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From Planning Support Systems to Urban Digital Twins: A Decision-Driven Framework for Participatory Spatial Planning

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Abstract:

Purpose: *The paper develops a conceptual framework in which an urban digital twin (UDT) is derived from planning decisions and the statutory planning procedure rather than from a predefined technical architecture. The Polish municipal general plan serves as the procedural case.*
Design/Methodology/Approach: *The methodological approach combines conceptual framework analysis with an integrative review of participatory planning, planning support systems (PSS), public participation GIS (PPGIS) and UDT literature, alongside a legal-procedural analysis of the Polish general-plan procedure. Plausibility is examined* ex ante *through a scenario on accessibility standards in Szczecin.*
Findings: *The framework identifies three conditions that characterise decisions particularly suited to participatory UDT support, four functional domains and six traceable knowledge flows linking local knowledge, analysis, deliberation and formal decisions. It proposes decision-proportional fidelity: representational detail and technological complexity should be matched to the requirements of the planning decision. For accessibility standards, a periodically updated digital shadow may suffice.*
Practical Implications: *Municipalities can start with measurable and contested decisions, use geo-questionnaires as provenance-aware inputs to the knowledge base and keep a traceable register of contributions, revisions and responses. Staged implementation based largely on public data may lower the entry threshold.*
Originality/Value: *The framework shifts UDT conceptualisation from technical architecture towards the organisation of planning decisions, knowledge flows and accountability.*

Keywords: *Land use, accessibility standards, municipal general plan, PPGIS, local knowledge, Poland.*

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1. Introduction

Spatial planning decisions increasingly combine heterogeneous evidence, conflicting interests and expectations of meaningful public participation. The evidence they require – official data, model outputs, expert judgement and residents' local knowledge – is dispersed across administrative departments, planning teams and the public. Participation, in turn, is expected to move beyond information and consultation towards real influence on how problems are framed and which alternatives are considered (Arnstein, 1969; Healey, 1997).

Digital tools have long promised to integrate such resources. Planning support systems (PSS) were designed to support rather than automate planning, yet capable tools remained underused when poorly matched to tasks, organisations and users (Vonk *et al.*, 2005; Geertman, 2006; Pelzer, 2017).

UDTs renew this promise by connecting representations of urban conditions with models, scenarios and feedback. Recent reviews, however, show a persistent gap between technical development and realised planning value, particularly in procedural operationalisation and citizen influence (Adade and de Vries, 2025; Azadi *et al.*, 2025; Luo *et al.*, 2025).

This paper therefore treats the planning decision, not the platform, as the design anchor. The resulting framework is general, but it becomes operational only through a specific statutory procedure, and the Polish municipal general plan (*plan ogólny gminy*) serves here as the case. Introduced by the 2023 planning reform as an act of local law, the general plan combines spatially measurable categories – planning zones, infill development areas and optional accessibility standards for primary schools and public green space – with formalised consultation tools, including workshops, study walks, surveys and geo-questionnaires (Republic of Poland, 2023).

It thus offers both explicit spatial thresholds and formally defined entry points for participant knowledge, which makes it a demanding but tractable test case.

Three research questions follow from this approach. RQ1: for which decisions and at which procedural stages can a UDT enable participation to move beyond information provision and commenting towards shaping the diagnosis, alternatives

and evaluation criteria? RQ2: through which flows and forms of contribution can participant input inform revisions to the diagnosis, model, criteria or set of alternatives while remaining traceable through to the formal decision? RQ3: what representational detail and resources are sufficient for a given decision, and when is a UDT not justified? The contribution is threefold: a planning-driven logic of UDT use, a traceable set of participatory knowledge flows and the principle of decision-proportional fidelity. Local plans and operational city management remain outside the scope.

2. Literature Review

Arnstein's (1969) ladder measures participation by citizens' actual influence rather than by the existence of a channel. Collaborative planning, in turn, treats planning as joint knowledge production and negotiated action among interdependent actors with divergent interests (Healey, 1997). An interface can therefore widen access without changing who frames a problem, which evidence counts or which alternatives are considered.

Public participation GIS (PPGIS) and geo-questionnaires connect place-based knowledge to spatial objects (Jankowski *et al.*, 2016; Czepkiewicz *et al.*, 2017), but self-selection, data quality and the weak translation of mapped input into planning practice remain problematic (Czepkiewicz *et al.*, 2017; Kahila-Tani *et al.*, 2019). The bottleneck lies less in collection than in giving local knowledge a defined route into diagnosis, modelling and the revision of alternatives.

Accessibility provides a planning context in which such a route can be specified particularly clearly. It links land-use, transport, temporal and individual components, and its measurement depends on the purpose of the planning task (Geurs and van Wee, 2004). Polish law makes it directly operational. If a municipality adopts social-infrastructure accessibility standards, access to a primary school is measured along a publicly accessible pedestrian route, with a baseline threshold of 1,500 m in cities.

Green-space standards combine network distance with minimum area thresholds (Republic of Poland, 2003, Art. 13f). A legal standard thus becomes a network-analysis problem whose reliability depends less on visual realism than on a correct pedestrian graph and on knowledge of barriers, crossings and routes that official databases may omit.

PSS research has long examined how digital tools can incorporate such knowledge into planning analysis. It has shown that planning support should be evaluated against tasks, users and context rather than technical capability alone (Geertman, 2006). Organisational and human factors can block otherwise capable systems (Vonk *et al.*, 2005), and utility – whether a tool actually helps perform the planning task – must be distinguished from usability (Pelzer, 2017). The UDT concept extends beyond a 3D city model towards connected data, models and simulations,

and remains broad and fluid (Ketzler *et al.*, 2020; Batty, 2024). Kritzinger *et al.* (2018) distinguish a digital model, shadow and twin by the degree of automated data exchange: none, one-way from the physical object, and bidirectional. In this paper, UDT denotes the broader socio-technical twinning environment, in which these categories mark degrees of data coupling. What separates it from a task-specific PSS is a persistent, updatable representation of urban conditions that is maintained across planning cycles, linked to versioned alternatives and fed by monitoring.

Implementation barriers are organisational as well as technical, involving interoperability, practical value, resources and governance (Lei *et al.*, 2023). Moreover, a twin is a selective representation capable of steering action rather than a neutral mirror (Korenhof *et al.*, 2021; Charitonidou, 2022).

Recent work seeks to make this steering capacity more participatory, conceptualising UDTs as instruments of participatory steering rather than technical replicas (Dawkins and Kitchin, 2025). Systematic reviews nevertheless show that citizen participation commonly takes two forms: providing data to a twin and using its outputs to articulate issues or proposals (Adade and de Vries, 2025). Procedural integration into planning still lags behind these ambitions (Azadi *et al.*, 2025; Luo *et al.*, 2025).

Existing frameworks typically start from the twin – its layers, data and interfaces – and then ask how participation can be added. Even recent work integrating legal and geospatial data for participatory planning follows a layered architecture, from data acquisition to governance (Koeva *et al.*, 2026). The unresolved problem is the reverse: how the functions of a twin should be derived from the decision to be taken and from the procedure through which it is taken. A planning-driven framework must specify where participant input enters, what it can change, how an alternative is recalculated after a change and how the contribution remains traceable to the formal decision.

3. Research Methodology

The study is conceptual and design-oriented. Framework development draws on selected stages of Jabareen's (2009) conceptual framework analysis: mapping sources and identifying, categorising, integrating and synthesising concepts. The external validation stage is left to future research. Requirements were derived from three bodies of literature (participatory planning, PSS and PPGIS research, and UDT research) and from a legal-procedural analysis of the Spatial Planning and Development Act. This analysis mapped procedural stages, actors, formal outputs, participation forms and entry points for participant knowledge.

The framework is assessed against six planning-utility criteria developed for this study and informed by the task-technology fit perspective of PSS research (Pelzer, 2017): spatial adequacy, capacity to construct alternatives, distributional insight,

participatory responsiveness, transparency and institutional usability. An illustrative Szczecin scenario provides an *ex ante* analytical walkthrough. The city was chosen because it had made a real-world decision on accessibility standards and published the documents needed to reconstruct the decision-making context. The scenario is neither an empirical test nor an evaluation of that decision: no system was implemented, no alternative was modelled or quantitatively evaluated, and no user validation was conducted.

4. Research Results and Discussion

4.1 The Planning-Driven Framework

Participatory UDT support is particularly warranted when a planning decision combines three characteristics. First, its consequences are spatially measurable. Second, they are distributional: alternatives affect places or groups differently. Third, relevant knowledge exists outside official databases and can materially alter the assessment. In the general plan, accessibility standards and infill development areas can meet all three conditions, whereas some planning-zone boundaries require less analytical or participatory sophistication. Where few or none of these characteristics are present, a conventional GIS or PSS may be more proportionate.

The three characteristics correspond to spatial adequacy, distributional insight and participatory responsiveness. The remaining criteria – capacity to construct alternatives, transparency and institutional usability – apply regardless of decision type. The core analytical object is a decision alternative: not necessarily a different future urban form, but any answer to the planning question with spatially representable consequences, such as a different set or spatial differentiation of accessibility thresholds.

Around this core object, the twin organises four functional domains maintained throughout the planning cycle, defined by planning function rather than technology (Figure 1). The spatial knowledge base combines official and local knowledge, recording provenance and validation status. The analysis-and-alternatives domain supports diagnosis, comparison, distributional effects and sensitivity analysis. Alternatives are formulated by planners and participants; the twin does not select among them.

The deliberation space combines digital and analogue channels and can audit spatial participation coverage against a population grid, although socio-demographic representativeness requires additional participant data. The decision-and-accountability domain preserves comparisons, version history and a register of contributions and responses, while the formal decision remains with the competent authority. Rules for access, data protection, model approval and versioning frame all four domains.

Decision alternatives are not a fifth domain but the shared object that links them: they are generated and recalculated in analysis, proposed and debated in deliberation, and passed in versioned form to the decision.

Six knowledge flows connect the domains (Table 1) and form two feedback loops. In the revision loop, analysis and deliberation exchange results and revisions (F2–F3). In the monitoring loop, F6 returns implementation evidence to the knowledge base, which in turn feeds analysis and keeps the representation current between planning cycles. Participant contributions take four forms.

Table 1. *Knowledge flows in the municipal general-plan procedure*

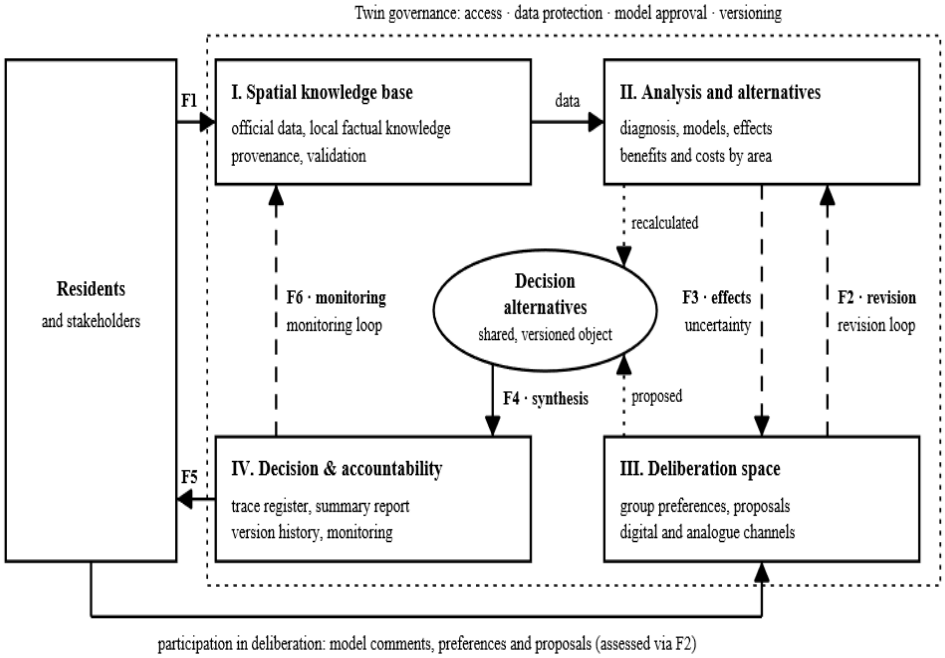
Flow	**Procedural anchor**	**Information object**	**Contribution and trace**
F1 residents → knowledge base	applications; study walks, geo-questionnaires (Arts 13i, 8i)	pedestrian barriers and routes with provenance	factual knowledge → validation → diagnosis version
F2 deliberation → analysis	workshops, open meetings (Art. 8i)	alternatives, indicators, group preference profiles	model comments, preferences, proposals → assessment → model, criteria or alternative versions
F3 analysis → deliberation	consultation of the draft (Arts 8i–8j)	results, uncertainty, maps of distributional effects	basis of the F2–F3 revision loop
F4 analysis and deliberation → authority	draft and justification (Art. 13h)	comparison of alternatives, sensitivity, minority positions	synthesis for a formal decision, not an automated choice
F5 authority → participants	application list and consultation report (Art. 8k)	response linked to the affected version	closes the trace of each contribution, including rejected ones
F6 implementation → knowledge base	review of whether the plan is up to date (Art. 32)	monitoring indicators	feeds the next planning cycle

Source: *Own elaboration based on the Spatial Planning and Development Act.*

Factual local knowledge is routed through F1 for validation and may revise the diagnosis. Model comments, preferences and proposed alternatives are assessed through F2 and may lead to revisions of the model, the criteria or the set of alternatives. Preferences are kept as group-specific profiles rather than collapsed into one aggregate value. The register records each contribution's assessment, outcome (accepted, partly incorporated or rejected), affected version and justification.

Because the Act allows applications and comments on the same issue to be answered jointly (Art. 8k(3)), the register also preserves individual traces that a collective formal response would blur.

Figure 1. *Planning-driven UDT: functional domains, knowledge flows and feedback loops*



Source: *Own elaboration.*

Under the principle of decision-proportional fidelity, the shared representation should be matched to the decision in four dimensions: spatial detail, update frequency, modelling complexity and scope of user interaction. For accessibility standards, the central data are a reliable pedestrian network, the locations of services and green areas, population distribution, parcel information and planning constraints, complemented by validated local knowledge.

Real-time streams and photorealistic 3D geometry add little to the core network calculation, and periodic or event-based updating suffices. In the terminology of Kritzinger *et al.* (2018), this task requires a level of data coupling consistent with a digital shadow. What makes this a twinning environment is maintaining a single, updatable representation across alternatives and planning cycles. Fidelity should increase only when a decision requires it.

The required resources are GIS and planning expertise, facilitation, data protection expertise, maintainable spatial data and institutional rules for model approval and

versioning. Costs may therefore lie more in data quality, moderation and accountability than in visualisation technology (Lei *et al.*, 2023).

Staged implementation based largely on public data can lower the entry threshold, but actual costs remain an empirical question.

4.2 Illustrative Scenario: Accessibility Standards in Szczecin

Under the Act, accessibility standards are optional. Only adopted standards condition the designation of new residential land in local plans and decisions on development conditions, and municipalities may modify the thresholds or apply them to selected areas only (Art. 13f(4)–(7)). Szczecin adopted its general plan by Resolution No. XXIII/594/26 of 24 June 2026 without such standards, 'owing to the spatial and organisational conditions of the municipality' (City of Szczecin, 2026a; own translation).

The justification cites 76.16% coverage by local plans, sufficient access ensured by the city structure and public transport, fluctuating educational provision, abundant green space and the risk of obligations to build facilities for dispersed housing.

The consultation produced 2,575 comments, while an online survey – not a geo-questionnaire – drew 76 respondents (City of Szczecin, 2026b). One comment from the Pogodno area described a fenced allotment-garden complex that lengthens the walk to a park to 1–1.8 km and explicitly requested an analysis against accessibility standards.

Without judging the decision, each premise can be translated into a testable analytical proposition, indicator or spatial comparison: the share of residential parcels within baseline thresholds inside and outside local plans, network maps of deficits, walking and public-transport accessibility side by side, sensitivity to school closures, green-space access with and without reported barriers, and parcels where new housing would be excluded under Art. 13f(4).

Three alternatives follow from the legal structure: no standards (A0, the adopted decision), baseline thresholds city-wide (A1) and standards differentiated spatially or limited to compact urban areas (A2), the latter directly addressing the concern about infrastructure obligations.

Under F1, a geo-questionnaire in Pogodno would record barriers and routes, which the planner would validate before updating the pedestrian graph. F2 would define A0–A2, competing criteria and group preference profiles. F3 would present accessibility and distributional effects, with uncertainty, for the original database-derived network and for the network revised following validated resident input.

Participants could propose a new connection through the barrier rather than merely a different threshold. Once formalised by the planner, this would become alternative A2′ and return to F3. F4 would present trade-offs and minority positions to the council, F5 would record the treatment of each contribution, and F6 would monitor subsequent change. The critical technical representation would therefore be the pedestrian graph rather than a detailed 3D model. Moderation, validation and accountability are as integral to the framework as analysis.

5. Discussion

Regarding RQ1, the three decision conditions indicate where participatory UDT support is most relevant. A UDT can support deeper participation where effects are spatially measurable, distributional and dependent on local knowledge.

Its greatest potential lies in stages before the decision is closed, while participants can still alter the representation of current conditions, problem framing, criteria or the set of alternatives. Merely presenting a sophisticated model does not constitute stronger participation (Arnstein, 1969; Kahila-Tani *et al.*, 2019).

For RQ2, the key mechanism is the closed knowledge loop: each of the four contribution types has an entry route (F1–F2), visible consequences (F3) and an accountability trace (F5). This extends PPGIS beyond collection and addresses the procedural gap identified in recent reviews (Adade and de Vries, 2025; Azadi *et al.*, 2025).

RQ3 concerns representational sufficiency and is addressed through decision-proportional fidelity. The required representation is the minimum sufficient one for the planning question.

The accessibility-standard task does not by itself justify real-time sensors, artificial intelligence or high-detail 3D geometry. When a decision lacks the three anchoring characteristics, the organisational burden of a UDT may not be justified and a GIS or PSS may be preferable.

The framework therefore treats technological restraint as part of planning utility, not as a deficit. Assessed against the six criteria, the scenario shows how the framework could address each of them, with institutional usability depending more on moderation capacity than on technology.

The framework does not remove participation bias, unequal digital competences or institutional power. Spatial coverage does not guarantee socio-demographic representativeness, and a traceable register does not guarantee influence. False precision, model boundaries and the legal status of analytical outputs remain governance questions.

6. Conclusions, Proposals, Recommendations

The usefulness of an urban digital twin in planning depends less on technological sophistication than on its capacity to deliver adequate knowledge for a specific statutory decision and to connect analysis, local knowledge, alternatives and accountability. Four functional domains, six traceable knowledge flows and decision-proportional fidelity operationalise this principle without automating the final choice.

Municipalities should begin with measurable and contested decisions rather than with a platform, treat geo-questionnaires as provenance-aware knowledge inputs and maintain a contribution-response register from the start. The framework has not been implemented, costed or validated with users, and its procedural mapping is specific to Polish law.

The decision anchors, functional domains and knowledge flows themselves are not tied to a particular legal system, but transferring them requires mapping them onto another statutory procedure. Further research should develop and test a computational implementation for Szczecin, evaluate it with planners and participants, and compare municipalities that made different choices on accessibility standards.

The purpose is not to build the most comprehensive urban digital twin, but to provide the minimum sufficient representation, analytical capability and participatory functionality required by a given planning decision.

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