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Mapping Urban Digital Twins Across Regions: An Exploratory Study of Maturity, Implementation Status, and Authority

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Highlights

What are the main findings?

- The majority of the reviewed UDTs are not yet operational, and their maturity level is mid-range; local authority involvement is one of the main drivers for scalability.
- The main implementation challenges include data availability and accessibility, data segregation, stakeholder coordination, standards, resources, and data security.

What are the implications of the main findings?

- Our findings suggest that UDT readiness depends not only on technology, but also on organizational readiness, governance capacity, and relevant available data.
- From our exploration of the non-representative sample, we conclude that common frameworks and data formats are necessary for advancement, and collaborations with the economy and research can support long-term sustainment and growth.

Abstract

An increasing number of municipalities are adopting urban digital twins (UDTs) to improve urban management. Although the models differ widely, municipalities face similar challenges in their implementation. Therefore, sharing insights on UDTs provides an opportunity for collective growth. To facilitate this growth, the present exploratory study maps the characteristics, challenges, and potentials of 99 UDTs in Europe, North America, and Asia. We first estimate the UDT readiness based on established features, along with contextual and local authority involvement indicators. Next, we conduct semi-structured interviews with key individuals from eight selected cities to contextualize the review findings. The mapping results indicate that most UDTs in our sample operate at the municipal level, and that over half (57%) are not in series operation. The reviewed UDTs are mid-level in maturity, and local authority involvement is a key driver of scalability. We infer that UDT progress depends as much on common frameworks, organizational readiness, governance capacity, and relevant data as on technology. Collaborations with private companies and researchers can play a central role in the long-term sustainment and growth of UDT infrastructures.

Keywords: urban digital twin; urban planning; urban infrastructure; municipal management; authority involvement; city information modeling; smart city

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1. Introduction

In an age of constant urban transformation, the demand for sustainable redevelopment is increasing. Urban growth, climate change, and the demand for efficient resource utilization pose challenges that require innovative approaches to accompany this transformation. In this context, digital technologies gain prominence. Virtual replicas of physical systems, cycles, or services, known as digital twins [1], offer promising opportunities for optimizing processes and supporting sustainable development strategies by applying measures of monitoring, modeling, and simulating [1]. Among these digital twins, urban digital twins (UDTs)—also known as city digital twins [2–4], city-scale digital twins [5], local digital twins [6], and similar names—represent a particularly complex form. They encompass entire cities and their physical environment [1]. By integrating diverse data sources, UDTs support local governments in making informed decisions, optimizing resource allocation [2], managing challenges [3], and advancing sustainable urban development [7].

Municipal leaders worldwide acknowledge the potential of UDTs, resulting in their implementation across various domains. These domains include use cases related to urban planning [8,9], municipal infrastructure management [10], environmental impact monitoring [11,12], and traffic flow simulation [5].

While the application domains remain consistent across municipalities, the characteristics of the UDTs vary widely. Furthermore, UDT adopters lack a common understanding (e.g., structure, content, application) of UDTs [13,14] and face several challenges in implementing them. These challenges arise, among other reasons, from data management issues as integrating heterogeneous, multi-modal sources into a cohesive framework represents a complex task. In addition, not all relevant data are complete, reliable, or up-to-date [2,7]. Standardization and interoperability are lacking [7,15,16]. Moreover, technical and operational obstacles complicate the development of UDT frameworks [17,18]. For example, large volumes of data require substantial computational resources for processing and storage [17,19], and developing the platform demands knowledgeable staff and financial capital [7]. Given these and other challenges, sharing insights on UDT developments with other municipalities creates an opportunity for joint learning and collective growth.

To support this growth, this study presents an exploratory, cross-regional overview of a non-representative sample of existing UDTs. We systematically compile and map their characteristics to identify patterns, common challenges, and opportunities. We then compare this compilation with qualitative findings from interviews with selected UDT stakeholders. This study focuses primarily on UDTs in Germany, but also includes cases from North America, Asia, and other European countries. While this composition prevents us from drawing general conclusions about global developments, the sample provides a foundation for mapping and comparing the socio-technical readiness of UDTs across contexts. This mapping allows us to identify patterns, recognize challenges, and locate opportunities. The insights derived can support municipalities, policy makers, and private companies in further developing UDTs and providing the necessary socio-technical infrastructure for their applications.

2. Literature Review

Recent research increasingly compares UDTs across different contexts to identify their common characteristics and evaluation criteria. A range of publications from 2022 to 2024 investigate UDTs in diverse geographical regions. Table 1 provides an overview of these publications, including the number of case studies analyzed, their geographical distribution, and the evaluation criteria applied.

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Table 1. Overview of selected literature sources in alphabetical order.

Literature Source	No. of Case Studies	Geographical Location						Criteria										
		Africa	Asia	Europe	North America	Oceania	South America	Purpose	Application	User	Scale	Status	Maturity [1]	Model Features	Technical Features	Data Types	Governance	Key Lessons
Calzati [20]	3			x										x		x	x	
Caprari et al. [8] [2] Castelli et al. [21] [2]	6 (23) [3]		x	x	x [4]	x		x	x		x				x			x
Ferré-Bigorra et al. [15]	19	x	x	x	x			x	x	x		x			x	x		
Jeddoub et al. [22]	19		x	x		x		x			x	x	x	x	x	x		
Lei et al. [23]	40		x	x	x	x								x	x	x		
Masoumi et al. [24]	10		x	x			x	x					x		x	x		
Riaz et al. [25]	37 [5]		x	x	x				x				x	x	x			
Mazzetto [16]	6		x	x				x	x		x			x	x			x

x: selected by respective author(s); [1] or: "level of detail"; [2] same authors in different order, same selection of case studies and criteria; [3] 23 use cases mentioned but only six selected; [4] not part of selection; [5] contains general models without location and not classified as "digital twins".

These comparative studies of UDTs adopt diverse perspectives, ranging from model features such as purpose [8,15,16,21,22,24], scale [8,16,21,22], status [15,22], and maturity [22,24,25], to technical features like platforms, data integration, and simulation methods [8,15,16,21–25], governance structures [20], and key lessons [8,16,21]. However, these frameworks exhibit systematic gaps in operationalizing multi-dimensional assessments across diverse municipal contexts. For example, Calzati et al. [20] is the only comparative study that explicitly foregrounds governance as a core analytical dimension, analyzing institutional frameworks and stakeholder coordination across three European cases. The study treats governance primarily as a contextual background rather than as an explanatory variable, and the limited case selection constrains generalizability. Riaz et al. [25], the most extensive review, synthesize 68 papers encompassing 37 case studies and provide the most comprehensive technical classification of UDT implementations and maturity levels, yet largely exclude governance, organizational readiness, and institutional capacity from their analysis. Jeddoub et al. [22] present the most technically comprehensive comparative framework. It covers data integration architectures, modeling standards, levels of detail, and maturity across case studies spanning 19 countries. Despite this breadth, the study prioritizes technical interoperability while systematically omitting governance arrangements, socio-organizational factors, and resource constraints, framing implementation challenges predominantly as technical rather than institutional.

Taken together, the comparative studies synthesized in Table 1 offer valuable cross-continental perspectives on UDT implementations, systematically documenting technological configurations alongside emergent challenges. Nevertheless, critical examination reveals three fundamental limitations.

First, the reviewed literature demonstrates pronounced technical determinism: while all eight studies comprehensively document technical characteristics, governance arrangements receive explicit analytical treatment in only a single study [20] examining three European cases. This asymmetry contradicts socio-technical systems theory, which posits that implementation outcomes emerge from the co-evolution of institutional capacity and technical infrastructure [26]. The systematic exclusion of governance as an explanatory variable constitutes a significant analytical gap, particularly given public administration scholarship identifying organizational capacity and inter-agency coordination as central determinants of technology adoption trajectories [7,27,28].

Second, authority involvement and governance capacity remain inadequately operationalized. While Guckenbiehl et al. [29] propose a five-stage authority engagement model, this framework lacks empirical validation and integration with technical maturity assessments, treating governance and technology as parallel rather than interdependent dimensions. Consequently, existing research cannot explain why municipalities with comparable technical infrastructure achieve divergent implementation outcomes.

Third, the broader municipal context receives insufficient analytical attention. Although reviewed studies span diverse regions (n = 6 to n = 37), they do not systematically account for how structural municipal characteristics—population scale, functional specialization, mobility regimes, and infrastructure complexity—condition UDT feasibility. Urban typology research [30] demonstrates that cities exhibit distinct configurations, suggesting that UDT solutions optimized for compact, transit-oriented municipalities may prove inappropriate for sprawling, automobile-dependent regions. This contextual neglect contradicts implementation science frameworks [31], which emphasize that intervention effectiveness depends critically on fit between solution design and local contextual enablers. By treating municipalities as functionally equivalent and applying uniform technical criteria, comparative UDT research implicitly assumes context-independence—an assumption at odds with both urban theory and implementation scholarship.

Therefore, the objective of this study is to address this gap in the literature. It advances the field by synthesizing insights from a sample of 99 UDTs across three continents and by incorporating relevant model features from reviewed studies, namely location, scale, status, and maturity. Moreover, because we aim to develop governance-related recommendations, we map overall socio-technical readiness rather than focusing primarily on technical features and add three neglected dimensions: (1) the municipality's population and (2) urban archetypes as proxies for contextual readiness and (3) the role of local governments as a driver of institutional and technical integration. This structured perspective allows us to identify cross-cutting patterns, reveal systemic barriers, and outline opportunities for future UDT application in diverse municipal contexts.

3. Methodology

To achieve our goal, we employed a three-stage, mixed-methods approach and systematically identified, compared, and evaluated 99 UDTs, as illustrated in Figure 1.

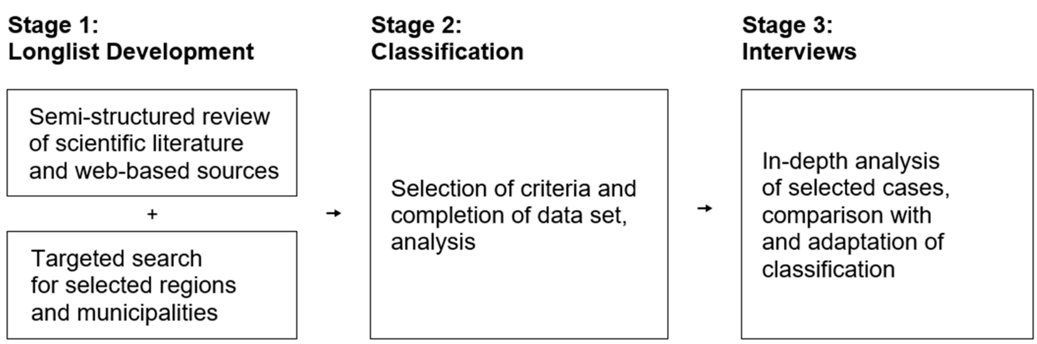

Figure 1. A three-stage, mixed-methods approach was employed to evaluate UDTs.

3.1. Stage 1: Longlist Development

In stage 1, we developed a longlist of 99 international municipalities engaged in UDT development and application, covering the three continents Europe, North America, and

Asia, with particular attention to German municipalities. Figure 2 illustrates the flow diagram of the search strategy and paper selection.

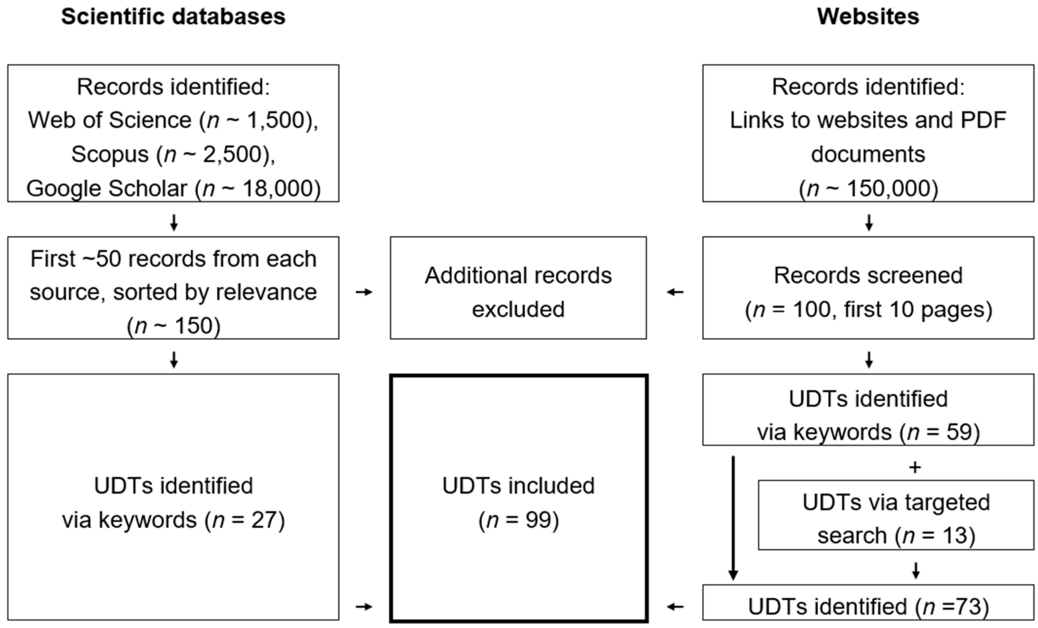

Figure 2. Flow diagram of search strategy and paper selection.

We began by conducting a semi-structured review of scientific literature and web-based sources to identify and compile the mentioned UDTs. Academic sources included peer-reviewed articles and conference proceedings retrieved from Scopus, Web of Science, and Google Scholar databases. Identified web-based sources covered project pages, press releases, and municipal websites found through a Google search. These sources included government publications, smart city reports, project documentations, technology vendor case studies, and regional and national digital strategy documents.

Using predefined keyword combinations in English and German (see Table 2), we conducted the search in mid-2024 and excluded records published before 2015. In the academic databases Scopus and Web of Science, we included only the title, author keywords, and abstract in our research. As a complementary approach, we applied backwards research, i.e., we checked the resources mentioned in the literature sections of previously identified papers, documents, and websites.

Table 2. Initial keywords and their combinations for the literature review.

Primary Keywords		Secondary Keywords		Tertiary Keywords	
"urban" "local" "city" "city-scale"	AND	"digital twin*" [1] "virtual twin*" [1]	AND	"case stud*" [1] "location*" [1] "example*" [1] "implementation*" [1] "development" "application*" [1]	"smart city*" [1] "model*" [1] "infrastructure monitoring" "urban planning" "traffic management" "city utilit*" [1]

[1] We included, e.g., plural forms and verbs with "-ing". In scientific databases, we used "*".

For each database and search engine query, we focused on the top-ranked results sorted by the respective platform (cf. Figure 2). We screened the titles, abstracts, full texts, or web pages and consolidated the UDTs mentioned in a longlist. We manually removed duplicates and entries with only a mention but no further information, and merged references to the same municipal UDTs. Where municipalities employed multiple UDTs for different use cases, we aggregated them into a single UDT entry.

To increase conceptual consistency despite the heterogeneous use of the term "digital twin", we only retained initiatives that were described as going beyond purely static 2D/3D visualization (e.g., GIS viewers, VR demonstrations) by automatically integrating or updating data, supporting analysis or simulation, or linking to operational workflows. In most cases, we could not verify the description by examining the actual UDT platform.

With our semi-structured review, we identified 27 UDTs in academic sources and 59 on websites. These UDTs still vary in scope and technical depth, which we capture through the selected model features in the following classification step.

This initial sample was dominated by European—particularly German—municipalities, a bias likely caused by language barriers and the accessibility of published information, rather than reflecting the actual global distribution of UDTs. To broaden the regional coverage, we supplemented our review with a targeted, non-probabilistic search for municipalities that are strategically relevant to smart city development and digital innovation. In this second step, we applied the same keywords (Table 3) in combination with selected municipalities from the United Kingdom, the United States, and technology-leading Asian countries, such as China, Singapore, South Korea, and Japan. We proceeded with the same steps of aggregating and checking UDTs as described for the semi-structured review. The targeted search added 13 more UDTs to our sample.

Table 3. Additional keywords and their combinations to diversify the dataset.

Primary Keywords		Secondary Keywords		Additional Keywords
"urban" "local" "city" "city-scale"	AND	"digital twin*" [1] "virtual twin*" [1]	AND	Selected municipality Selected region

[1] We included, e.g., plural forms and verbs with "-ing". In scientific databases, we used "*".

The combined search approach resulted in a purposive sample of 99 UDTs from several regions, with a clear focus on Europe and Germany (Supplementary Materials, Table S1). Given the emphasis on top-ranked results in a rapidly evolving field, accompanied by an increasing number of publications and individual search engine algorithms, this purposive sample is neither globally representative nor fully reproducible. Nevertheless, it serves as a suitable basis for our exploratory, cross-regional mapping and comparison of the identified UDTs.

3.2. Stage 2: Classification of Selected UDTs in Longlist

We evaluated the UDTs in the longlist using a set of criteria derived from the literature (see Section 2). This set encompassed (1) location characteristics and (2) model features, summarized in Tables 4 and 5. Rather than focusing solely on technical details, we aimed for a comprehensive picture of the socio-technical readiness of the selected UDT to enable governance-related recommendations. Additionally, the reviewed sources rarely disclosed information about model schemas, software, and types of data, and most UDTs are not publicly accessible. Therefore, we excluded this information and selected the maturity spectrum as the only indicator for the technical advancement of UDTs to complete the criteria set.

Table 4. (1) Location characteristics used to evaluate UDTs.

Characteristic	Classification
Geographical location	• Continent • Country
Population size (Classification by authors)	1 <10,000 2 <50,000 3 <100,000 4 <500,000 5 <1,000,000 6 >1,000,000 7 >5,000,000
Urban archetypes [30]	1 Traffic-saturated cities 2 Paratransit cities 3 Hybrid commuter 4 Auto cities 5 Dynamic megacities 6 Transit cities 7 Car and bus cities 8 Ancient hybrid cities 9 Well-functioning cities

Table 5. (2) Model features used to evaluate UDTs.

Feature	Classification
Scale of implementation [22,32]	1 Campus/neighborhood/urban district 2 Municipality 3 Rural district or region
Development status [15]	0 Research project only 1 Under development 2 Prototype 3 In Operation
Maturity spectrum [24,33]	0 Reality capture1 1 2D maps/3D model 2 Connected model to static data 3 Real-time data enriched model 4 Two-way data integration and interaction between virtual and physical twin 5 Autonomous operations and maintenance
Involvement of local authority [29]	1 Unknown 2 Interested 3 Explorative 4 Engaged 5 Embedded

Based on these pre-defined criteria, we complemented our dataset of 99 UDTs. We reviewed the literature and web-based resources identified in stage 1 again to complete the respective information for every UDT (Supplementary Materials, Table S1).

To map the identified UDTs onto our model features, we applied a five-step set of pragmatic decision rules: (1) If publications or official project websites explicitly described a UDT as a research prototype, pilot, or operating system, we adopted this classification for the implementation status. The classification of involvement and maturity spectrum followed the same procedure. (2) If no textual descriptions included an explicit classification, we additionally reviewed figures, screenshots, and, if available, actual UDT models. (3) In some cases, two or more sources included conflicting information. In these cases, we selected the information that was both more reliable and more up-to-date. (4) In several instances, the documentation was incomplete or ambiguous, which led us to estimate the classification. For these estimations, we employed a conservative coding strategy and assigned the lower plausible level. (5) For the eight municipalities covered by interviews, we compared our coding with the stakeholders' self-assessments from the pre-surveys and adjusted classifications where necessary. After mapping, count matrices for each category served as a basis to visualize the patterns and to easily identify distinct distributions and trends.

3.3. Interviews

3.3.1. In-Depth Analysis of Selected Use Cases

The initial phase of the analysis involved the selection of 23 municipalities based on the defined location characteristics and model features (see Tables 4 and 5). This selection resulted in a balanced representation across various factors, including maturity, development status, scale of implementation, and involvement of local authorities. It also included "pioneering cities" or "lighthouse cities" mentioned in various publications. Furthermore, the selection process considered the accessibility of information, since many municipalities limit public access to their UDT model.

For each selected municipality, we developed comprehensive profiles that included demographic information such as population size, archetype, name, scale, status, maturity level, involvement, specific use cases, literature sources, and a visual representation of the covered UDT. These profiles provided the basis for the subsequent selection and recruitment of interview partners.

3.3.2. Selection of Interview Stakeholders

Based on these 23 in-depth profiles, we invited key individuals and pairs from practice and research to participate in semi-structured expert interviews. Our goal was to maximize diversity across geographical contexts, maturity, status, and interviewees' professional backgrounds. Their perspectives contextualized and illustrated the patterns observed in the cross-regional mapping.

For each municipality, we identified between three and eight potential interview candidates who were directly involved in the development or operation of the UDT. These individuals were municipal staff, such as digital innovation or digital city managers, municipal geodata and GIS managers, project leads, or researchers who contributed to the UDT's design or implementation. We contacted the candidates by email, referring to the respective municipal UDT and inviting them to participate in an interview.

The approached candidates of 14 municipalities did not respond despite follow-up attempts. Candidates of one municipality declined participation. We proceeded with the remaining municipalities, of which at least one person agreed to be interviewed. The set included different criteria levels but lacked any North American locations.

In total, we conducted eight interviews with individual experts or pairs who were actively involved in developing UDTs. The municipalities of our experts were: Differdange (researcher), Gothenburg (staff), Klagenfurt (staff), Leipzig (staff, dual interview with two participants), Rotterdam (staff), Shenzhen (researcher), Singapore (researcher), and Zurich (staff, dual interview with two participants).

3.3.3. Interview Conduction and Evaluation

We conducted the interviews (n = 8; ~60 min.; online; German/English) in summer 2024. They followed a semi-structured format and included 20 guiding questions that we sent out in advance. These questions covered the following topics: UDT status, administrative conditions, use cases, necessary and desirable data, potential measurements, changes observed in the work processes, challenges faced, and future steps planned.

Prior to the interview, participants completed a pre-survey with 20 questions designed to update our profiles and to prepare for the discussions. It collected key details about the respondent and the UDT, including the primary objectives and scale of implementation, as well as the self-assessed maturity spectrum and development status. It also asked about stakeholder engagement strategies, departments involved, service providers contracted, and technical standards employed.

We recorded and transcribed the interviews and analyzed the content using MAXQDA 26.0 software. For the qualitative content analysis, we used inductive category formation, meaning that we developed and coded the categories directly on the interview documents. Four main categories with 23 subcategories emerged. We revised and back-checked these categories during the analysis process. To exemplify the categories, we reviewed the transcripts again, extracted associated key statements, compared them with the descriptive findings, and synthesized the interviews. Given the small, self-selected sample, we treat the interview findings as illustrative insights that stabilize, nuance, and enrich the mapping results, rather than as a basis for causal claims or generalizations.

4. Results

4.1. Descriptive Analysis of Individual Categories

4.1.1. Location Characteristics of Evaluated UDT Cities

Section 3 clarified that this study places strong emphasis on Europe but also includes UDTs from Asia and North America. Figure 3 shows that three-quarters of our 99 reviewed UDTs are in Europe. At the country level, the majority operate in Germany (representing almost one-third of the total), followed by 12 in the US and seven in the UK.

Although this distribution of UDTs offers no basis for drawing conclusions about the extent of development gaps between countries, the patterns discovered in our set provide a valuable benchmark and allow for a conclusion about their state of readiness.

One observable pattern in our sample is an association between the municipality size and the presence and development level of UDTs. While municipalities with more than 500,000 inhabitants account for nearly half of the UDT sample (47%, see Figure 4), those with fewer than 100,000 inhabitants are less frequently represented among the reviewed UDT initiatives. The largest group consists of innovative mid-size municipalities with populations between 100,000 and 500,000. However, the sample also includes 11 megacities with populations exceeding 5 million. We assume that these cities have a critical need for efficient urban management and digital support through UDTs and may therefore provide staff and budget to invest in such initiatives. In addition, large cities may be more active in publishing material. These assumptions may help to explain their relatively strong presence in our dataset. Within the limitations of our non-representative sample, these descriptive results suggest that municipality size should be considered when analyzing UDT implementation.

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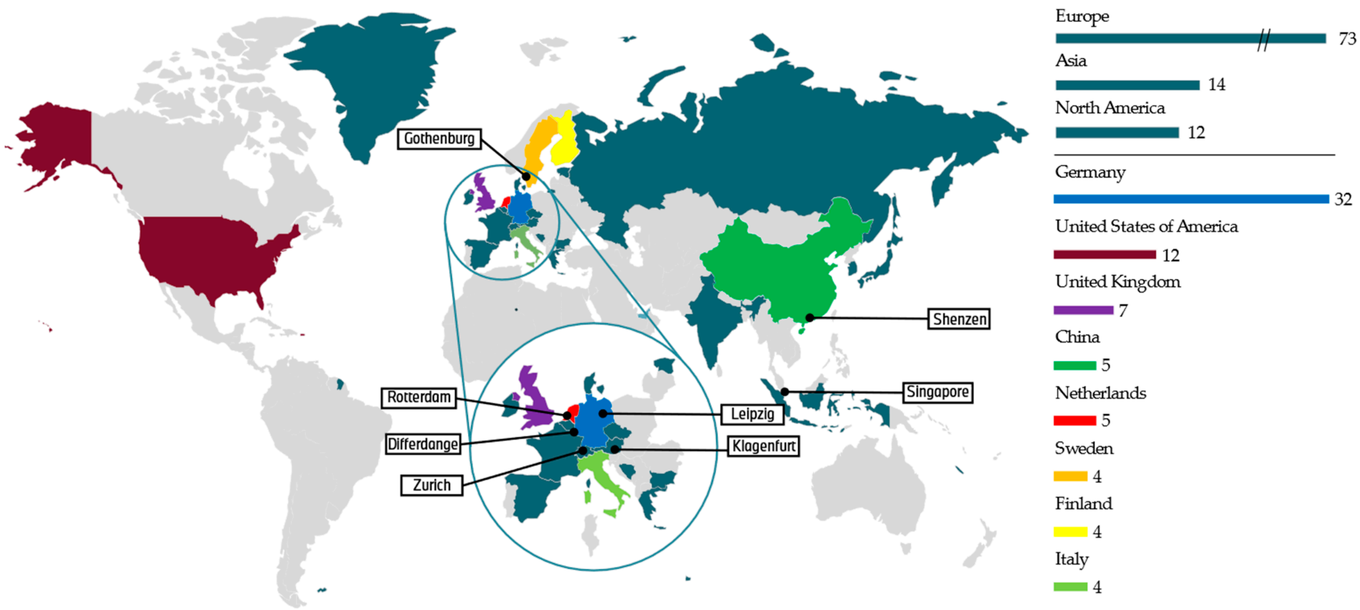


Figure 3. Geographical distribution of included UDT.

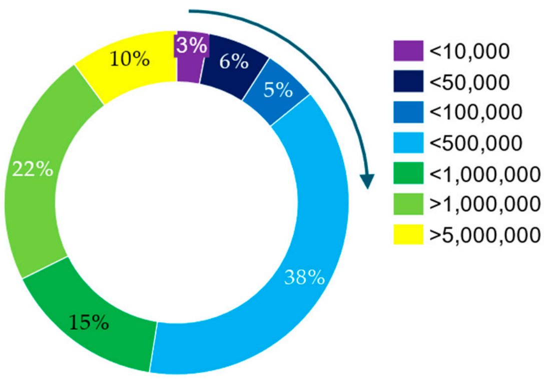


Figure 4. Distribution of population in UDT municipalities. The arrow indicates the increasing population size. Due to rounding, the sum of the percentages equals 99%.

Figure 5 shows the distribution of urban archetypes among the 99 UDT municipalities. The largest group, accounting for 43% of the total, comprises "well-functioning cities" (e.g., Amsterdam), with multimodal transportation systems. "Auto cities" (e.g., Los Angeles) follow with 17%, and "ancient hybrid cities" (e.g., Rome) represent 11%. "Transit cities", like Tokyo, are rare worldwide due to their unique characteristics (e.g., advanced transit systems, high population density, and large size) [30,34]. Nevertheless, nearly every transit city in the world has initial implementations of UDTs. Above all, our sample of 99 UDTs strongly represents cities that are less dependent on cars ("well-functioning cities", "ancient hybrid cities").

This picture may be influenced by the strong representation of European cities, which typically fall into these categories. Therefore, we refrain from conducting in-depth analyses on this topic and use the criterion only for mapping purposes.

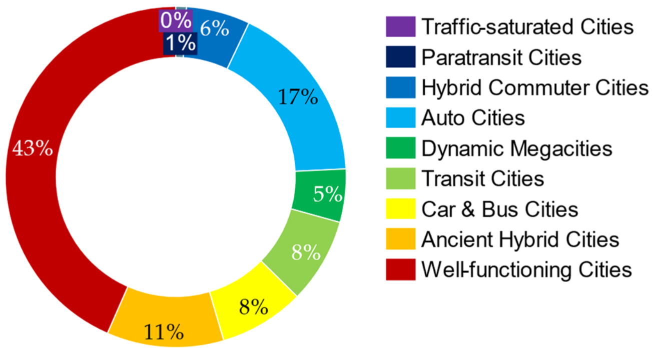


Figure 5. Urban archetypes of municipalities with identified UDTs. Urban archetypes of UDT municipalities. The sum equals 99% due to rounding.

4.1.2. UDT Model Features

The in-depth model analysis includes the four features listed and classified in Table 5: scale of implementation, development status, maturity spectrum, and involvement of local authority. Figure 6a–d summarizes the results of the analysis of these features. In addition, Figure 7a,b illustrates the comparison of the features "maturity spectrum" and "involvement of local authority" with the population size of municipalities.

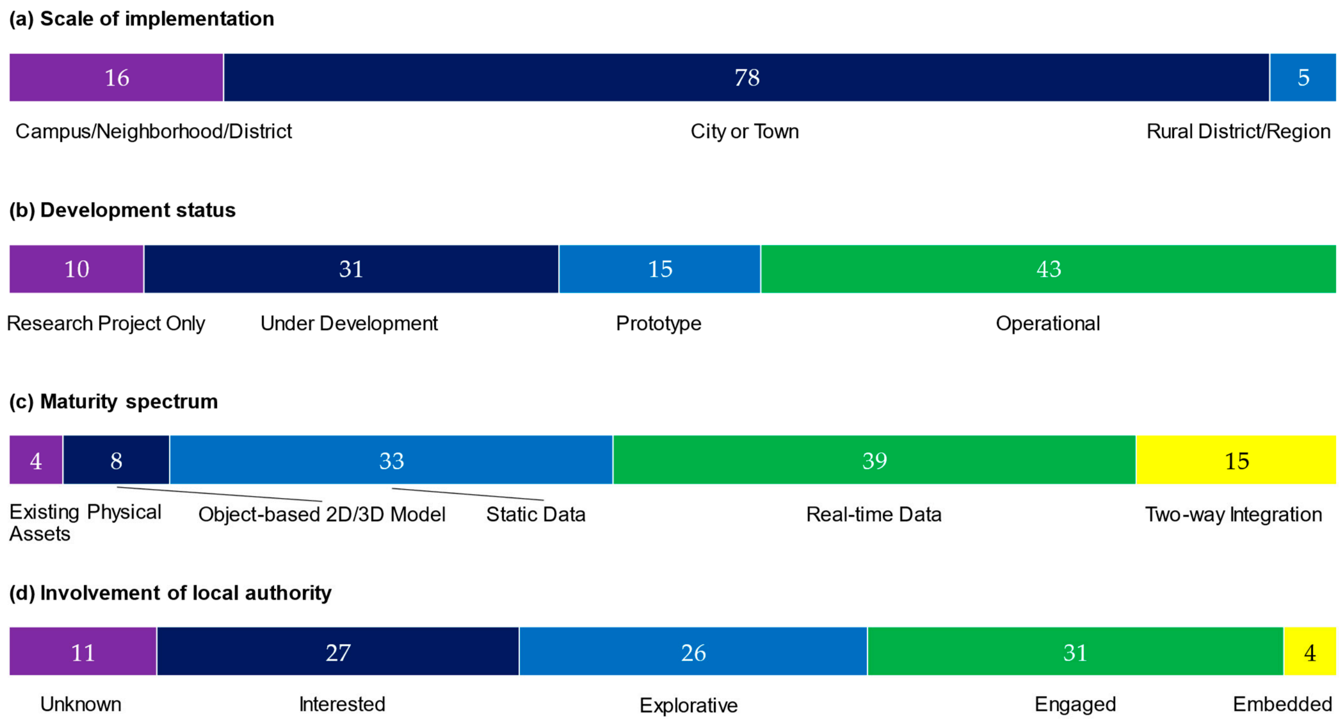


Figure 6. Model features of analyzed UDTs: (**a**) scale of implementation, (**b**) development status, (**c**) maturity spectrum, and (**d**) involvement of local authority. The colors only serve for visualization.

Figure 6a shows the distribution of UDT implementation scales. The majority of UDTs operate at the municipal level (city or town), with a few examples covering regions. Only 16 models span a campus, a neighborhood, or an urban district (scale 1). Nonetheless, in the context of these smaller UDTs, communication and scientific publications may be limited, in contrast to the more extensive activities in city-wide UDTs. The majority of models in our sample, 78, provide a UDT on the municipal level (scale 2).

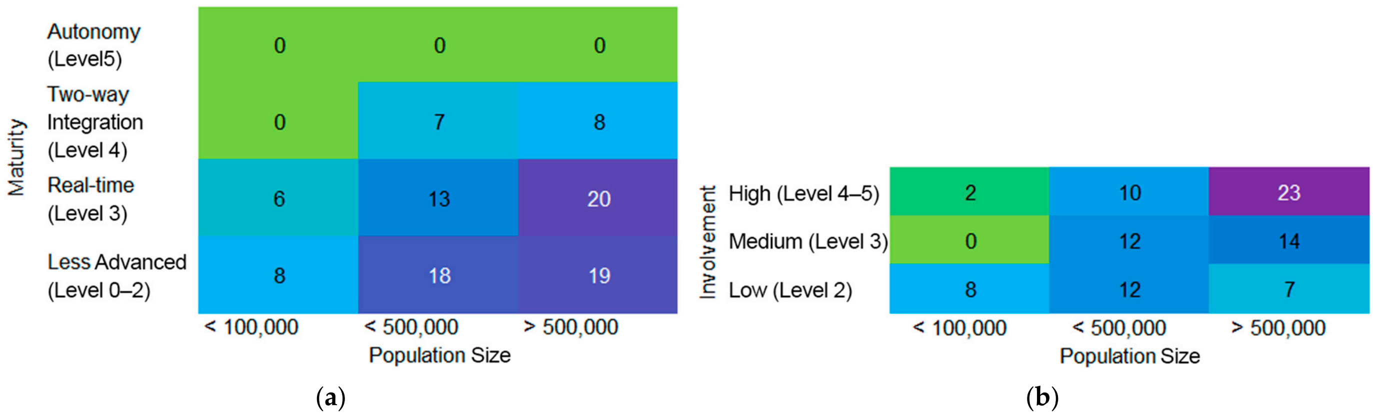


Figure 7. Combining the population of cities with (**a**) maturity spectrum and (**b**) involvement of local authorities (without unknown involvement). The colors from light green to purple illustrate the frequency.

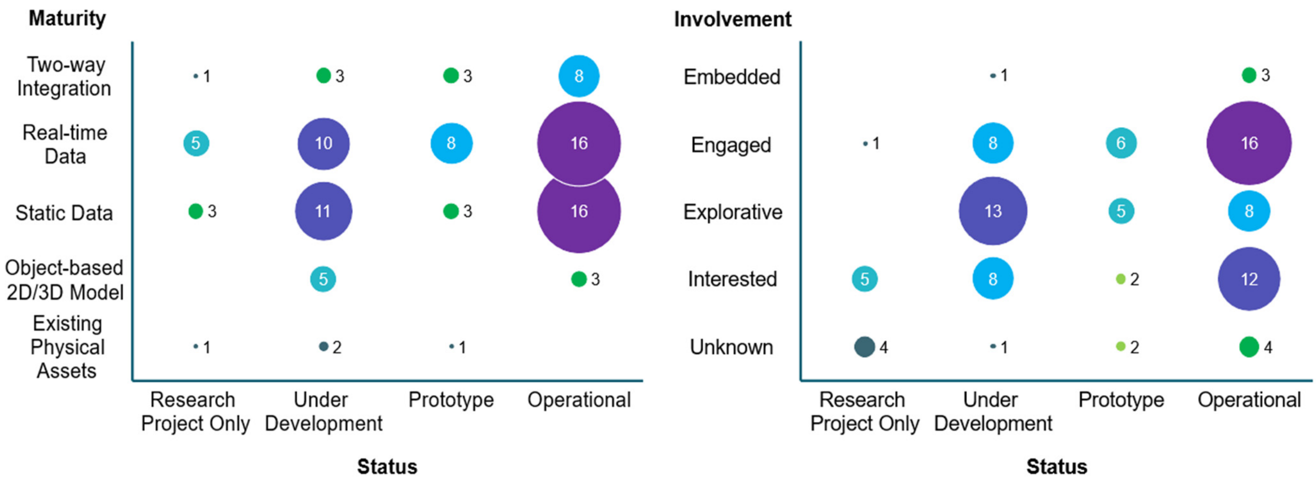
Examining the development status reveals that we mapped more than half of the UDTs (57%) as not yet in series operation (see Figure 6b). These 56 UDTs are research projects (status 0), in development (status 1), or in the "prototype" phase (status 2). Conversely, we classified 43 models as operational (status 3). We explain the underrepresentation of prototypes by the rare use of this term and the diffuse border between the status levels. Most municipalities may refer to their UDT status as "in development" or "operational," even though "prototype" would also be appropriate.

The maturity spectrum, as a technical criterion, is a key consideration of the current study. To our knowledge, 39 of 99 assessed UDTs can already process real-time data (see Figure 6c). Only a small number, 15 larger municipalities such as Barcelona and Hamburg, report reaching bidirectional integration (level 4). These achieved levels highlight the progress these municipalities have already made. In the examined UDTs, we identified no full automation (level 5) yet. However, no discernible disparities in maturity levels emerged between medium-sized and large locations (see Figure 7a). We conclude that municipalities with a certain population size have the capacity (e.g., staff or budget) and need to foster developments like UDTs. Again, the overrepresentation of municipalities of this size in our sample may weaken this conclusion.

Local authority involvement ensures scalability and long-term implementation (see Section 2). Figure 6d illustrates the extent of reported local authority involvement across the analyzed digital twin models, using scales according to Guckenbiehl et al. [29]. In 35% of the UDTs, the authorities engage in the UDT development or embed the model into their work. In cities like Rotterdam, the administration is the main driver of development. For most other models in the sample, the authorities express interest and explore options. We categorized only 11 UDTs as "unknown", meaning the published UDT is developed and maintained by researchers or external companies. Figure 7b suggests that especially large cities engage in the development and application. In this relatively new field, we assume that the remaining municipalities either need to build capacity or strengthen the administration's and politicians' belief in the benefits of UDTs before they embed them. This may be particularly true for small cities. On the other hand, these small cities may prefer a ready-made solution from an external partner to building their own capacities.

4.1.3. UDT Status of Development

To better understand the relationship between the implementation status, the maturity spectrum, and the involvement of local authorities, we correlate these features. Figure 8a and Table 6a show the count distribution across the dimensions "Maturity spectrum" and "Development status" in the sample. We cannot observe that a higher status leads to a higher level of maturity. However, apparently, almost all included municipalities report working with static data at a minimum. This pattern suggests that the transition from development to operational use may remain a critical threshold. Governance, data availability, and legal issues seem to slow down the scaling of development projects (cf. Section 2). Once operational, a UDT relies on certain technical fundamentals, such as standardized data pipelines between physical and digital systems, along with regularly or continuously updated data. Cities with a "two-way integration" maturity level use different types of data. This usage often results in hybrid architectures containing both static and real-time data. Of the 99 UDTs in our sample, 24% are in operation and are already very mature, using two-way integration or real-time data.



(a) (b)

Figure 8. Bubble diagrams showing the development status of UDTs in correlation with the (**a**) maturity spectrum and (**b**) involvement of local authorities. The colors from light green to purple illustrate the frequency.

Figure 8b and Table 6b demonstrate the uneven distribution of local authority involvement across development stages. The large bubbles in the middle to high range indicate that local authorities in our sample are increasingly moving from being "data users" to "data orchestrators". They report to explore or work with UDTs, regardless of their development status. Higher authority involvement tends to coincide with more advanced implementation across development stages. On the other hand, research projects may be a possible starting point for municipalities that are interested but not yet engaged. These projects can lead to co-design and collaboration between researchers and municipal staff, ultimately resulting in higher status and involvement levels.

In summary, the descriptive analysis shows that the UDTs in our sample are concentrated in Europe, especially Germany, and predominantly located in medium and large cities. Municipalities with fewer than 100,000 inhabitants are underrepresented. Most UDTs operate at the municipal level, and over half (57%) are not yet in series operation. This indicates that the field is still transitioning from development to embedded use. Thirty-nine cases integrate real-time data, and 15 report to work bi-directionally, but none reach full automation. Local authority involvement is the strongest indicator of scalability. Within the limits of our non-representative sample, these patterns suggest that progress and scalability depend as much on institutional embedding, data governance, and cross-departmental coordination as on technical capabilities.

Table 6. (2) Matrices showing the development status of UDTs in correlation with the (**a**) maturity spectrum and (**b**) involvement of local authorities. Sums are in bold.

	Research Project Only	Under Development	Prototype	Operational	∑
Two-Way Integration	1	3	3	8	**15**
Real-time Data	5	10	8	16	**39**
Static Data	3	11	3	16	**33**
Object-based 2D/3D Model	0	5	0	3	**8**
Existing Physical Assets	1	2	1	0	**4**
∑	**10**	**31**	**15**	**43**	**99**

(**a**)

	Research Project Only	Under Development	Prototype	Operational	∑
Embedded	0	1	0	3	**4**
Engaged	1	8	6	16	**31**
Explorative	0	13	5	8	**26**
Interested	5	8	2	12	**27**
Unknown	4	1	2	4	**11**
∑	**10**	**31**	**15**	**43**	**99**

(**b**)

4.2. Interview Insights

4.2.1. Comparison of Descriptive Results with Interview Insights

The following qualitative interview insights are exemplary and serve to contextualize the descriptive results. Findings refer to individual statements; quotes illustrate the interviewees' key points. For reasons of clarity, the expert number (cf. Table 7) is given in the text or in parentheses in the following section. The word "expert" is in the singular form, regardless of whether the interview was one-on-one or dual.

Table 7. Comparison of UDT characteristics based on interviews.

Expert	Municipality	Location	Population	Archetype [1]	Scale	Status	Maturity
1	Differdange	Luxembourg	<50,000	9	2	1	3
2	Gothenburg	Sweden	<1,000,000	9	2	3	2
3	Klagenfurt	Austria	<500,000	9	2	2	3
4	Leipzig	Germany	<1,000,000	9	2 [2]	3	3
5	Rotterdam	the Netherlands	>1,000,000	9	2	3–4	3–4
6	Shenzhen	China	>5,000,000	5	2	1–3	1–3
7	Singapore	Singapore	>5,000,000	6	1	1	3
8	Zurich	Switzerland	<500,000	9	2	3	2 + 4 [3]

[1] archetype based on authors' classification; [2] several specialist twins and applications in different scales; [3] level 2 operational, level 4 under development.

Prior to the interviews, written pre-surveys asked participants to self-assess their digital twins in terms of maturity, status, and scale, among other factors (cf. methodology in Section 3). Table 7 summarizes these self-assessments, combined with the population and archetype of the municipalities. The eight municipalities range in population from under 50,000 (Differdange) to over 5 million inhabitants (Shenzhen, Singapore). Almost all cases are city-scale UDTs (scale 2). The European municipalities fall into the same urban archetype category (code 9), while Shenzhen and Singapore represent different archetypes (codes 5 and 6). The self-assessments of status and maturity span from early development (e.g., Differdange, Singapore) to operational UDTs (e.g., Gothenburg, Leipzig, Rotterdam, Zurich). Several respondents reported intermediate or range values, indicating ongoing evolution. Overall, the set includes UDTs at various stages of development across a broad spectrum of city sizes and contexts.

The subsequent online interviews produced 480 min (eight hours) of audio that we transcribed into 138 pages of text. A qualitative content analysis with inductive category formation (cf. Section 3) produced the following four main topics: (1) UDT development and maturity, (2) organizational involvement and scale, (3) potential and use cases, and (4) challenges in development and application. Based on the main categories, we identified 23 subcategories (cf. selection of subcategories in Table 8).

Table 8. Subcategories from the main category UDT development and maturity.

Subcategory	Characteristics	Quote Examples
Early-stage experimentation and pilot character	Project-driven experimentation (Differdange, Shenzhen, Singapore)	"It's on the development stage, so it's an experimentation we have with the city" [expert 1]
	Dependence on external funding/programs (Differdange, Gothenburg, Singapore)	"It was funded by National Research Foundation [...] many use cases were research-based proposals" [expert 7]
	Transition intention but incomplete implementation (Klagenfurt, Shenzhen)	"We have been working on this topic [UDT] for quite some time [...] further expansion stages are planned" [expert 3]

Table 8. *Cont.*

Subcategory	Characteristics	Quote Examples
Transition from research projects to operational phases	Structured phase model (Rotterdam)	"We first developed a proof concept, then we developed a prototype, and now we have developed a minimal viable product" [expert 5]
	Implementing administrative routines (Gothenburg, Leipzig)/scalable architectures (Differdange)	"[. . .] we are pushing 'Twin as a Service' so departments themselves can visualize their own data in real time" [expert 2]
Institutional involvement/ municipal leadership	Direct in-house management (Gothenburg, Leipzig)	"[. . .] the development of digital twin is entirely in the department of urban planning" [expert 2]
	Hybrid partnerships retaining strategic control (Klagenfurt, Rotterdam)	"We focus intensively on datasets and functionalities [. . .] that cooperation between us as the city and the external company works really well as an innovation partnership" [expert 3]
	Structured departmental division (Zurich)	"[. . .] IT service operates servers and networks; geoinformation office manages data infrastructure; 3D applications lie with the department of Urban Planning. So each part has its role inside the city organization" [expert 8]
	Progressive transfer from research institute to municipality (Differdange)	"Who operates it? For now it's us [research institute] because we're developing it [. . .]" [expert 1]

The subcategories in Table 8 show that early-stage UDTs in our sample (Differdange, Shenzhen, Singapore) primarily function as experimental environments, which are valuable for testing concepts and building technical capacity but are still detached from routine administrative processes. According to our interviewees, the evolution of UDTs depends largely on the establishment of stable funding mechanisms and the embedding of responsibilities within municipal structures, to enable progression from research projects to sustainable operational platforms.

In the transition to the operational phase, municipalities try to follow a structured phase model (cf. Rotterdam) or implement tools such as the "twin as a service" approach for scalability (cf. Gothenburg). Both approaches have proven successful.

Deep involvement of public authorities is an additional key indicator of maturity for a UDT in our interview sample. The most advanced cities, such as Rotterdam or Zurich, engage specialist departments at an early stage, adapt processes (rather than just introducing technology), break down data silos, and have a long-term digital strategy in place. Rotterdam is focusing on hybrid partnerships, retaining strategic control, while Zurich is focusing on a structured department division. Clear division of labor among specialized municipal units in Zurich demonstrates embedded institutional responsibility across departments. The municipality of Klagenfurt involves several departments, subsidiaries, and partners in the development process.

In expert 1′s view, smaller municipalities tend to adopt more use-case-specific, vendor-provided solutions, whereas larger cities are more inclined to pursue centrally coordinated and strategic approaches with stronger internal control over the UDT infrastructure. These interview insights resonate with the descriptive analysis, which suggests an association between municipal involvement and maturity (cf. Section 4.1.2).

Differdange has also achieved a high degree of maturity through the involvement of the research institute responsible for development. Expert 1 suggests that "…actors like us, we could create, we could help you to adopt the technology, and then you run alone" [expert 1]. For expert 4, cooperation with universities and companies is important to facilitate testing concrete use cases, while working on joint, funded projects with other municipalities accelerates standardization.

4.2.2. Potential of UDT Application and Use Cases

Based on the self-selected set of eight interviews, the main identified objectives of implementing a UDT are: enhancing transparency [expert 3–6], increasing efficiency [expert 1–6] to reduce costs [expert 4, 6], and preparing for a digital era [expert 5, 6]. Most interviewees see the main field of application in decision support through processed digital data [expert 1–3]: UDTs can accelerate planning [expert 4], enable predictions, examine the effects of measures [expert 3], and answer specific questions as a temporal-spatial representation of the city [expert 8]. Expert 4 emphasizes this point, saying, "It's all about generating knowledge from data." Automating data enables faster decision-making, leading to cost reductions in the planning process [expert 2, 3].

Interviewees emphasize that a UDT is the total sum of digital resources [expert 4, 5] and the fundamental basis for various applications that will go far beyond current purposes [expert 6]. Expert 5 is convinced that "all parties will benefit when there is a good digital infrastructure". Therefore, UDTs are ideal tools for collaborative planning in a common reference space, according to expert 7.

In addition, the experts agree that 3D visualizations and VR applications allow a transparent and effective communication of goals [expert 2–4; 7, 8] and support the convincing of politicians, clients, and the public. This, in turn, can lead to secured funding, according to expert 2. The potential to make the model accessible to companies and individuals is also very high [expert 6]. Municipalities like Gothenburg and Rotterdam already test this approach with their "Twin-as-a-Service" [expert 2] and "Open Urban Platform" [expert 5].

4.2.3. Challenges in the UDT Development and Application

According to the interviewees, the challenges of implementing UDTs include data availability and accessibility, data segregation, coordination, a lack of financial resources and staff, along with data security.

Most interviewees identify data availability, accessibility, and segregation in silos as the main obstacles to developing and applying UDTs [expert 1–3, 5, 6]. Coordinating data from different sources of varying quality is complex and time-consuming [expert 3, 6]. Expert 7 emphasizes that, above all, data should be reliable and of high quality. Experts 2 and 4, on the other hand, state that only relevant data in the municipalities' interest is important. According to experts 1, 4, and 7, standardization and interoperability through unification [expert 1] and open, manufacturer-independent standards are necessary [expert 4, 7]. Examples of evolving standardization include the German DIN SPEC 91607:2024-11 [35] on UDTs [expert 4] and a planned European toolbox [expert 1].

"The biggest challenge is coordination," says expert 3. Experts 5–8 also point out how challenging the process is of bringing different users and perspectives to the table. According to expert 6, one reason for this complicated process may be the lack of a clear vision for a UDT. Expert 5 also sees different definitions as an obstacle.

Expert 2 names "money" as the main challenge, with a considerable gap between the required and available budget. According to experts 4 and 6, there is also a lack of qualified personnel, such as data specialists. There is also a lack of suitable storage facilities, says expert 3. A lack of resources may also result from the difficulty of convincing others

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because "it is hard to measure success, no measures because no definite starting and ending point of UDT" [expert 3]. Furthermore, "digitalization is not a mandatory task," which is why there is a "lack of recognition" [expert 4]. Expert 8 also mentions fears of job losses, restructuring, and redistribution of work.

The security of the infrastructure is also an important consideration. For expert 2, "it's not possible [. . .] to share detailed 3D data". The municipality of Gothenburg instead plans to use a lower level of detail for citizen applications.

5. Discussion

5.1. Interpretation of Results

This exploratory study mapped and compared 99 UDTs across three continents using literature-based characteristics and expert interviews. The findings suggest that UDTs only grow and generate sustainable value when they are firmly embedded within municipalities. Technological capacity appears not to be the only factor promoting UDT progress. Organizational and governance readiness also play a role. The most advanced cases in our sample—e.g., Rotterdam and Zurich—demonstrate that deep integration into administrative processes, supported by governance structures and cross-departmental collaboration, is necessary to advance beyond isolated pilot projects.

In contrast, cities such as Leipzig and Differdange, which are still in the process of establishing these structures, highlight that institutional readiness is a primary obstacle to UDT development. Experts 3 and 5 agree that lacking coordination and achieving a common understanding remain challenging. This finding aligns with results reported by Weil et al. [7] and Guckenbiehl et al. [29], who emphasize the importance of local governments in UDT implementation. According to expert 1, however, a strong involvement with many financial and personnel resources might not be feasible for small municipalities. They would rather rely on externally provided platforms with a focus on specific use cases, while large municipalities develop UDTs for several use cases themselves.

Taken together, the interviews suggest a tendency for larger cities to pursue more centrally coordinated UDT strategies embedded in broader digitalization programs, while smaller municipalities more often describe incremental, use-case-driven implementations based on ready-made, vendor-provided tools.

Experts 2 and 4 point out that financial and staff constraints apply not only to small municipalities, but to larger ones as well. Weil et al. [7] also highlight the general challenges of finding knowledgeable staff and acquiring financial resources.

On the other hand, UDTs can support securing funds by generating knowledge from data [expert 4] and by providing 3D data for visualization and better communication [expert 2]. Furthermore, partnerships with private companies or data-driven business models, as exemplified by Rotterdam's Open Urban Platform and Gothenburg's "Twin-as-a-Service," demonstrate how the private sector can become an integral part of UDTs and generate new revenue streams. Joint projects with research institutes can promote testing and progress, as emphasized by experts 1 and 4.

The patterns discovered in this study further stress the importance of interoperability and common frameworks. The effectiveness and scalability of UDTs depend on unified data models and open, manufacturer-independent interfaces. Without ongoing efforts such as the DIN SPEC 91607:2024-11 [35] standard [expert 4] and the planned European toolbox [expert 1], UDTs risk becoming siloed technical entities rather than integrated operating systems, according to our set of experts. This risk reveals a structural tension in current UDT deployments where technical progress often exceeds institutional and regulatory alignment. This suggestion aligns with the findings of Wu et al. [13] and Azadi et al. [14], who also identified the lack of common standards as an obstacle.

Additionally, incomplete and unreliable data are an obstacle in UDT implementation, according to Shahat et al. [2] and Weil et al. [7]. Across all interviewee municipalities, data quality emerges as a foundational requirement, as well. While Klagenfurt emphasizes the competitive advantage of a wide set of data, Zurich highlights the primacy of reliability over granularity, and Differdange and Leipzig stress the relevance and applicability of data for administrative decision-making. The interview results suggest that not only the access to data, but also its fitness-for-purpose constrains UDT development. The increasing adoption of real-time data streams indicates a trajectory toward more responsive and predictive urban systems.

Due to our Europe-heavy sample and the limited number of self-selected interviews, we treat the discovered patterns as an indicative tendency. Nevertheless, they support the findings of previous studies and can be used as the basis for recommendations.

5.2. Research Limitations and Future Work

Our study faced several limitations: (1) Data availability and reliability remain limited. Many UDTs are not publicly accessible, and the documentation often consists of brief mentions on websites rather than technical specifications or peer-reviewed material. Classifying UDTs into criteria relied on self-description and our estimation. (2) The absence of established definitions and mature standards limits comparability. Municipalities label heterogeneous tools as “digital twins”. Despite using keywords like “digital twin” and focusing on common, literature-based criteria, variations in scope and functionality may remain. We could only compare our mapping with self-assessments in eight cases, and without ground-truth data, we cannot verify that all interviewees understand the criteria in the same way. Also, without a robust baseline, no sensitivity analysis is possible. Until interoperable vocabularies and reporting templates mature, cross-case synthesis will remain provisional. (3) The coverage is incomplete and time-bound. The mid-2024 sample is a snapshot, not a census. Projects may have emerged or advanced since then, and due to the semi-structured review approach with a focus on top results and changing search engine algorithms, the longlist is not reproducible. (4) The selected UDTs are mostly from Europe, particularly Germany, because of language, network, and publication biases, and the sampling is purposive rather than random. Additionally, large and pioneering municipalities tend to release more information. Global patterns and UDTs in small municipalities may therefore be underrepresented, and we cannot infer global prevalence or statistically robust trends from this sample. This Europe-heavy composition likely amplifies characteristics typical of European urban governance and mobility systems. Consequently, some associations we observed may primarily reflect European practices and could behave differently in other contexts. (5) We analyzed the semi-structured interviews and pre-surveys with inductive category formation. However, we excluded other quantitative approaches and did not further add intercoder agreements. We therefore refrain from making causal claims or generalizing interview contents. (6) The small, response-based sample of eight interviews provides illustrative depth but cannot support statistically robust generalizations about UDT practice. Taken together, these limitations imply that our study should be understood as an exploratory cross-regional mapping of documented initiatives. It reveals a lack of standards and data, which hinders the objective characterization of a large set of UDTs. Nevertheless, it can lay the groundwork for further research in this field.

Future work should build on this exploratory mapping by expanding the dataset to include more locations and validating key indicators with municipal stakeholders. Methods should include email surveys followed by interviews to prevent different interpretations. Adding intercoder agreements to a subset of the formal coding of the interview results can strengthen inferences. To improve comparability, data collection should align with emerging standards, such as the German DIN SPEC 91607:2024-11 [35] and the European toolbox. Researchers should use a standardized reporting template and common vocabulary. The dataset should be periodically extended and revisited as projects evolve. Larger datasets allow for the reweighting of observations and exclusion of overrepresented countries, which can strengthen the results. Extending the dataset will also enable clustering and identification of typologies. Furthermore, expanding the scope of analyses on the relationship between urban archetypes and UDT developments beyond its use as a selection criterion reveals a new area of research and could answer the research question of whether certain car-independent urban archetypes, such as "well-functioning cities" or "transit cities," develop and adapt UDTs more quickly.

A complementary line of research should address data segregation by making relevant data discoverable and usable for municipalities through governance mechanisms, secure data spaces, and interoperable interfaces. Finally, collaboration among academia, industry, and municipalities via testbeds and co-design can validate methods, accelerate standardization, and produce guidance. Such advances would allow future studies to move beyond exploration toward more robust cross-regional analyses and, where appropriate, statistically generalizable inferences.

6. Conclusions

This meta-study offers an exploratory cross-regional mapping and descriptive comparison of 99 UDTs across Asia, Europe, and North America, complemented by expert interviews. Given the purposeful, Europe-focused sample, the findings highlight contextual patterns, recurrent challenges and potential among documented initiatives in these regions, rather than constituting a global census of UDTs. With the objective of evaluating the overall socio-technical readiness of UDTs and deriving key governance recommendations, this study incorporated additional literature-based location characteristics (population and archetype), as well as model features (authority involvement) into existing comparison approaches. Building on this foundation, the study provides a structured, context-aware overview of evolving configurations and dynamics within this rapidly advancing field.

Within our sample, most reviewed UDTs operate at the municipal level. More than half are not yet in series operation. Maturity is at a mid-level, with growing real-time capabilities in 39 cases, but limited two-way integration in 15 cases, and no autonomy. Institutional involvement is the strongest indicator of scalability. Developments involving the authorities or embedded UDTs (35%) were associated with progress beyond the pilot stage. Interviewees suggested that smaller municipalities more often implement targeted use cases with ready-made tools. Mentioned challenges included data availability and segregation, coordination across stakeholders, filling standardization gaps, overcoming funding and staffing constraints, and securing the UDT environment and involved data.

Looking ahead, and assuming that the trajectories observed in our sample continue, UDTs are likely to expand from isolated flagship projects to integrated, cross-domain applications. As real-time capabilities grow, UDTs may increasingly act as operational decision-support layers that trigger automated responses to environmental or infrastructural events. Reaching this stage will require stronger standardization, shared data vocabulary, and viable business models to secure financing. New data partnerships with private companies and researchers will be essential to sustaining and scaling UDT infrastructures. Ultimately, the evolution of governance, data quality, and institutional readiness will determine whether UDTs mature into the long-term digital backbone of resilient, anticipatory urban management. In line with the exploratory nature of this study, these conclusions should be interpreted as indicative hypotheses and directions for further research on the socio-technical dynamics of UDTs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/smartcities9030049/s1, Table S1: 99 selected UDTs with criteria and references.

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Abbreviation

The following abbreviation is used in this manuscript:

UDT	Urban Digital Twin

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