METACITIES Excellence Hub in South-Eastern Europe

A Methodological Framework for Socio-Techno-Economic Requirements Elicitation in Smart City Open Digital Twin Systems

White paper

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Glossary of Terms and Abbreviations

Abbreviation / Term	Description
AI	Artificial Intelligence
DT	Digital Twin
ODTF	Open Digital Twin Framework
QH	Quadruple Helix

Executive Summary

Open Digital Twin Systems are increasingly adopted in smart city initiatives to support urban planning, mobility management, energy optimization, and evidence-based governance. Despite their technological sophistication, many digital twin deployments remain infrastructure-driven and insufficiently grounded in structured stakeholder requirements. As a result, systems often face limited adoption, misalignment with governance priorities, and challenges to long-term sustainability.

Smart city digital twins operate within complex socio-technical environments where technological infrastructure, institutional arrangements, economic constraints, and citizen expectations intersect. In such contexts, requirements cannot be defined solely through technical specifications or vendor-led design processes. Instead, they must be systematically elicited, prioritised, and translated into formal system specifications that integrate socio-economic, governance, and operational dimensions.

This white paper proposes a methodological framework for the elicitation of socio-techno-economic requirements in Smart City Open Digital Twin (DT) Systems. The framework introduces a structured seven-step process that integrates domain-specific use-case definition, Quadruple Helix stakeholder mapping, quantitative prioritisation mechanisms, requirement classification, and architectural alignment.

The proposed approach bridges participatory governance principles with established requirements engineering practices, providing a clear pathway from stakeholder input to system design. By explicitly capturing both functional and non-functional requirements and systematically translating them into architectural decisions, the framework enhances system legitimacy, interoperability, and long-term viability.

The methodology is designed to be replicable across urban domains and adaptable to diverse governance contexts. It is intended for municipalities, DT developers, research institutions, and innovation consortia seeking to implement stakeholder-driven Open DT Systems in smart city environments.

1 Introduction

The rapid advancement of DT technologies has significantly reshaped the landscape of smart city development. A DT is a virtual representation of a physical object, system, or process, and can be used for a variety of purposes, such as simulation, analysis, testing, maintenance, and control. Urban DT Systems are increasingly being deployed to support mobility optimisation, infrastructure monitoring, energy-efficiency planning, environmental assessment, and evidence-based governance. When designed effectively, these systems enable real-time monitoring, predictive modelling, and scenario-based decision support across complex urban environments.

However, despite their growing adoption, many DT initiatives remain predominantly technology-driven. System architectures are often defined prior to comprehensive stakeholder engagement, and requirements are derived primarily from technical feasibility rather than socio-economic necessity. This technology-first approach often leads to over-engineered solutions, misalignment with governance priorities, limited citizen adoption, and long-term sustainability challenges.

Smart city DTs operate within inherently socio-technical ecosystems. They integrate physical infrastructure, data flows, institutional processes, regulatory frameworks, and citizen interaction within a single digital environment. In such contexts, requirement definition cannot be confined to technical specifications alone. Instead, it must systematically incorporate social expectations, governance structures, economic feasibility, interoperability constraints, and ethical considerations.

While requirements engineering is a well-established discipline within software and systems development, there remains a methodological gap in its structured application to Open DT Systems for smart cities. In particular, limited guidance exists on integrating participatory stakeholder engagement with formal requirement translation and architectural alignment in complex urban settings.

This white paper addresses this gap by proposing a structured methodological framework for the elicitation of socio-techno-economic requirements in Smart City DT Systems. The framework provides a clear, replicable process for moving from stakeholder input to prioritised functional and non-functional specifications and, ultimately, to architecture-informed design decisions.

2 Why Socio-Techno-Economic Requirements Matter

2.1 Beyond Technology-Driven Development

Smart City Open DT Systems are not merely technical platforms. They function as integrative infrastructures that connect data ecosystems, public services, regulatory mechanisms, private-sector operations, and citizen interaction within a unified digital environment. As such, they are inherently socio-technical systems.

In practice, DT development is often technology-focused. Decisions about architecture design, platform choice, and data modelling are usually made before systematically engaging stakeholders. Although these methods are technically solid, they may neglect governance limits, operational challenges, economic feasibility, and user acceptance[1], [2], [3].

The consequences of technology-first development may include:

- Limited institutional adoption
- Low citizen engagement
- Misalignment with regulatory frameworks
- Over-engineered features lacking practical demand
- Scalability challenges
- Sustainability concerns

In contrast, the elicitation of socio-techno-economic requirements recognises that system performance alone does not determine success. Adoption, legitimacy, interoperability, governance integration, and economic feasibility are equally decisive factors in the long-term viability of Smart City DT Systems[4].

Accordingly, requirement engineering in this context must extend beyond functional system capabilities to incorporate:

- Governance expectations
- Data ownership and privacy concerns
- Economic sustainability and funding models
- Accessibility and inclusiveness
- Interoperability standards
- Ethical and societal considerations

2.2 The Quadruple Helix as a Structuring Principle

Given the multi-actor nature of smart city ecosystems, stakeholder representation must be systematically structured. The Quadruple Helix model provides a suitable governance-oriented framework for this purpose [5].

The model distinguishes four primary actor groups:

- Government (policymakers, municipal authorities, regulators)
- Industry (technology providers, infrastructure operators, SMEs)
- Academia (research institutions, domain experts, data scientists)
- Civil Society (citizens, NGOs, community organisations)

Each group interacts differently with DT Systems and prioritises distinct requirement dimensions. For example:

- Government actors emphasise regulatory compliance, accountability, and interoperability across administrative systems.
- Industry stakeholders focus on scalability, system performance, and economic sustainability.
- Academic actors prioritise data quality, modelling accuracy, and analytical capabilities.
- Civil society emphasises usability, transparency, privacy protection, and accessibility.

Failure to integrate perspectives across these groups often results in an imbalanced system design. Over-representation of technical actors may generate complex yet socially misaligned platforms, while insufficient industry input may undermine operational scalability. The Quadruple Helix framework, therefore, serves not only as a stakeholder classification model but also as a methodological safeguard against structural bias in requirement elicitation processes.

3 The Seven-Step Methodology for 'Open Digital Twin Framework-ODTF' Requirements Elicitation

This section presents a structured framework for the elicitation of socio-techno-economic requirements tailored to Smart City Open DT Systems. The framework integrates participatory stakeholder engagement principles with formal requirements engineering practices, providing a clear pathway from contextual problem definition to architecture-informed system design.

While the steps are presented sequentially for clarity, the methodology is inherently iterative. Feedback loops between stakeholder validation, requirement prioritisation, and architectural alignment are expected throughout implementation.

The seven steps are:

1. Define Domain-Specific Use Cases
2. Map Stakeholders Using the Quadruple Helix Model
3. Design Tailored Elicitation Instruments
4. Ensure Balanced Data Collection and Governance Integrity
5. Conduct Quantitative Prioritisation and Requirement Classification
6. Translate into Functional and Non-Functional Specifications
7. Align Requirements with DT Architecture

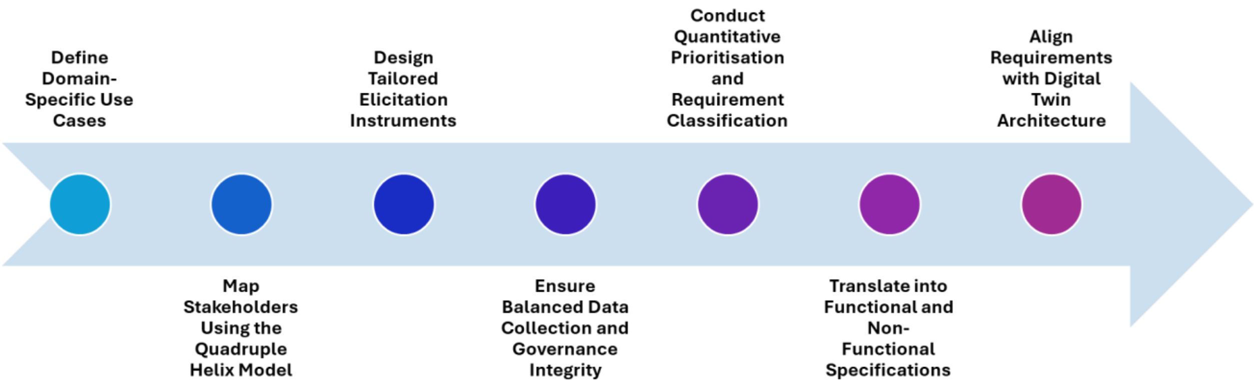

FIGURE 1: THE 7-STEP REQUIREMENTS ELICITATION FRAMEWORK.

3.1 Step 1 – Define Domain-Specific Use Cases

Effective requirement elicitation starts with clear scoping. Open DT Systems typically cover sectors such as mobility, energy, the environment, urban planning, and emergency response. Specifying requirements at a general framework level often leads to unclear or conflicting system expectations.

Each use case should therefore be clearly defined along the following dimensions:

- Target user groups and involved stakeholders
- Decision-making context (operational, strategic, regulatory)
- Relevant data sources and integration needs
- Expected system outputs (e.g., dashboards, simulations, predictive analytics, alerts)
- Governance scope and institutional boundaries

This structured scoping exercise keeps requirement elicitation focused on the context, measurability, and alignment with concrete decision-making processes instead of abstract technological features. Importantly, it creates a clear link between stakeholder needs and subsequent technical specifications.

3.2 Step 2 – Map Stakeholders Using the Quadruple Helix Model

Following the use case definition, stakeholder mapping must be conducted in a structured and balanced manner. Smart City Open DT Systems operate within multi-actor ecosystems where institutional, commercial, scientific, and societal interests intersect. A systematic identification and categorisation of stakeholders ensures that requirement elicitation reflects this diversity.

The Quadruple Helix model provides a suitable organising framework by distinguishing four primary actor groups: government, industry, academia, and civil society. Each group interacts differently with DT systems and prioritises different requirement dimensions. Government actors may emphasise compliance, interoperability, and accountability; industry stakeholders may prioritise scalability and performance; academia may focus on data quality and analytical depth; and civil society may stress usability, transparency, and privacy. Balanced representation across these groups enhances legitimacy and strengthens the long-term viability of the system.

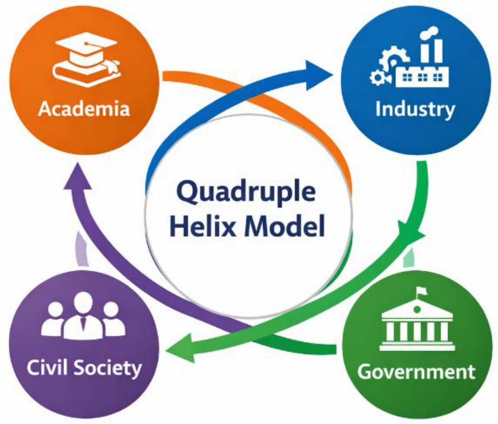

FIGURE 2: THE QUADRUPLE HELIX MODEL.

3.3 Step 3 – Design Tailored Elicitation Instruments

Once stakeholders are mapped, elicitation instruments must be systematically designed to capture the requirements and needs across technical, organisational, and societal domains. In complex urban digital systems, a single generic questionnaire is rarely sufficient. Instead, instruments should be tailored to the specific use case and stakeholder group while maintaining a structured format that enables comparability. Elicitation tools should explicitly address the following:

- **Technical requirements**: Simulation accuracy, real-time capabilities, analytical functionality, and system performance.
- **Data requirements**: Data availability, quality, update frequency, integration from heterogeneous sources, and data governance constraints.
- **Infrastructure requirements**: storage capacity, computational resources, networking constraints, and system scalability.
- **Economic requirements**: Cost-effectiveness, long-term maintenance viability, funding models, and return-on-investment considerations.
- **Socio-cultural requirements**: Usability, accessibility, institutional adaptation, changes in work practices, and user acceptance factors.

Beyond these dimensions, instruments must accurately capture both the functional expectations, which are the specific capabilities that the system is required to deliver, and the non-functional requirements, which encompass performance benchmarks, interoperability standards, privacy protections, and accountability frameworks. A combination of Likert-scale prioritisation and ranking mechanisms, structured multiple-choice questions, and open-ended responses enables both quantitative classification and qualitative interpretation. In large-scale smart city contexts, questionnaire-based approaches offer advantages in scalability, standardisation, anonymity, time efficiency, and cost-effectiveness. However, complementary techniques, such as workshops, interviews, focus groups, or user story formulation, may further refine and validate findings.

3.4 Step 4 – Ensure Balanced Data Collection and Governance Integrity

Outreach strategies should aim for balanced participation across stakeholder categories, avoiding over-representation of technically specialised or other actors. Where imbalances occur, they should be documented and considered during analysis to mitigate bias.

Ethical considerations are central at this stage. Participants should be informed of the purpose of the elicitation process and the intended use of collected data. Furthermore, governance integrity entails framing requirement elicitation as a participatory design process instead of just validating pre-established technical choices. This approach helps strengthen institutional trust and facilitates later system adoption.

3.5 Step 5 – Quantitative Prioritisation and Requirement Classification

Raw stakeholder input must be systematically transformed into structured and actionable priorities. Likert-scale importance ratings (e.g., 1–5) should be aggregated to compute mean values for each requirement. Predefined threshold criteria must then be established to map quantitative scores into qualitative classifications, such as:

- **Must Have:** Essential for system viability and core functionality.
- **Should Have:** Highly valuable but not strictly critical.
- **Could Have:** Desirable enhancements subject to resource availability.
- **Won't Have:** Low-priority or out-of-scope elements.

TABLE 1: REQUIREMENT PRIORITISATION AND STAKEHOLDER CLASSIFICATION TEMPLATE.

Req. ID	Requirement Description	Citizens	Government	Academia	Industry	Overall Priority
REQ-01		Must/Should/ Could/Won't	Must/Should/ Could/Won't	Must/Should/ Could/Won't	Must/Should/ Could/Won't	
REQ-02						
REQ-03						
REQ-04						

Threshold ranges should be defined prior to analysis to ensure methodological transparency and reproducibility. Where appropriate, requirement scores may also be analysed per stakeholder category to identify differences and similarities across the Quadruple Helix groups' perspectives. This structured classification mechanism prevents scope inflation, which leads to uncontrolled growth of a project's scope beyond its original plans or objectives. It typically occurs when additional features, requirements, or tasks are added without proper oversight or resource adjustments, leading to increased complexity, higher costs, and potential delays. The approach also supports phased development strategies and provides defensible justification for architectural trade-offs. By formally prioritising requirements before system design decisions are made, the methodology ensures that resource allocation and technical complexity remain aligned with documented stakeholder needs.

3.6 Step 6 – Translate into Functional and Non-Functional Specifications

Following prioritisation, stakeholder-defined needs must be formalised into structured system specifications. Functional requirements describe explicit system capabilities, such as real-time monitoring, predictive simulation, automated alerts, and data visualisation. Non-functional requirements define performance constraints and quality attributes, including scalability, interoperability, latency, security, accessibility, and privacy safeguards.

Each formalised requirement should be traceable back to stakeholder input, ensuring that system specifications reflect documented needs rather than implicit design assumptions. A traceability matrix linking stakeholder categories, requirement identifiers, and system modules strengthens accountability and facilitates iterative validation.

3.7 Step 7 –Align Requirements with DT Architecture

The final step involves systematic alignment between classified requirements and the architectural layers of the Open DT System. Requirements related to data acquisition, real-time updates, or sensor integration influence the device and data layers. Analytical and predictive capabilities shape the service layer. Visualisation and user interaction requirements inform the application layer. Security and interoperability considerations affect cross-layer architectural decisions. When architectural decisions are directly informed by prioritised stakeholder needs, the resulting system is more likely to achieve institutional adoption, operational relevance, and long-term sustainability. This alignment closes the methodological loop and transforms participatory input into an implementable system design.

4 Conclusion

Open DT Systems are increasingly becoming core infrastructures within smart city ecosystems, supporting governance, planning, and evidence-based decision-making. However, technological sophistication alone does not determine their effectiveness. Their long-term viability depends on how systematically socio-economic, institutional, and stakeholder dimensions are embedded into system design from the outset. As urban environments become more data-driven and interdependent, requirement engineering must move beyond purely technical specification and adopt a structured, multidimensional approach.

This white paper presents a methodological framework for eliciting socio-techno-economic requirements for Smart City Open DT Systems. By combining domain-specific scoping, structured stakeholder mapping through the Quadruple Helix model, tailored elicitation instruments, transparent prioritisation mechanisms, formal requirement classification, and architectural alignment, the framework offers a clear and replicable pathway from stakeholder input to system design. The objective is not only methodological clarity, but practical applicability across diverse urban contexts.

Future DT initiatives should adopt requirement-driven development as a foundational principle rather than relying on architecture-first deployment strategies. Institutional adoption, interoperability across administrative systems, governance safeguards, and user trust should be embedded as primary design criteria from the outset rather than addressed retrospectively. Structured elicitation processes function both as technical instruments and as governance mechanisms, ensuring that system specifications reflect documented and prioritised stakeholder needs.

As Open DT Systems mature, systematic socio-techno-economic requirement engineering will increasingly determine their scalability, interoperability, and long-term operational viability. Integrating structured methodology during the early phases of system design does not introduce unnecessary complexity; rather, it establishes the conditions for coherent, accountable, and sustainable smart city innovation.

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