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A Participatory Urban Digital Twin Development Roadmap for Climate-Responsive Urban Planning: The Case of İzmir, Türkiye

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Abstract

This article presents a participatory roadmap for developing an urban digital twin (UDT) for Izmir within the Re-Value project to support inclusive, climate-responsive urban planning. It responds to technocentric urban digital twin models often developed with minimal stakeholder engagement, raising concerns about their relevance to local contexts and urban challenges. To bridge this gap, the study developed a locally grounded and citizen-informed UDT roadmap through three-stage participatory process: (a) a co-design workshop engaged local stakeholders to identify spatial challenges and climate-responsive interventions; (b) a technical workshop aligned local insights with digital simulation capabilities through collaboration between municipal decision makers and technology partners; and (c) a municipal multi-departmental roundtable addressed governance models, data-sharing protocols, and infrastructure needs. These processes respond to three strategic priorities: (a) addressing coordination and data integration challenges across municipal departments; (b) developing a governance model incorporating stakeholder needs and citizen contributions; and (c) prioritizing small-scale, scenario-based micro-analysis and simulations for pedestrianization, green infrastructure, and thermal comfort. To support these objectives, key urban digital twin components—such as the minimum viable dataset, sensor plans, and simulation parameters—were collaboratively identified alongside a governance model tailored to İzmir's administrative structure. The findings highlight that a meaningful urban digital twin must integrate cross-sectoral cooperation and spatial risk analysis (e.g., urban heat islands, air pollution, and flood-prone zones), supported by layered geographic information and 3D models. Overall, this model demonstrates a viable method for local governments to operationalize stakeholder participation before urban digital twin deployment, enabling context-sensitive, locally grounded, and democratically legitimate urban solutions.

Keywords
climate-responsive planning; digital twin; participatory urban digital twin; stakeholder engagement

1. Introduction

Climate change poses growing risks to urban environments by intensifying extreme heat events, exacerbating the urban heat island effect in cities, and placing pressure on urban infrastructure, public health, and quality of life (Intergovernmental Panel on Climate Change, Chapter 6, 2023). These challenges particularly affect the Mediterranean basin, where accelerated warming—approximately 20% above the global average—combined with increased drought risk, declining freshwater availability by around 15% in the coming decades, and sea-level rise by 1 meter by 2100, creates combined pressures particularly for coastal cities (Plan Bleu & Mediterranean Experts on Climate and environmental Change, 2019). In such multi-risk and complex environments, planning processes must address fundamental questions about what type of data to use, which uncertainties to account for, and whose interests to prioritize. In response, with the increased possibilities in information and communication technology (ICT) and big data, urban planning has increasingly turned toward data-driven and evidence-based approaches to better understand, simulate, and manage complex urban systems.

Within this context, the urban digital twin (UDT) concept, which enables a more integrated way to simulate complex urban challenges such as climate change (Hurtado & Gomez, 2021; Ricciardi & Callegari, 2022), has gained attention. UDTs are increasingly positioned as systems that monitor, model, simulate, and compare urban scenarios by realistically representing a city's physical assets and processes within a digital environment through continuous data flows managed over feedback loops (Abdelrahman et al., 2025; Batty, 2018; Deng et al., 2021; Marçal Russo et al., 2026; Patel et al., 2024; Weil et al., 2023).

Despite these potentials, the integration of UDTs into city management often reproduces technocentric and data-driven approaches (Azadi et al., 2025; Cardullo & Kitchin, 2019; De Jaeger & Swerts, 2026) that reduce complex urban problems to measurable indicators, reinforcing technocratic decision-making, raising concerns about data politics, corporate dependency, and surveillance capabilities (Kitchin, 2014; Sadowski & Bendor, 2019; Söderström et al., 2020). This underscores a key gap in the literature that limited attention has been given to governance models, participatory processes, and the ways UDTs are operationalized within local government before implementation (Azadi et al., 2025; Batty, 2013; Dawkins & Kitchin, 2025; Dembski et al., 2020; Deng et al., 2021; Luo et al., 2025; Nochta et al., 2021; Qanazi et al., 2025). In particular, factors such as usability of UDTs in planning decisions, the clarity of generated scenario content, stakeholder participation, and inter-departmental interaction need to be ensured in order to provide decision support rather than generic systems with limited relevance for local planning contexts and detached from citizens' everyday experiences (Maiullari et al., 2024; Sánchez-Vaquerizo, 2025).

This limitation highlights the need for context-specific UDT approaches grounded in both local knowledge and institutional realities. Developing such systems requires not only an understanding of residents' needs and everyday urban experiences, but also a clear recognition of the capacities, constraints, and operational logics of the institutions responsible for developing and managing digital twins (Nochta & Oti-Sarpong, 2024). Without this dual alignment, UDTs risk remaining at the operational dashboard level without

influencing planning processes (De Jaeger & Swerts, 2026; Weil et al., 2023). In this regard, participatory and multi-stakeholder approaches are essential for enabling context-sensitive UDT development that supports the joint identification of locally relevant problems, the definition of data and modelling requirements, and the assessment of institutional feasibility. This provides the basis for UDTs that are both responsive to local priorities and compatible with existing governance structures (Kitchin, 2014; Nochta & Oti-Sarpong, 2024).

This article addresses this gap by presenting a participatory UDT development roadmap for climate-responsive planning in İzmir within the Re-Value project, which aims to support climate-responsive and participatory urban transformation by integrating digital technologies across European waterfront pilot cities. This study offers a context-sensitive and governance-oriented approach to UDT development at the local government level. The roadmap adopts a three-stage participatory framework: a local co-design workshop, a technical alignment workshop, and a governance roundtable, to define the minimum viable dataset, sensor plan, and simulation parameters in a manner consistent with local needs and capacity, thereby integrating participation, institutional coordination, and data governance into the early stages of UDT design before the platform establishment.

In the upcoming sections, we will first discuss UDTs and their participation gap in urban planning, grounding our discussion in the existing literature, including technocentric critiques and emerging governance-oriented perspectives. After that, we will introduce the methodological framework and present the design and outputs of the roadmap developed in this study. Finally, the article evaluates the implications of these findings for climate-sensitive and inclusive urban planning.

2. UDTs and Participation Gap in Urban Planning

Despite the growing recognition of UDTs as advanced tools for data integration, simulation, and evidence-based decision-making, a significant gap remains between their technological capabilities and their capacity to support meaningful participation in urban planning processes that take into account socio-institutional considerations (Azadi et al., 2025; Nochta et al., 2021; Yang et al., 2025). This limitation is particularly critical in climate-responsive urban planning, where effective decision-making depends not only on advanced modelling capabilities but also on integrating local knowledge and experiences, institutional capacities, and stakeholder perspectives. For UDT development, this creates a tension between data-driven optimization and the need for inclusive, participatory, and context-sensitive planning.

The following sections examine this gap in two steps: first, by situating UDTs within the broader evolution of smart city thinking and identifying their limitations in addressing social and institutional dimensions; second, by exploring participatory approaches that can be integrated into UDT development, highlighting current issues such as “limits-by-design,” institutional constraints, and predefined system architectures restricting the incorporation of meaningful stakeholder engagement and citizens’ lived experiences.

2.1. UDTs

The UDT concept is closely linked to the evolution of the smart city paradigm, which is defined by Batty et al. (2012) as an urban model that embeds ICT into traditional urban infrastructures to monitor and manage cities. At the core of this urban model are integrated databases that bring together different sectors, real-time sensing

systems, decision-support tools, and participatory governance mechanisms to make urban environments more efficient (Bibri & Krogstie, 2017; Kitchin, 2014). Over time, smart city agendas expanded alongside big data, sensors, and real-time monitoring, with urban data increasingly "streamed from sensors," reshaping how cities are managed and how decisions are made (Batty, 2013). However, the smart city paradigm has also been criticized for being technology-driven and corporate-led, often prioritizing efficiency and control over citizen participation and social inclusion (Hollands, 2008; Kummitha & Crutzen, 2017).

Building upon the technological and data infrastructures developed within the smart city paradigm, UDTs have emerged as a more advanced and integrative approach that combines real-time data, simulation models, and 3D urban representations into dynamic digital environments (Abdelrahman et al., 2025; Azadi et al., 2025; Lei et al., 2023; Yang et al., 2025). The concept of the digital twin itself originates from engineering and manufacturing, where digital replicas of physical assets are used for monitoring, prediction, and optimization (Grieves & Vickers, 2016). UDTs extend digital-twin logics to urban governance by integrating 3D/geo-spatial representations, data flows, models, and simulations for planning and decision support (Weil et al., 2023). When applied to the urban scale, UDTs integrate geographic information systems (GIS), internet of things (IoT) sensors, urban simulation models, and data platforms into interactive digital representations of cities (de Matos et al., 2022; Nochta et al., 2021; Sánchez-Vaquerizo, 2025; Weil et al., 2023).

UDTs therefore extend the smart city concept by moving from data collection and monitoring toward simulation, prediction, and decision-support systems, that increasingly support climate-responsive urban planning. Recent studies demonstrate their application in assessing urban heat islands (Qi et al., 2022), supporting water-sensitive urban design (Altındaş et al., 2026), enabling green infrastructure (Zellner et al., 2026), and evaluating climate adaptation scenarios (Maiullari et al., 2024; Nochta et al., 2021). As a result, UDTs are increasingly seen as strategic tools for urban governance, planning, and climate-adaptive urban development, as in the notable example of the Kera UDT from Espoo, Finland (Tartia & Hämäläinen, 2024). Recent empirical studies show that participatory UDT approaches can support collaborative scenario development, stakeholder learning, and more informed decision-making in green infrastructure planning and urban decarbonization (Maiullari et al., 2024; Zellner et al., 2026).

However, recent reviews stress that UDTs still remain predominantly focused on the physical aspects of urban spaces, thereby limiting their capacity to address multi-stakeholder collaboration that also integrates citizens' lived experiences (Marçal Russo et al., 2026; Qanazi et al., 2025). Furthermore, empirical work cautions that participation can be undermined by "limits-by-design," where planners and administrators control the UDT's design and fail to embed it into actual decision-making structures, curtailing citizen power rather than enabling it (De Jaeger & Swerts, 2026). While a smaller but growing body of research reframes UDTs as tools for participatory steering and knowledge co-production, realizing this promise requires participation to be operationalized as a core governance and process-design principle (problem framing, scenario-building, deliberation, and uptake), not merely as data collection or interface feedback (Dawkins & Kitchin, 2025). In this study, UDTs are conceptualized as socio-technical decision-support systems integrating geospatial data, simulation models, governance structures, and stakeholder knowledge to support climate-responsive urban planning.

2.2. Technocentrism vs. Participatory Multi-Stakeholder Collaboration Approaches for UDT Development

The interplay between technocratic planning models and participatory governance approaches shapes contemporary debates on UDTs and smart urbanism. While digital technologies are often framed as enablers of more inclusive, transparent, and improved urban planning (Anthopoulos & Reddick, 2016; Batty et al., 2012; Bibri & Krogstie, 2017), critical scholarship questions whether these claims materialize in practice (Cardullo & Kitchin, 2019; De Jaeger & Swerts, 2026; Kitchin, 2014). Much of the current UDT discourse remains embedded within a technocentric paradigm that prioritizes data-driven optimization, efficiency, predictive capacity, real-time data integration, advanced analytics, 3D visualization, and scenario simulations, while offering limited clarity on how these capabilities translate into improved planning outcomes (Azadi et al., 2025; Batty et al., 2012; Dawkins & Kitchin, 2025; Ferré-Bigorra et al., 2022; Nochta et al., 2021; Qanazi et al., 2025).

A central critique is that UDTs reframe urban problems as technical challenges to be addressed through data modelling and simulation, where standardized datasets and system design choices prioritize measurable indicators, embed institutional assumptions, and constrain participation within predefined interfaces, resulting in decontextualized solutions and what has been described as "limits-by-design" (De Jaeger & Swerts, 2026; Nochta et al., 2021). Importantly, participation is often reduced to involving citizens as data contributors or end-users of UDTs, rather than enabling them to influence the design of UDTs and related planning outcomes.

Participation in UDT development requires engaging citizens at the early stages of design, which is especially relevant for context-specific UDTs, as they depend on the alignment of multiple forms of expert and citizen knowledge (Nochta & Oti-Sarpong, 2024). This perspective implies that UDTs are understood as planning tools embedded within broader socio-technical systems where citizens identify locally experienced problems, needs, and priorities, while institutional and technical actors translate these inputs into data structures, modelling approaches, governance arrangements, and feasible implementation pathways (Nochta & Oti-Sarpong, 2024; Nochta et al., 2021). Without such multi-stakeholder alignment, UDTs, just like any other digital planning tool, risk becoming either disconnected from local needs or infeasible within existing institutional and data infrastructures (Goncalves et al., 2026). At the same time, immersive and experiential tools such as virtual reality and AI-based co-design can strengthen participation by allowing stakeholders to explore and evaluate "what-if" scenarios, improving comprehension, engagement, and decision-making in co-design processes (Dane et al., 2024; Dembski et al., 2020; Luo et al., 2025).

Based on the preceding discussion, this article argues that the integration of participatory approaches into UDT development cannot be assumed as a natural outcome of technological innovation, but requires deliberate governance design and methodological frameworks that enable meaningful multi-stakeholder collaboration between citizens and institutional actors to influence planning processes and outcomes (Yang et al., 2025). In response, this article proposes a methodological framework that integrates a participatory approach into UDT development that departs from standardized, top-down models. Instead of treating UDTs as pre-defined technical systems, the study develops a roadmap grounded in local context and institutional capacities through an iterative process that brings together citizen inputs, stakeholder perspectives, decision-making requirements, and available data. By doing so, the article aims to develop a methodological

framework for constructing UDTs as participatory and institutionally embedded decision-support tools rather than generic technological solutions, in the context of climate-responsive urban planning.

3. Methodological Framework: Multi-Stakeholder Collaboration-Supported UDT Development—A Participatory Roadmap Approach

This study adopts a qualitative, participatory case study approach, combining elements of co-design (maps, facilitator canvases, thematic group discussions, cross-table exchanges, and guided reflection) and collaborative knowledge production. The three-stage process was derived from participatory planning and co-design literature (Arnstein, 1969; Friedmann, 1973; Healey, 1997; Nochta & Oti-Sarpong, 2024; Sanders & Stappers, 2008) and was designed to progressively translate local knowledge into technical requirements and governance arrangements. The research design is process-oriented and exploratory, aiming not to test predefined hypotheses but to develop a context-sensitive framework for UDT development through iterative multi-stakeholder engagement and institutional alignment. The case study was conducted in İzmir, Türkiye's third-largest metropolitan city, located on the Aegean coast with a population of approximately 4.5 million. İzmir faces increasing climate-related challenges, including urban heat islands, flooding, and drought, making climate-responsive planning an important policy priority. Within the Re-Value project, the pilot area comprises the Alsancak, Kültür, and Mimar Sinan neighborhoods in the city center, which were selected for their dense urban fabric, mixed land uses, and exposure to climate-related urban challenges (see Figure 1). These characteristics provide an appropriate context for developing and evaluating the proposed participatory UDT roadmap.

Figure 1. The location of the pilot area of Alsancak, Kültür, and Mimar Sinan neighborhoods in İzmir. Source: Author's own elaboration using data from Esri's ArcGIS Online.

The methodology follows a process-based approach structured in three interrelated stages, designed to integrate multiple forms of knowledge by bringing together citizens, local stakeholders, and relevant institutional actors involved in UDT development for climate-responsive urban planning of İzmir. The three stages include: first, identifying locally experienced challenges, needs, and proposals through a participatory engagement workshop with citizens and local stakeholders; second, exploring relevant modelling approaches, simulation scenarios, and digital applications through a technical alignment workshop bringing

together municipal actors and technical experts; and third, evaluating and refining these outputs through a multi-departmental governance roundtable in relation to institutional structures, operational constraints, and available data (Figure 2).

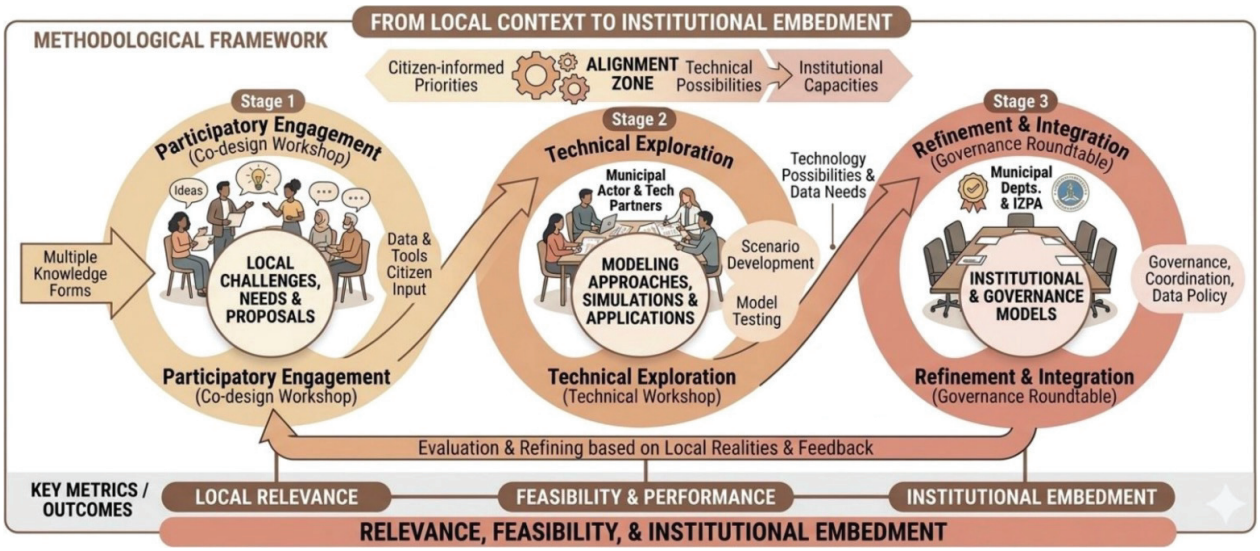

Figure 2. Participatory methodology for the co-design and roadmapping of İzmir's UDT. Notes: Generated with the assistance of AI tools; in the figure, abbreviation IZPA refers to İzmir Planning Agency.

The study develops a methodological framework that supports the co-design of UDT components while ensuring their relevance, feasibility, and institutional embedment. Participants were purposively selected according to their roles in community representation, technical expertise, and institutional decision-making. The three stages of this process-based methodology are summarized in Table 1 and discussed in detail in the following sections.

Table 1. Overview of the three-stage participatory UDT methodology.

Stage	Actors	Actor Selection Rationale	Key Outputs	Role in UDT Development
1st stage Co-design workshop	Residents, NGOs, *muhtars**	Local experience and knowledge	Spatial problems, thematic priorities, citizen inputs on data & tools	Identifies local needs and priorities
2nd stage Technical workshop	Municipal actors, tech partners	Technical feasibility	Simulation scenarios, data needs, modelling possibilities	Translates needs into technical possibilities
3rd stage Governance roundtable	Municipal departments, IZPA (Izmir Planning Agency)	Governance feasibility	Data requirements, governance model, coordination mechanisms	Aligns UDT with institutional structures

Notes: * *muhtar* is an elected neighborhood head in Türkiye, acting as a liaison between residents and local authorities.

Data were collected through workshop outputs, facilitator notes, and presentation materials generated during the three-stage process. The collected data were analyzed using qualitative content analysis to

identify recurring themes, stakeholder priorities, and governance requirements that informed the development of the proposed UDT roadmap.

3.1. Local Co-Design Workshop

The first stage of the methodology focuses on identifying locally grounded challenges, needs, and expectations through a co-design workshop. The aim is to elicit place-based knowledge and capture how urban issues are experienced, interpreted, and prioritized by residents and local stakeholders. A total of 18 participants took part in the workshop, including local residents (citizens), civil society organizations (NGOs), and *muhtars* who serve as neighborhood representatives and act as intermediaries between communities and local administrations. Participants were formally invited by the İzmir Metropolitan Municipality Urban Design and Urban Aesthetics Directorate, ensuring the inclusion of diverse stakeholder groups relevant to urban climate challenges and vulnerable populations. This composition enabled the integration of everyday experiences with locally embedded institutional and community perspectives. The overall framework, including the three-stage process, is illustrated in Figure 3.

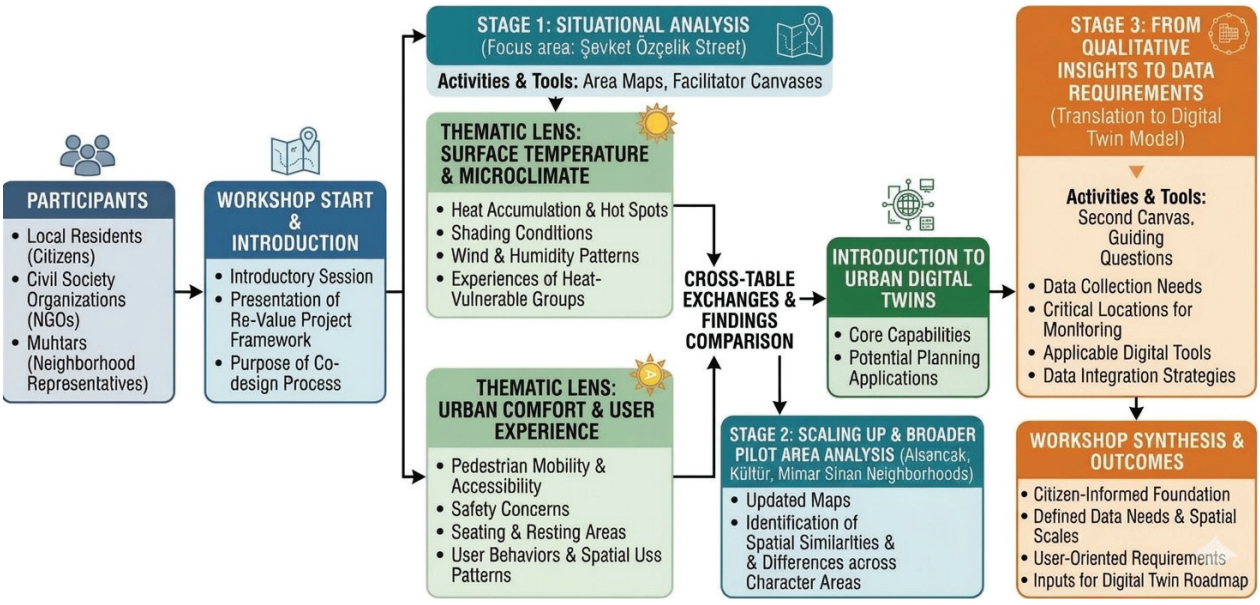

Figure 3. Methodological framework for the co-design workshop: identifying place-based challenges, needs, and expectations. Note: Generated with the assistance of AI tools.

The workshop was held on 20 May 2025 to integrate local knowledge into the development of a UDT roadmap, with a particular emphasis on urban comfort, microclimate conditions, and the pedestrian experience. The participants shared their observations and experiences of the area, identified challenges and opportunities related to shading, temperature, seating, and pedestrian movement, and contributed to the definition of relevant datasets, user perspectives, and local priorities for the UDT model.

The workshop began with an introductory session on the Re-Value project and the purpose of the co-design process, followed by a structured discussion session focusing on Şevket Özçelik Street as a representative case within the pilot area. Using maps and facilitator canvases, participants conducted a situational analysis of current conditions, needs, and spatial opportunities. Discussions were organized around two thematic lenses:

(a) surface temperature and microclimate, including heat accumulation, shading conditions, wind and humidity, and the experiences of heat-vulnerable groups; and (b) urban comfort and user experience, including pedestrian mobility, accessibility, comfort, safety, user behaviors, and spatial use. Themes were identified through preliminary discussions within the Re-Value project and reflected the pilot area's major climate-related concerns, including heat stress, pedestrian comfort, public space quality, and green infrastructure.

Following the thematic discussions, cross-table exchanges were conducted to compare findings across groups, and the scope was expanded to cover sub-character areas within the pilot zone, where participants identified spatial similarities and differences across neighborhoods. In the final phase, participants were introduced to the concept of UDTs, their capabilities and applications in urban planning. Building on this, participants transferred their spatial evaluations onto a second canvas. They responded to guiding questions on data needs, critical locations, relevant digital tools, and data integration strategies, translating qualitative insights into structured data requirements and system inputs. The session concluded with a synthesis of findings, defining key problem areas, data needs, spatial scales, and user-oriented requirements, thereby establishing a citizen-informed foundation for the subsequent UDT roadmap.

3.2. Technical Alignment Workshop

The second stage focuses on identifying how locally defined problem areas can be addressed through relevant modelling approaches, simulation scenarios, and digital tools. Rather than translating citizen inputs into abstract technical requirements, this stage explores which types of UDT applications and analytical methods are suitable for addressing the issues identified in the first stage. The aim is to connect locally grounded challenges with feasible and context-appropriate technological capabilities of UDTs.

This stage included a total of 13 participants, comprising municipal actors, project partners (ECOTEN urban comfort, VITO, and AugmentCity), and academic representatives from İzmir Institute of Technology. Among them, six participants represented municipal departments, primarily from GIS, transportation, and climate-related units of the İzmir Metropolitan Municipality and the Konak Municipality (the district municipality encompassing the pilot area within Izmir). In addition, three participants were project partners, and four participants were from İzmir Institute of Technology. By bringing together technical expertise and planning perspectives, this workshop enabled a joint assessment of how specific problem areas could be addressed using existing modelling practices and digital applications.

Methodologically, the workshop was structured as a multi-phase technical alignment process combining knowledge transfer, expert input, and collective scenario evaluation (Figure 4). It began with a short framing session presenting key findings from the first stage of problem-definition and data-collection activities. This was followed by a series of targeted technical presentations delivered by project partners (ECOTEN urban comfort, VITO, and AugmentCity), introducing specific modelling approaches and analytical tools, such as microclimate simulations, pedestrianization scenarios, and earth observation-based spatial analysis, that could respond to the identified urban challenges.

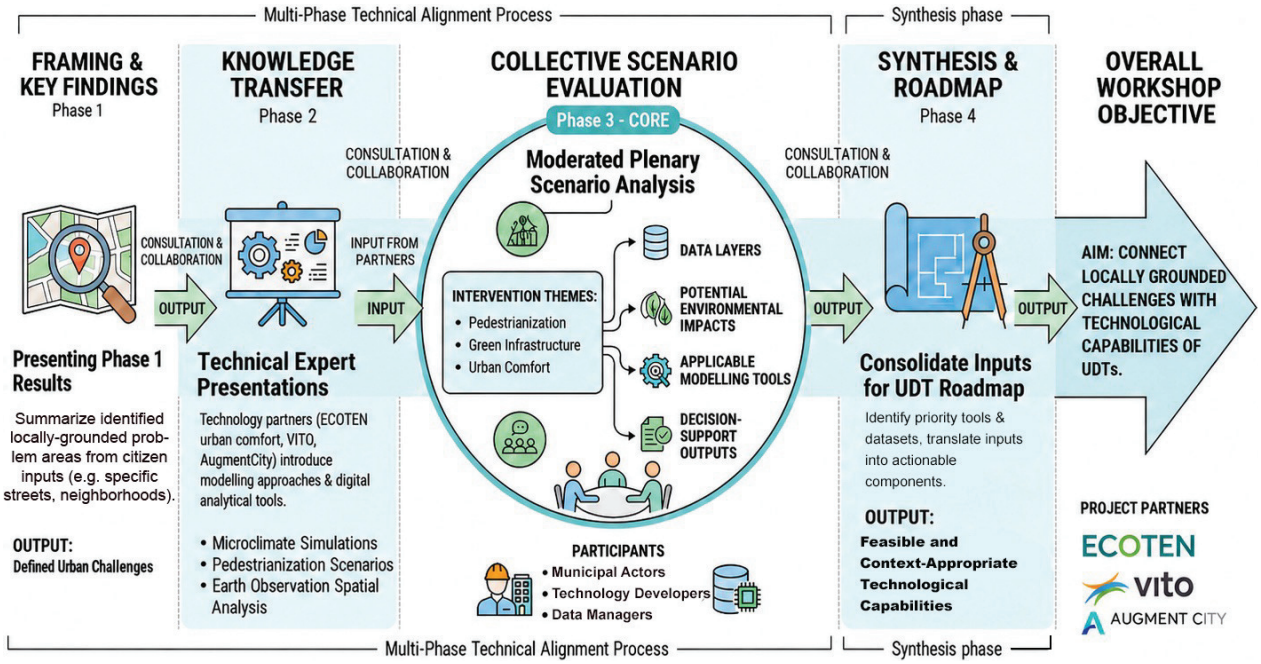

Figure 4. Methodological framework for technical alignment workshop. Note: Generated with the assistance of AI tools.

The core of the workshop consisted of a moderated, plenary-based scenario analysis session, in which participants collectively examined predefined intervention themes, including pedestrianization, green infrastructure, and urban comfort strategies through guided discussion. These discussions were structured around key analytical dimensions, including potential environmental impacts, required data layers, applicable modelling tools, and decision-support outputs. The workshop concluded with a synthesis phase that consolidated the discussions, identified priority tools and datasets, and translated the inputs into actionable components for the UDT roadmap.

3.3. Multi-Departmental Governance Roundtable

The third stage focuses on institutional integration and governance design through a multi-departmental roundtable. The aim is to evaluate the feasibility of the proposed UDT components within existing governance structures and to define coordination mechanisms across departments. The roundtable brought together 10 participants from multiple institutional levels and organizations. At the metropolitan level, participants included representatives from İzmir Metropolitan Municipality, including the Departments of GIS, Clean Energy and Climate Change, Transportation, and Agricultural Services. At the district level, representatives from Konak Municipality included the Departments of GIS and Climate Change. In addition, associated agencies such as the İzmir Development Agency were involved, ensuring that both the operational and strategic dimensions of governance were represented.

The roundtable was structured as a facilitated, multi-session dialogue to systematically elicit institutional perspectives and enable cross-departmental alignment (Figure 5). The session began with an introductory session and a short "warm-up round," in which participants reflected on their institutional capacities and key constraints related to data management, technical infrastructure, and organizational coordination. This was

followed by three thematic sessions focusing on (a) data and infrastructure requirements, (b) pilot area interventions and UDT scenario development, and (c) governance and coordination models. Each session combined guided discussion to identify data gaps, clarify departmental responsibilities, and explore feasible implementation pathways. The process also incorporated a final consensus-building discussion, where participants collectively reflected on critical success factors for the UDT initiative.

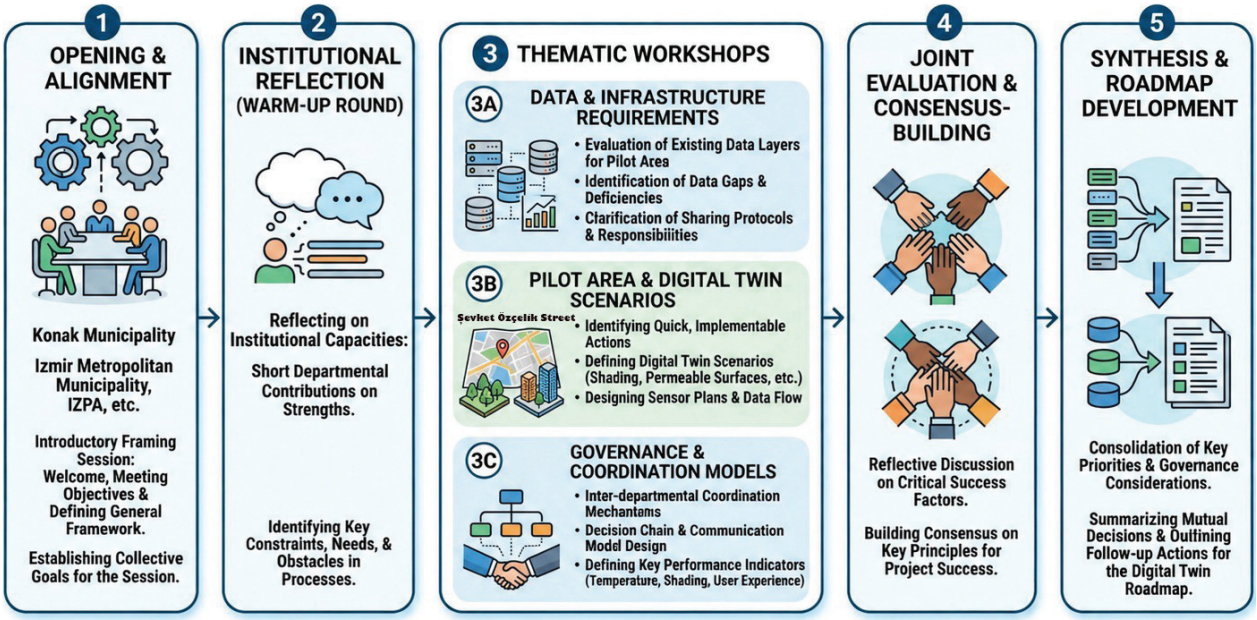

Figure 5. Methodological framework for multi-departmental roundtable for institutional integration and governance design. Note: Generated with the assistance of AI tools.

The roundtable concluded with a synthesis phase in which key priorities, governance considerations, and follow-up actions were consolidated to inform the UDT roadmap. This structured process enabled the integration of technical, operational, and institutional perspectives in the development of the governance model for a UDT construction.

4. Results: Strategic Directions for İzmir's UDT Development

4.1. Local Co-Design Workshop Outputs

The workshop generated a set of outputs related to (a) the identification of spatial problems and priority areas, (b) the thematic clustering of key issues such as mobility, green infrastructure, thermal comfort, and public space use, and (c) initial insights into relevant data needs and potential digital tools. Beyond identifying problem areas, participants discussed the types of data and digital tools required to support their visualization and analysis (Figure 6).

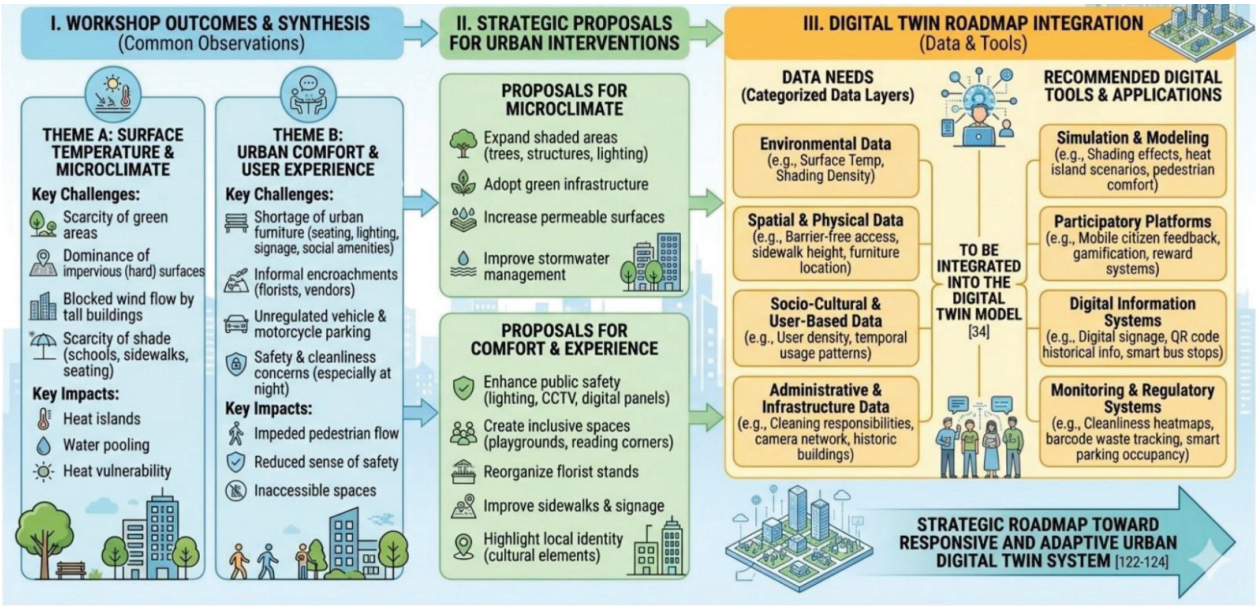

Figure 6. Local co-design workshop key findings. Note: Generated with the assistance of AI tools.

Participants consistently highlighted the dominance of impervious surfaces and limited presence of green spaces in the pilot area, which were associated with increased heat vulnerability and reduced wind circulation due to dense building formations. Simultaneously, everyday usability of the streetscape was reported to be affected by the lack of urban furniture, unregulated parking, and informal encroachments, such as florist stands, which obstruct pedestrian movement and reduce perceived safety and accessibility. These locally identified issues formed the basis for the technical alignment workshop, where they were translated into corresponding datasets, modelling approaches, and simulation scenarios.

To address the identified environmental and social gaps, the findings highlighted the need for microclimate and comfort-oriented spatial interventions. These include tree planting and shading systems, alongside green infrastructure and permeable surfaces to improve stormwater management. The results also indicated the importance of inclusive and multi-functional public spaces, including reading corners and playgrounds, as well as measures to enhance nighttime safety through CCTV and digital information panels. Together, these insights informed the intervention directions aimed at strengthening local identity while improving the adaptability of the urban environment to diverse user needs.

The findings also informed the identification of data and analytical requirements for the UDT framework. In response, the UDT roadmap development process points to the need for a multi-layered data strategy supported by the deployment of appropriate modelling and analytical digital tools. In particular, data needs can be organized into several interconnected layers including environmental, spatial, socio-cultural, and administrative layers, capturing variables related to surface temperature, shading density, temporal usage patterns, and urban infrastructure networks. These datasets provide the basis for simulation and modeling processes that support analyses on heat island scenarios and pedestrian comfort.

In addition, the discussions highlighted the relevance of participatory digital tools, such as mobile feedback applications and gamified reporting platforms, to facilitate citizen engagement and ongoing data input.

When combined with monitoring systems related to urban services such as waste management and parking, these data layers contribute to the formation of an integrated analytical framework capable of supporting evidence-informed and inclusive decision-making in İzmir.

These findings demonstrate that locally articulated spatial experiences can be systematically translated into structured data requirements and analytical inputs, highlighting the potential of participatory processes to inform both problem definition and the data architecture of UDTs. This reinforces the argument that citizen knowledge is operationally relevant to shaping simulation parameters and decision-support capabilities.

4.2. Technical Alignment Workshop Outputs

The technical alignment workshop aimed to connect the problem areas identified in the first stage with relevant modelling approaches, simulation scenarios, and digital tools from comparable contexts. The outputs of this stage included (a) the alignment of locally identified challenges with modelling approaches and simulation scenarios, (b) the identification of analytical tools and comparable use cases for UDT applications, and (c) the clarification of data requirements, available datasets, and modelling capacities to support these analyses. Through this process, participants explored how pedestrianization, green infrastructure, and heat mitigation could be supported by UDT applications and scenario-based analysis.

The alignment workshop resulted in a structured mapping of the problem areas identified in the first stage to potential modelling approaches, datasets, and analytical tools. The discussions were organized around three thematic areas—pedestrianization and mobility, public green spaces, and urban comfort interventions—allowing participants to systematically examine how UDT applications could support each topic (Figure 7). Building on the findings of local co-design workshop, locally identified challenges such as heat stress, pedestrian constraints, and lack of urban amenities were translated into corresponding modelling approaches, datasets, and analytical tools.

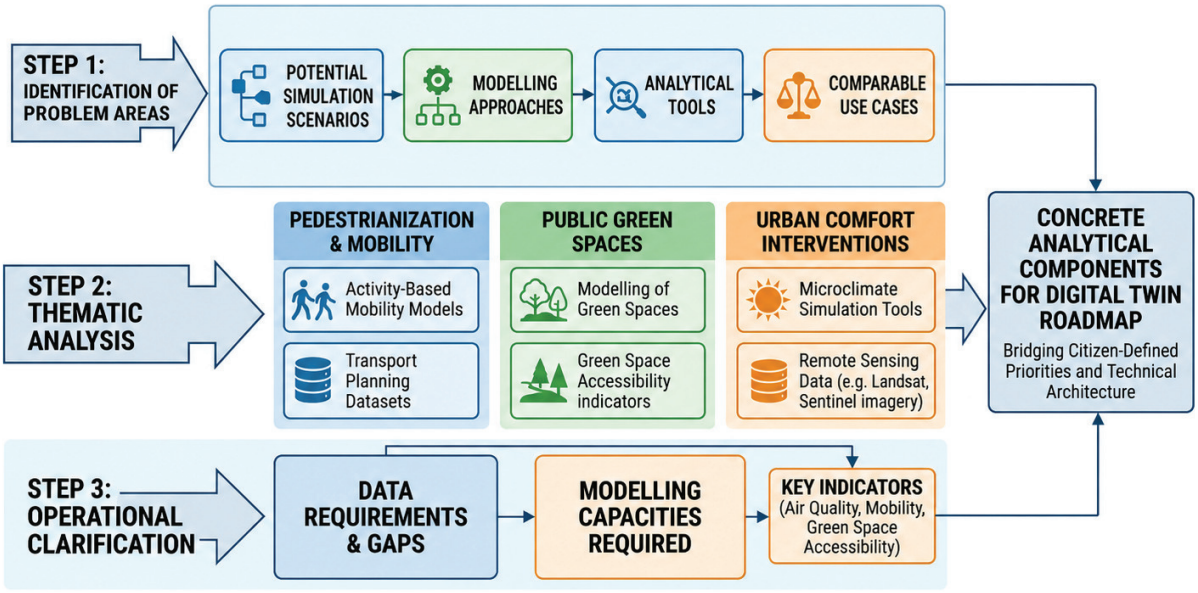

Figure 7. Technical alignment workshop outputs linking identified urban challenges with modelling approaches, datasets, and indicators for the UDT roadmap. Note: Generated with the assistance of AI tools.

For each thematic area, relevant modelling approaches and data sources were identified. Mobility-related challenges were linked to activity-based mobility models and existing transport planning datasets, while urban heat and comfort issues were associated with microclimate simulation tools and remote sensing (e.g., Landsat and Sentinel imagery). The workshop also identified key indicators, including air quality measurements, mobility indicators, and green space accessibility, that could support scenario-based analysis within the UDT framework.

In addition, the discussions clarified data availability, potential gaps in existing datasets, and the modelling capacities required to operationalize these analyses. This process helped translate the locally identified challenges into concrete analytical components, bridging citizen-defined priorities and the technical architecture of the UDT roadmap. For example, heat stress identified during the co-design workshop informed thermal comfort analyses, while pedestrian accessibility issues informed mobility analyses within the proposed UDT framework.

This stage illustrates that the alignment between locally identified challenges and technical modelling approaches is not a linear translation but a negotiated process that depends on available data, modelling capacities, and institutional priorities. The findings highlight the importance of intermediary processes that bridge qualitative problem definitions and quantitative simulation frameworks, ensuring that UDT applications remain both context-sensitive and technically feasible.

4.3. Multi-Departmental Governance Roundtable Outputs

The multi-departmental governance roundtable aimed to evaluate the feasibility of the previously identified problem areas and technically aligned use cases within existing institutional structures. Building on the findings of the preceding participatory stages conducted in the Re-Value pilot area, this stage translated locally grounded insights and technically explored use cases into an institutional and governance framework relevant to the wider urban system of İzmir. The outputs of this stage included (a) the evaluation of problem areas and use cases identified in earlier stages, (b) the identification of required datasets and existing data gaps, and (c) the assessment of institutional constraints and opportunities. Based on these discussions, a preliminary UDT governance model for İzmir was outlined, addressing key issues such as data sharing, inter-departmental coordination, and implementation responsibilities. In this way, citizen-informed priorities and technically feasible solutions were further refined in relation to institutional capacities and governance realities.

The roundtable discussions also clarified the conceptual scope of the UDT model proposed for İzmir. The outputs confirmed that the UDT model should not be conceptualized as a fully comprehensive virtual replica of the city, but rather as a modular and purpose-oriented decision-support system tailored to specific urban challenges such as the urban heat island, emission monitoring, flood risk, and mobility planning. The discussions also confirmed that the city already possesses a substantial data foundation, including municipal spatial datasets, SECAP (Sustainable Energy and Climate Action Plan) inventories, remote sensing outputs, and mobility surveys. However, important gaps remain, particularly regarding dynamic socio-economic data, real-time urban activity patterns, and integrated data infrastructures that link environmental, infrastructural, and social information layers.

Institutional considerations formed another key dimension of the discussions. The findings indicated that the main barriers for implementing a functional UDT system are not purely technological, but largely institutional. Challenges were identified related to fragmented data ownership, the absence of standardized data infrastructures, limited inter-departmental coordination, and bureaucratic obstacles to accessing and integrating datasets across institutions. These issues highlighted the need for stronger coordination mechanisms and a clearer institutional structure capable of managing data integration and analytical processes.

In response, the proposed governance model (Figure 8) prioritizes a centralized yet collaborative data management approach in which municipal GIS units play a key integrative role, supported by clearly defined data-sharing protocols and coordination mechanisms across departments. Within this framework, cooperation between the GIS units of the İzmir Metropolitan Municipality and the İzmir Development Agency emerged as a critical component for ensuring interoperability and long-term data governance. The model also proposes a phased implementation strategy, beginning with micro-scale analyses and pilot applications in areas such as the Alsancak pilot zone, allowing analytical tools, datasets, and institutional coordination mechanisms to be tested before scaling to the metropolitan level.

The proposed five-layer UDT architectural model (Figure 8) was developed by iteratively synthesizing the empirical findings from the three participatory stages. The local co-design workshop identified locally grounded priorities and user requirements, which were subsequently translated into data requirements, analytical functions, and simulation components during the technical alignment workshop. These outputs were then evaluated through the governance roundtable, resulting in a context-sensitive architectural model that integrates empirical findings into interconnected data, analysis, decision support, and governance layers. The model adopts a centralized yet collaborative data management approach, in which municipal GIS units play a key integrative role, supported by clearly defined data-sharing protocols and inter-departmental coordination mechanisms. Cooperation between the GIS units of the İzmir Metropolitan Municipality and the İzmir Development Agency emerged as a critical component for ensuring interoperability and long-term data governance. The model also proposes a phased implementation strategy, beginning with micro-scale analyses and pilot applications in the Alsancak pilot area before gradually scaling to the metropolitan level.

Under this approach, analytical capabilities such as spatial risk mapping, climate vulnerability assessments, and scenario-based simulations are positioned at the core of the system, directly informing decision-making processes on urban interventions and policy development. Starting from targeted applications enables the gradual expansion of the UDT framework while maintaining feasibility within existing institutional capacities. Overall, the roundtable outcomes demonstrate that the effectiveness of a UDT framework depends not only on technological capacity but also on institutional alignment, data ecosystems, and governance practices. The resulting model therefore reflects a context-sensitive and incrementally developed approach, grounded in the pilot-area findings of the Re-Value project while providing a scalable governance framework for the broader urban system of İzmir.

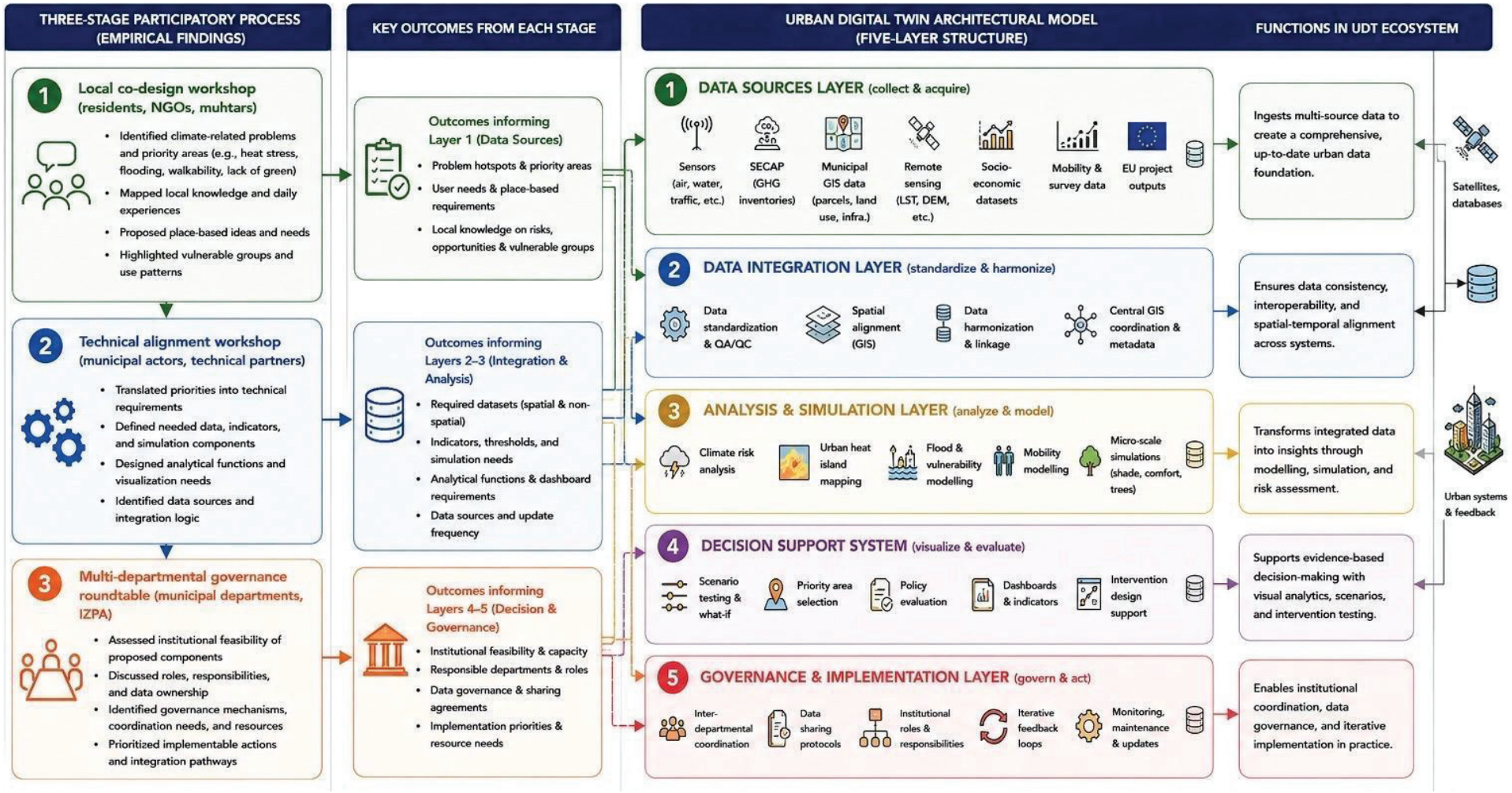

Figure 8. Integration of empirical findings from the three-stage participatory process into the proposed five-layer UDT architectural model of İzmir. Notes: Generated with the assistance of AI tools; in the figure, abbreviation IZPA refers to İzmir Planning Agency; LST refers to Land Surface Temperature; DEM refers to Digital Elevation Model; QA/QC refers to Quality Assurance / Quality Control.

5. Discussion: From Technocentric Models to Context-Sensitive UDTs

This study highlights that the development of UDTs cannot be reduced to a purely technological process, but must be understood as a socio-technical transformation shaped by governance structures, institutional capacities, and participatory multi-stakeholder practices. This is particularly important because urban conditions, governance structures, and data availability vary across cities, limiting standardized UDT models. Findings from the İzmir case indicate that early-stage participatory roadmapping, prior to UDT development, plays a critical role in determining whether UDTs function as meaningful decision-support systems or remain limited to technocratic visualization tools. In this sense, the study shifts the focus from "what a UDT is" to "how a UDT is constructed and embedded within urban planning processes."

Interpreted within the broader UDT literature, the roadmap's distinctive contribution lies in its shift away from a "model-everything" ambition towards a modular, context-specific twin focused on micro-scale, scenario-based analyses (e.g., pedestrianization, green infrastructure, thermal comfort). In the İzmir case, participants refined these priorities during the initial co-design workshop in the Re-Value pilot area by identifying locally grounded spatial challenges concerning microclimate, pedestrian mobility, and public space use. During the subsequent technical alignment workshop, they translated these challenges into modelling approaches, data requirements, and simulation scenarios for the UDT roadmap. Operationally, the "minimum viable dataset + incremental enrichment" strategy reflects constraints identified in the governance roundtable, where participants emphasized fragmented data infrastructures and the need to begin with targeted pilot analyses before scaling to the metropolitan level. This staged capability-building approach complements governance-focused maturity frameworks that highlight participation, interoperability, and inclusivity as persistent challenges over a twin's lifecycle (Haraguchi et al., 2024). Rather than repeating the entire participatory process, subsequent planning projects can build on the governance arrangements and baseline datasets established during the initial stages, while introducing project-specific stakeholder engagement and analytical updates where needed.

This staged logic can also be read as a practical response to critiques of technocentric smart urbanism. Kitchin (2014) argues that real-time, data-driven urbanism can enable new forms of technocratic governance and raise concerns about politics of data, corporatization, and lock-in. Parallel critical accounts emphasize how platform imaginaries can obscure power relations and narrow the scope of urban problems to what is measurable or optimizable (Sadowski & Bendor, 2019). Even citizen-centric initiatives can remain tokenistic if participation occurs after system parameters are already set, as argued in the literature on smart citizen participation (Cardullo & Kitchin, 2019). The İzmir case demonstrates that embedding participation at the early stages of UDT development helps address technocentric limitations. By anchoring the roadmap in early problem framing with citizens and local stakeholders, and subsequently requiring municipal and technical actors to evaluate how modelling approaches respond to those priorities, the process effectively shifts participation upstream. While the proposed process does not represent the highest level of participation described by Arnstein (1969), it brings citizens and other stakeholders together into subsequent technical and governance discussions throughout the roadmap process for developing a context-specific UDT.

The three-stage methodological structure can therefore be interpreted as a "translation mechanism" that connects lived experiences with computational representations and institutional action. In İzmir, the co-design workshop translated place-based knowledge into structured problem definitions and data

requirements; the technical workshop evaluated how these could be operationalized through modelling and simulation; and the multi-departmental governance roundtable assessed the feasibility of these outputs against institutional realities, including data-sharing constraints and administrative responsibilities.

Another important implication of the findings concerns the role of data governance as a central component of UDT development and its integration with existing municipal planning and maintenance practices. The roundtable discussions in İzmir revealed that the primary barriers to implementing UDTs were not purely technological, but largely institutional, particularly fragmented data ownership, limited inter-departmental coordination, and the absence of standardized data infrastructures. In this respect, the proposed UDT-enabled decision-making functionalities are intended to complement, rather than replace, existing planning procedures by linking locally identified urban challenges, cross-departmental data, and scenario-based analyses to ongoing municipal decision-making processes. Data governance therefore emerges as an institutional framework that enables or constrains participation, coordination, and decision-making. The identification of data gaps, particularly in dynamic socio-economic and real-time datasets, reveals that the limitations of UDTs are not solely technological, but also organizational. This observation supports recent arguments that governance, interoperability, and institutional integration remain critical bottlenecks in the operationalization of UDTs (Haraguchi et al., 2024; Lei et al., 2023; Yang et al., 2025).

Finally, the study contributes to participatory planning theory by demonstrating how co-design principles can be embedded within the development of digital planning tools. Unlike many existing UDT applications where participation is limited to interface interaction or data provision, the proposed approach integrates stakeholders into defining scenarios, data requirements, and governance structures. Within this process, citizens contribute by identifying locally experienced problems, informing data requirements, supporting the validation of locally relevant priorities, and shaping planning decisions through their continued integration into the technical alignment and governance stages. In the case of İzmir, this participatory process of context-specific UDT shaped not only the identification of priority interventions in the pilot area but also the broader governance model proposed for the city's UDT development. In this way, participation becomes a formative component of system design rather than a consultative add-on. Rather than providing statistically generalizable findings, the İzmir case serves as an exploratory demonstration of how a participatory UDT roadmap can be developed through iterative multi-stakeholder engagement.

6. Conclusion

This article has demonstrated that the development of UDTs requires a fundamental shift from technocentric, platform-driven approaches toward participatory, governance-oriented, and context-sensitive processes. By proposing a three-stage participatory roadmap comprising co-design, technical alignment, and governance integration, this study highlights how UDTs can be constructed as context-specific and socio-technical systems grounded in local knowledge, aligned with technical capacities, and embedded within institutional structures.

The findings underscore three methodological contributions. First, the study demonstrates the critical role of early-stage participatory engagement in shaping context-specific UDTs by defining urban-problem-related data requirements and the analytical logic of such systems. Second, it introduces a structured translation

mechanism that connects citizen needs and lived experiences with data requirements, modelling approaches, and governance frameworks, enabling a more coherent integration of diverse knowledge perspectives. Third, it advances a modular and incremental development logic based on a minimum viable dataset, so that UDTs can evolve progressively through scenario-based micro-analyses rather than comprehensive, large-scale modelling efforts.

From a policy and practice perspective, the results suggest that local governments should prioritize governance design, inter-departmental coordination, and data-sharing mechanisms before investing in large-scale UDT platforms. Without such institutional alignment, UDTs may risk remaining as visualization tools with limited influence on actual planning processes. Although the proposed roadmap has not yet been implemented as an operational UDT, it provides a transferable methodological framework for participatory UDT development by systematically aligning citizen priorities, technical requirements, and governance capacities during the early stages of development. Rather than prescribing a universal model, the framework offers a context-sensitive approach that can support future comparative studies and implementation-oriented research across different governance settings.

Despite these contributions, the study also has several limitations. First, the findings are based on a single case study and a specific pilot area, which may limit their generalizability to other urban contexts with different governance structures and data capacities. Second, the study focuses on developing a roadmap rather than implementing a fully operational UDT, meaning that its impacts on actual decision-making processes remain to be tested. Third, the relatively limited number and diversity of participants may not fully reflect the range of lived experiences within the study area. The proposed roadmap is expected to be most applicable to cities with established planning institutions and basic geospatial data infrastructures, while remaining adaptable to different governance settings through functionally equivalent local stakeholders. Future research should include larger and more diverse participant groups to strengthen the transferability of the findings and examine how participatory UDT roadmaps can be scaled to different urban contexts and integrated into the long-term lifecycle of UDT systems.

Overall, this study contributes a methodological framework for rethinking UDT developments not as static technological products, but as dynamic and evolving processes shaped by social, institutional, and technical interactions. By embedding participation and governance at the core of UDT development, it offers a pathway toward more inclusive, context-sensitive, and operationally effective urban digital infrastructures for urban planning.

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Conflict of Interests

In this article, editorial decisions were undertaken by Bernd Resch (Interdisciplinary Transformation University Austria) and Peter Zeile (Karlsruhe Institute of Technology).

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