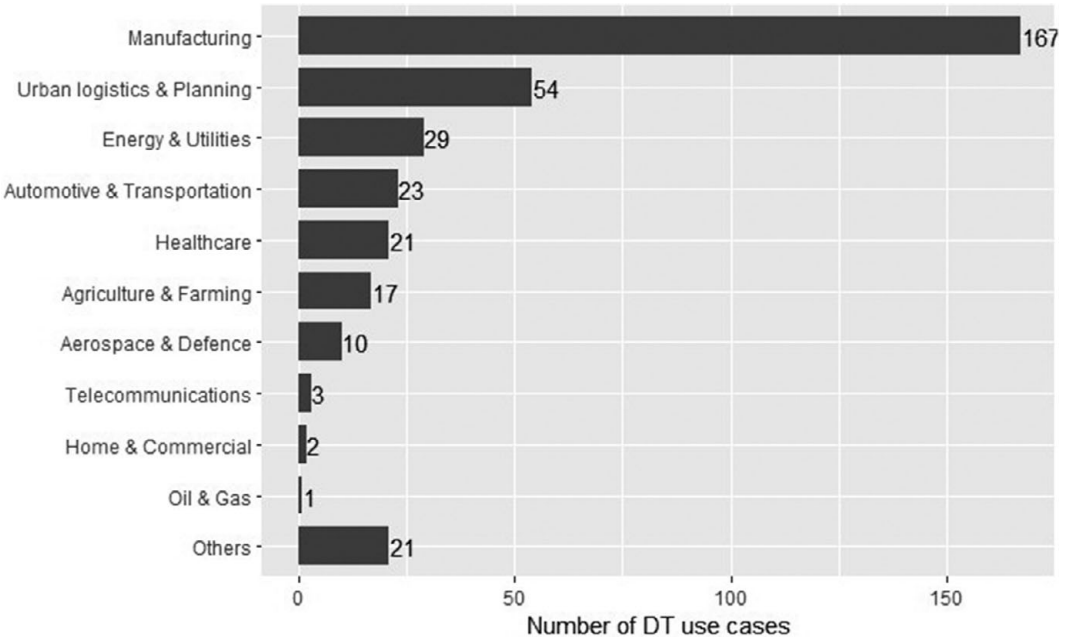

Figure 3. *Sectors of DT use cases (n = 348), 2017–2022.*

suggests that DT utility differs across industries, with some sectors adopting DTs faster due to clearer use cases, existing infrastructure, and economic incentives.

Despite sectoral differences, DT research consistently emphasises the technology's benefits. To systematically assess these benefits, we developed a taxonomy and keyword list using a deductive research approach, refined through an iterative coding process. Publications on DT definitions and state-of-the-art developments formed the taxonomy's foundation, while manual coding allowed for the inclusion of additional benefits identified in the reviewed studies.

Using this refined taxonomy, we identified 40 distinct DT benefits and grouped them into five categories: data management and analysis, maintenance and adaptation, scenario analysis and problem identification, collaboration and stakeholder engagement, and performance optimisation and efficiency. To determine the most significant benefits, we identified up to three key benefits per study. Table 1 provides an overview of the results of this analysis.

The three most frequently discussed benefits include what-if-analyses and scenario simulations (76 publications), physical twin performance optimisation (74), and simulations (72). These findings highlight the central role of data in the effective use of DTs while also reflecting varying degrees of human interaction with the technology. For example, simulations often operate autonomously, requiring minimal user input, whereas what-if-analyses depend on scenario-specific data provided by users. Performance optimisation, in contrast, necessitates active human interaction to fine-tune physical systems based on DT outputs.

Other widely discussed benefits include improved decision-making (58 publications), real-time monitoring (57), and real-time data and feedback loops (52). These reinforce the pivotal role of data in DT functionality and highlight how certain sectors, such as manufacturing, influence the perception of DTs as essential decision-making tools. To explore this further, we conducted an additional analysis on decision support. Sixty percent of publications explicitly linked DTs to decision-making, citing their ability to store and visualise data, run scenario simulations, and provide real-time monitoring. More specifically, 204 publications cited decision-making as a benefit of the DT, while 144 did not. These capabilities make DTs valuable for evidence-based policymaking, enabling more informed and strategic governance choices.

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Table 1. *Frequency of top three perceived benefits of DTs (n = 935), 2017–2022*

Data management and analysis	
Simulations	72
Real-time data and feedback loops	52
Data visualisation	32
Data storage	28
Multiple-source data acquisition	25
Big data utilisation	21
Long-term tracking	17
Data collection	14
Data-driven modelling	8
Maintenance and adaptation	
Real-time monitoring	57
Automated decision-making	15
Continuous maintenance	12
Corrective actions	12
Physical twin adaptation	11
Enhanced inspections	5
Scenario analysis and problem identification	
What-if-analyses and scenario simulations	76
Problem identification and diagnosis	36
Improved planning	20
Early warning system	15
Personalisation and individualisation (in production)	13
Reduced implementation risks	12
Collaboration and stakeholder engagement	
Improved decision-making	58
Performance anticipation	28
Information sharing	19
System understanding promotion	19
Enhanced transparency	8
Innovative approaches identification	7
Collaborative and participatory processes	6
Optimal resource allocation	5
Citizen participation and democratisation	3
Frequent updates	3
Stakeholder consensus building	2
Performance optimisation and efficiency	
Physical twin performance optimisation	74
Bridging physical and digital realms	29
Prolonged durability of the physical twin	28
Time efficiency improvement	27
Sustainable solutions	21
Cost reduction	20
Enhanced safety	19
Remote monitoring	6

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5.2. DTs, a niche topic in Germany's public sector: insights from document analysis and TAM-informed interviews

While DTs are increasingly recognised in academic research for their potential to enhance data-driven decision-making (Dawkins et al., 2018, 1; Kunath and Winkler, 2018, 228–229; Ricci et al., 2021, 2; Wan et al., 2019, 188; Quek et al., 2023), their integration into governance is scarce (notable exceptions include Marcucci et al., 2020; Nochta et al., 2019; Papyshev and Yarime, 2021; Wan et al., 2019). Scholars such as Papyshev and Yarime (2021, e16–22) emphasise that while DTs offer vast potential, particularly for simulating policy interventions in virtual environments, empirical research on their practical applications in policy domains is limited. Similarly, Wan et al. (2019, 187), who study city-level DTs, identify substantial knowledge gaps surrounding the technology, particularly its purpose, governance, and the practical challenges of implementation. To address these gaps, this study examines how DTs are perceived and discussed in German politics and public administration. The findings draw on two key data sources: an analysis of parliamentary records from the DIP database and semi-structured interviews with politicians and public servants.

5.2.1. Findings from parliamentary records (DIP database)

An analysis of 42 parliamentary records from the DIP database reveals that DTs first entered Germany's political discourse in 2018. Since then, mentions of DTs have steadily increased (Figure 4a), reflecting growing interest at the federal level. However, discussions predominantly framed DTs as a future-oriented innovation rather than an immediately applicable tool, reinforcing their nascent positioning in political discourse.

DTs were most frequently discussed in the context of research funding, digitalisation, and sustainability, often linked to Building Information Modelling (BIM), Smart Cities, and climate-related initiatives (see e.g., BT 19/18229, 17.03.2020; BT 20/2254, 17.06.2022; BT 20/3761, 28.09.2022; BT 19/21250, 24.07.2020; BT 19/20375, 18.06.2020; BT 19/10625, 31.05.2019). They also appeared in less prominent policy areas, such as healthcare, maritime policy, and aerospace engineering (see e.g., BR 138/21, 12.02.2021; EU 311/22, 05.07.2022; BT 19/15792, 10.12.2019). Despite this thematic breadth,

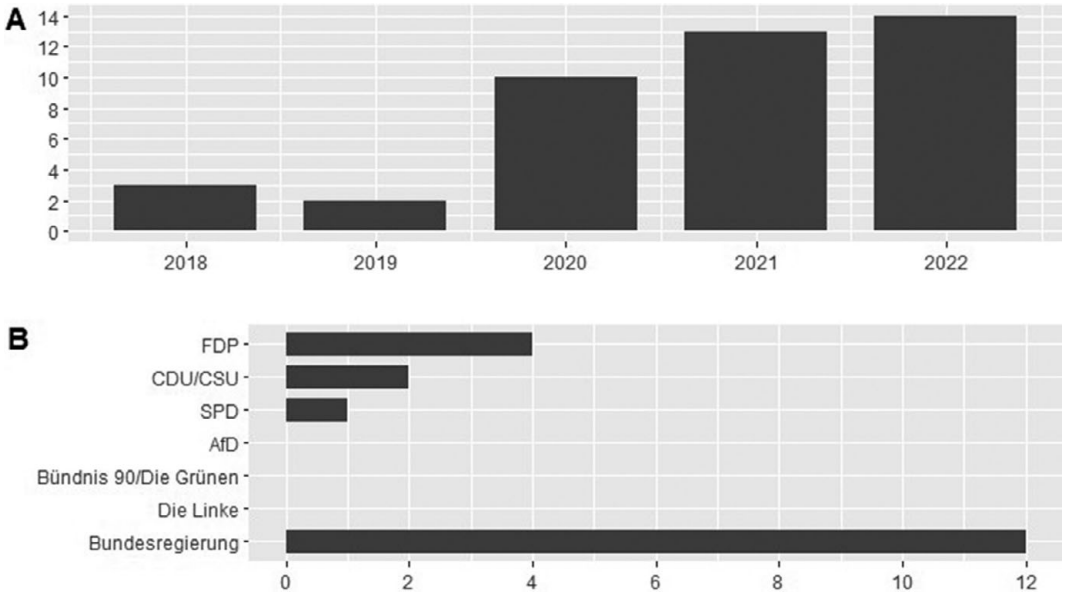

Figure 4. *Attention to DTs at the federal level (2018–2022). (a) Parliamentary activities all parties combined (government and parliamentary factions). (b) Number of parliamentary activities by party (government or parliamentary faction).*

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DTs were rarely examined in detail and often mentioned alongside other emerging technologies. During a plenary debate on climate change policy, Judith Skudelny from the Free Democratic Party (FDP) emphasised the need to consider the role of technology in achieving change. She illustrated her point by stating that DTs could be effective tools for long-term recycling and re-use of materials in the building sector, but her remarks stopped short of specifying practical steps for implementation (BT 19/147, 14.02.2020, p. 18413).

Political engagement with DTs varied significantly across parties. The German federal government (which changed in 2021) and the FDP, as the only opposition party in the Bundestag, were the most active in DT-related discussions, primarily emphasising their role in innovation and sustainability. In contrast, the Social Democratic Party (SPD) and the Christian Democratic Union/Christian Social Union (CDU/CSU) only discussed DTs while in opposition, and even then, only sporadically. Other parties, including the Alliance 90/The Greens (Bündnis 90/Die Grünen), the Alternative for Germany (AfD) and The Left (Die Linke), did not address DTs at all in the analysed records (Figure 4b). This fragmented engagement suggests that DTs remain a niche topic in policymaking, largely driven by opposition parties rather than a cross-party priority.

This trend is further reflected in government responses to parliamentary inquiries. In response to a query on DTs in medical applications, the SPD-CDU/CSU coalition government described DTs as "dynamic" and "promising," emphasising their long-term potential while acknowledging significant knowledge gaps (BT 19/29607, 12.05.2021, pp. 9–10). This dual framing is characteristic of broader discussions about DTs, which frequently highlight their promise while underscoring the need for further research, clearer definitions, and practical applications.

As a result, most DT-related discussions in the DIP database focus on research funding and pilot projects, such as "Modellprojekte Smart Cities," rather than efforts to integrate DTs into government workflows. For instance, an FDP inquiry sought updates on the development of the first city-level DT and ongoing pilot projects. The government's response stressed the exploratory nature of these initiatives and highlighted the importance of knowledge transfer from pilot projects to broader applications, reaffirming the perception of DTs as an emerging rather than a fully operational technology in governance.

5.2.2. Findings from semi-structured interviews

Insights from politicians. Our interviews with two German politicians provided insights into the potential of DTs and the challenges associated with their adoption in politics. Both interviewees acknowledged the wide-ranging applications of DTs, yet emphasised that the technology remains largely future-oriented, confined to research funding and pilot projects rather than immediate policy priorities.

Interviewee 1 described DTs as an example of how digitalisation can help solve complex societal problems. They highlighted the technology's ability to simulate processes and test potential outcomes before implementation, repeatedly emphasising the value of "planning things digitally first." According to Interviewee 1, DTs could be instrumental in advancing climate policy, particularly through applications in circular economy initiatives, emission trading, and Smart Cities. They also expressed a strong belief that DTs could help change the often-negative perception of digitalisation by demonstrating tangible, impactful use cases.

Interviewee 2, whose familiarity with DTs stemmed from related concepts such as BIM, Smart Cities, and Industry 4.0, noted that high-cost or high-risk sectors are more likely to adopt DTs due to their financial and operational benefits. They pointed to offshore wind energy as an example where DTs are already being explored for remote monitoring and maintenance and in hazardous or inaccessible environments.

Both politicians noted significant barriers to the broader DT adoption. Interviewee 2 emphasised technical challenges, including the lack of nationwide 5G infrastructure and insufficient server capacities to process the large datasets required for DTs. Both interviewees also expressed concerns about data privacy and sovereignty, citing the need for strong regulations to govern data ownership, anonymisation, and security. Interviewee 1 identified institutional resistance within the public sector as a key obstacle,

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while Interviewee 2 noted that a lack of skilled personnel further hinders adoption. Interviewee 2 additionally stressed the importance of clear case studies and pilot projects to demonstrate the technology's practical value, explaining that the abstract nature of DTs makes it difficult for both politicians and the public to grasp their utility.

Both interviewees agreed that DTs remain a niche topic in German politics, characterised by limited and exploratory discussions. According to Interviewee 2, DTs are largely confined to research funding initiatives and pilot projects, with little attention to operational use cases. As a result, DTs are rarely addressed in legislative contexts and are instead discussed in academic settings, stakeholder workshops, or research committees focused on digital transformation, sustainability, and defence. These discussions tend to be exploratory, emphasising DT's long-term potential rather than immediate implementation.

Political engagement with DTs was described as relatively uncontroversial. Interviewee 2 noted that the ruling coalition parties (at the time of the interview, FDP, SPD, and Greens) share a common vision of DTs as vital to Germany's digital and sustainable transformation, though they diverge on strategies for achieving this goal, particularly regarding issues like infrastructure development and workforce training.

Both interviewees highlighted that the lack of operational examples and practical frameworks significantly impedes broader political support for DTs. Interviewee 2, therefore, emphasised the importance of promoting accessible, real-world use cases to demonstrate DTs' tangible benefits. Without such examples, DTs are likely to remain overshadowed by more immediate policy concerns, continuing to occupy a peripheral role in German politics.

Insights from public servants. The relevance of DTs within federal ministries varies significantly, largely depending on policy domains and ministerial priorities. Interviewee 3 described Earth system modelling as a key area where DTs are being examined to enhance environmental data visualisation, analysis, and simulation. Discussions have also considered whether DTs could improve existing geoinformation systems by integrating real-time data with simulation models to support urban climate modelling, energy consumption tracking, and emissions monitoring. Additionally, there have been internal discussions about developing a DT for organisational purposes, which would enable dynamic modelling of internal processes and knowledge management. Such an application could provide insights into workflow optimisation and resource allocation, though it remains in an early conceptual stage.

Interviewee 4, whose ministry is more closely aligned with industrial digitalisation initiatives, described DTs as a critical tool for enhancing manufacturing processes and industrial data ecosystems. Rather than being used for internal government functions, DTs are primarily integrated into industry-focused standardisation efforts, supporting the development of digital administration shells to enable data exchange, process automation, and industrial efficiency. In this policy domain, standardisation is a key priority, as greater interoperability is necessary to scale and deploy DTs across different economic sectors.

Despite growing ministerial interest in DTs, both interviewees identified several key challenges that limit their broader adoption in governance. Interviewee 3 cited the difficulty of linking physical and digital objects in a reliable way. They also argued that the complexity and abstraction of DT models make it difficult to define system boundaries, particularly given that DTs operate across multiple scales. Ensuring interoperability and consistency between different models remains another major hurdle. Another key issue is ensuring continuous and meaningful data flow from real-world environments into digital models to support accurate calculations and decision-making. Interviewee 4 pointed to additional challenges related to standardisation, governance, and data security. The lack of a harmonised approach to DT implementation means that projects often remain isolated rather than fully integrated into broader digital ecosystems. Legal and regulatory concerns also play a role, particularly questions around data access, ownership, and security. Uncertainties around who can use DTs, how they should be managed, and how sensitive information is controlled further complicate their adoption.

Both interviewees also raised concerns about cost–benefit considerations. The high initial costs of DT implementation contrast with longer-term benefits, which often take time to materialise. Interviewee 3 thus noted that for DTs to be widely adopted, they must provide value from the outset, rather than requiring years of development before demonstrating practical benefits. Interviewee 4 emphasised that

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the most significant costs are not related to DTs themselves but rather to the infrastructure required to store, process, and secure the vast amounts of data they generate.

While both interviewees acknowledged that DTs have long-term potential in government decision-making, they differed in their views on the pace of adoption. Interviewee 3 noted that although DTs are referenced in broader digitalisation strategies, they have yet to be fully integrated into formal policy frameworks. While they recognised that digital system models will continue to evolve, they argued that terminology might change over time, and DTs as a concept might eventually be absorbed into a broader trend of real-time data-driven decision-making. Interviewee 4 took a more pragmatic and industry-focused stance, emphasising that DT adoption depends heavily on federal budget allocations. While several DT-related projects are currently underway or planned, future developments will depend on funding priorities and how digital transformation policies evolve. They also expressed scepticism about whether public administration has the capacity to fully leverage DTs for internal decision-making, pointing out that even well-established digital modelling frameworks, such as BIM, have faced significant hurdles in public sector adoption.

6. Discussion: barriers and opportunities for DTs in politics and public administration

Our findings reveal a persistent gap between academic and private sector advancements in DT technology and their adoption in politics and public administration. While research and industry continue to expand DT applications, political and administrative actors either do not prioritise DTs or perceive them as future-oriented rather than immediately applicable. This mirrors broader trends in emerging technology adoption in governance, where technological readiness, organisational acceptance, and regulatory constraints shape implementation.

In line with the TRL framework, our analysis indicates that most DT applications remain in early developmental stages (TRL 1–7). Despite significant academic interest, DTs in political and administrative contexts are rare and largely conceptual. Politicians and public servants described DTs as promising in theory, yet struggled to identify fully implemented use cases in their work. This aligns with TAM, which highlights user perceptions of usefulness and ease of use as critical factors in adoption. Our findings suggest that uncertainty about tangible benefits, combined with technical and financial barriers, has hindered the willingness of political and administrative actors to integrate DTs into decision-making and policy implementation.

These insights have important implications for the role of DTs in governance. While the literature highlights DTs' potential to support data-driven policymaking, our case study suggests that politicians and public servants lack concrete examples of DT effectiveness. Politicians often framed DTs as tools for future sustainability and optimisation, yet struggled to articulate how they could address immediate governance challenges. Public servants, in contrast, saw potential for DTs in Earth system modelling, Industry 4.0, and smart cities, but remained uncertain about how to operationalise them within government workflows.

6.1. Barriers to adoption: technological, organisational, and regulatory challenges

Several key barriers were identified in our study that help explain the limited adoption of DTs in politics and public administration.

First, technological maturity remains a major constraint. While DTs have been widely conceptualised and prototyped in research, their integration into real-world policy applications is still in its infancy. Public servants cited challenges in linking physical and digital systems, particularly in areas such as urban emissions tracking and industrial data ecosystems, where ensuring data consistency and interoperability remains a technical hurdle. The complexity of multi-scale modelling further complicates DT implementation, raising concerns about system reliability and accuracy.

Second, organisational resistance and lack of expertise hinder adoption. In line with TAM, our findings indicate that perceived ease of use is a significant barrier to adoption in public administration. Public

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servants noted that internal knowledge of DTs is limited, and there is no established framework for incorporating DTs into decision-making. This lack of familiarity also contributes to a hesitancy among policymakers to prioritise DT initiatives, reinforcing the view that DTs are distant rather than immediate policy concerns.

Third, regulatory and financial challenges present significant obstacles. DTs operate on large-scale, real-time data flows, raising privacy, security, and liability concerns. Public servants pointed to uncertainties around data ownership, particularly in cross-agency collaborations. Additionally, the high initial costs of DT applications, compared to the delayed realisation of benefits, were cited as a deterrent. As our findings suggest, for DTs to gain traction in public administration, they must demonstrate immediate, incremental value rather than relying on long-term projections of efficiency gains.

The limited prioritisation of DTs in political decision-making is further reflected in how DTs have been placed on the political agenda in Germany. Our data suggest that opposition parties, rather than governing coalitions, played a key role in introducing DTs into political discourse, particularly through "minor interpellations" ("kleine Anfragen")—a parliamentary instrument that allows opposition members to submit written questions to the government. Notably, all 11 minor interpellations referencing DTs were submitted by opposition parties at the time (FDP: 6; CDU/CSU: 3; The Greens: 2; AfD: 2). This trend was reiterated by Interviewee 1, who explained that DTs were strategically used in minor interpellations to position their party as the "Digitalisierungspartei" (digitalisation party) in contrast to the governing parties. These findings suggest that DTs are often leveraged as a political narrative rather than as a concrete policy priority, further reinforcing their status as a niche and future-oriented topic in public administration.

6.2. Opportunities and future directions

Despite these barriers, our findings also highlight opportunities for DT adoption in governance. First, DTs could serve as decision-support tools, helping policymakers simulate policy interventions before implementation. Interviewees pointed to the potential for DTs to be used in climate policy, infrastructure resilience, and energy management, but these applications remain largely conceptual at present.

Second, greater standardisation and knowledge transfer could facilitate broader adoption. Both the TRL and TAM frameworks suggest that technology adoption increases as it becomes more standardised and familiar to users. Public sector engagement with Industry 4.0 initiatives and smart city applications suggests that collaboration with private sector actors could provide insights into scaling and operationalising DTs in government settings.

Third, the expansion of funding initiatives could help bridge the cost–benefit gap associated with DTs. Many discussions about DTs in policymaking currently focus on research funding, but public servants expressed interest in pilot projects that could demonstrate real-world utility. Establishing targeted DT initiatives in political and administrative settings—such as environmental monitoring, infrastructure maintenance, or even internal use like workflow—could serve as test cases for broader adoption.

6.3. Rethinking the role of DTs in politics and public administration

The current perception of DTs as distant, future-oriented technologies rather than practical governance tools reflects a broader challenge in public sector digitalisation. Our findings suggest that bridging the gap between research, industry, and public administration will be key to fostering DT adoption in governance. This requires not only technological advancement but also organisational adaptation, regulatory clarity, and tangible case studies that illustrate the concrete benefits of DTs in policymaking and public administration.

If DTs are to move beyond research and isolated industry applications, political and administrative actors must focus on scaling proven use cases, clarifying governance structures, and investing in workforce training. Without these steps, DTs will likely continue to be discussed primarily in academic and research settings, rather than as tools shaping real-world policy decisions.

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7. Conclusion

This study highlights the gap between academic and private sector advancements in DT technology and their limited adoption in politics and public administration. While DTs are widely used in industry and research, they remain largely conceptual and underutilised in governance. Ministries actively fund DT research, but primarily for external applications, such as Industry 4.0, environmental monitoring, and urban planning, rather than for internal administrative use. This reflects a broader trend in governance, where technological readiness, organisational acceptance, and regulatory constraints shape the uptake of emerging innovations.

Using the Technology Readiness Level (TRL) and Technology Acceptance Model (TAM) frameworks, this study shows that most DT applications remain in early development stages (TRL 1–7), limiting their immediate applicability in governance. In line with TAM, political and administrative actors question the usefulness and feasibility of DTs in decision-making, reinforcing their perception as future-oriented rather than an actionable policy tool. The combination of technological immaturity and scepticism about user acceptance helps explain why DTs are discussed more as research initiatives rather than integrated into governance strategies.

The findings suggest that for DTs to be effectively integrated into public administration, several barriers must be addressed. Policymakers and public administrators require clearer knowledge transfer mechanisms to bridge the gap between technical expertise and policy applications. While DTs are frequently linked to funding initiatives, there is little emphasis on how they could support administrative processes or governance structures. The absence of demonstrable policy use cases exacerbates this issue, making it difficult for political and administrative actors to justify investment in operational DT systems. The high initial costs of DT infrastructure further complicate decision-making, as long-term benefits are difficult to quantify in the short term. Privacy and data security concerns add another layer of complexity, particularly in cross-agency collaborations where data-sharing agreements remain uncertain and inconsistent.

Despite these barriers, the study identifies several opportunities for DT adoption in governance. Decision-makers could benefit from DT-supported scenario simulations, enabling them to test policy interventions before implementation. The ability to visualise complex policy issues through interactive, data-driven models could improve communication, transparency, and crisis management. Public administration could also leverage DTs for infrastructure resilience and environmental monitoring, but only if concrete applications are developed and tested. Standardisation efforts could facilitate broader adoption, particularly if policymakers collaborate with industry leaders and researchers to develop scalable and interoperable DT frameworks. Pilot projects focusing on policy-relevant DT applications, such as public service optimisation and resource allocation, could serve as test cases for broader implementation.

While DTs hold long-term potential for decision-making, their adoption in public administration remains constrained by political priorities, technical uncertainty, and a lack of institutional frameworks for integrating them into governance. Ministries and policymakers must focus not only on funding research and industry applications but also on developing clear pathways for DTs to become integral to administrative and political processes. Without a concerted effort to translate DT research into practical governance tools, these technologies will likely remain confined to academic discussions and experimental projects, rather than shaping real-world policy decisions.

In spite of its insights into the barriers and opportunities for DT adoption in politics and public administration, this study has several limitations. The case study of Germany provides detailed insights into DT adoption in a federal, innovation-driven governance system, but the findings may not be fully generalisable to other political contexts. Expanding the scope to comparative studies across different governance systems could offer a more nuanced understanding of how institutional, regulatory, and cultural factors shape DT adoption. The limited number of interviews reflects both the emerging nature of DTs in governance and the reluctance among political and administrative actors to engage with the topic. Future research could broaden the analysis by incorporating survey-based studies or additional qualitative interviews with policymakers, public servants, and industry experts.

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To advance the role of DTs in politics and public administration, greater emphasis must be placed on developing practical applications, refining governance frameworks, and ensuring that DTs are not only research-driven but also policy-relevant. If these challenges are addressed, DTs could become valuable tools for data-driven governance, strategic foresight, and administrative efficiency. However, if the current trajectory continues, DTs risk remaining an underutilised technology in policymaking, discussed more for their long-term potential than for their immediate impact on governance.

Abbreviations

DT	Digital Twin
IoT	Internet of Things
PEOU	Perceived Ease of Use
PU	Perceived Usefulness
TAM	Technology Acceptance Model
TRL	Technology Readiness Level

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Data availability statement. The data that support the findings of this study are openly available in OSF at http://doi.org/10.17605/OSF.IO/8ZCQ6.

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