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CONCEPT OF A DIGITAL DECISION-MAKING FRAMEWORK FOR THE DEVELOPMENT OF INTEGRATED AND SUSTAINABLE TRANSPORT SYSTEMS

Abstract. Modern cities and regions are increasingly challenged to effectively plan and develop transport systems that are not only functionally integrated but also long-term sustainable. Digital technologies offer new opportunities for collecting, processing, and evaluating data that can significantly enhance decision-making processes in the field of transport. This paper presents a concept of a digital decision-making framework that combines data-driven analytical tools, participatory platforms for stakeholder engagement, and multi-level evaluation based on sustainability criteria. The proposed framework is modular and is applied at the level of strategic planning of transport investments. The result is a more transparent, flexible, and evidence-based decision-making process that supports the balanced development of various modes of mobility.
Keywords: intelligent transportation systems, sustainable mobility, decision-making process, smart cities

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Introduction

Currently, transport systems are at a critical juncture, facing unprecedented pressure caused by urbanization, climate change, increasing mobility demands, and public expectations for high-quality and accessible services (Ribeiro et al., 2021; Papageorgiou et al., 2024). These trends are not only intensifying the complexity of mobility patterns but also challenging the capacity of traditional planning tools to respond effectively and equitably. A key challenge for cities and regions is to design and implement transport policies that ensure the functional integration of various modes of transport—including public, private, alternative, and freight systems—while simultaneously aligning with long-term sustainability objectives (Elassy et al., 2024). This requires planning strategies that go beyond isolated interventions and address systemic, cross-sectoral, and dynamic aspects of mobility.

In this context, the role of intelligent technologies is growing significantly. Advanced data infrastructures, sensing technologies, and digital platforms now enable the real-time collection, analysis, and interpretation of complex transport-related data streams. These technologies not only enhance the operational management of transport networks but also contribute to strategic planning by offering evidence-based insights and predictive capabilities. Their integration into decision-making processes holds considerable promise for more transparent, adaptive, and inclusive approaches to urban mobility planning (Zhu, 2022; Aspen, 2023). Nevertheless, a major unresolved issue is how to effectively align these technological innovations with the spatial, environmental, and institutional realities of transport systems, as well as with the participatory needs of diverse stakeholder groups.

In recent years, the significance of digitalization and Intelligent Transportation Systems (ITS) has been steadily increasing. ITS applications allow for real-time monitoring of traffic flows, dynamic route optimization, and modelling of passenger behaviour, thereby contributing to more responsive and resilient urban mobility systems (Alanazi and Alenezi, 2024). In parallel, the development of digital decision-making tools—capable of generating visualizations, simulations, and impact predictions—has opened new avenues for strategic foresight and scenario planning (Huzzat et al., 2025; Žak, 2010). Despite these advancements, the integration of such tools into policy and planning remains fragmented, particularly in relation to comprehensive sustainability assessments and active stakeholder participation.

The aim of this article is therefore to present a novel concept of a digital decision-making framework designed to support the planning, management, and evaluation of integrated and sustainable transport systems. The framework is conceived in response to the need for a multidisciplinary approach that interconnects technical innovations, strategic governance objectives, and the practical needs of stakeholders in diverse territorial settings. The proposed methodology for developing this framework builds on the convergence of systems planning, data analytics, and participatory design principles. At its core lies a modular architecture capable of flexibly responding to the varying requirements of transport planning and governance across different geographic, technological, and institutional contexts. This approach not only enhances the functionality and interoperability of decision-support systems, but also strengthens their legitimacy, transparency, and alignment with long-term sustainability transitions.

1. Theoretical Foundations of the Digital Decision-Making Concept

Digital decision-making in transport planning represents a set of tools, processes, and methodologies that utilize digital technologies to support informed, transparent, and participatory decisions (Ocalir-Akunal, 2015, 2016). In the context of the current development of smart cities and adaptive transport systems, new opportunities are emerging to integrate these tools into both strategic and operational mobility management (Xenon et al. 2022). These concepts align with broader paradigmatic shifts in public administration, emphasizing data openness, interdisciplinarity, and flexible decision-making within complex systems.

The concept of a digital decision-making framework is based on several interrelated principles that collectively provide the foundation for a methodologically robust approach. Figure 1 illustrates the concept of the digital decision-making framework.

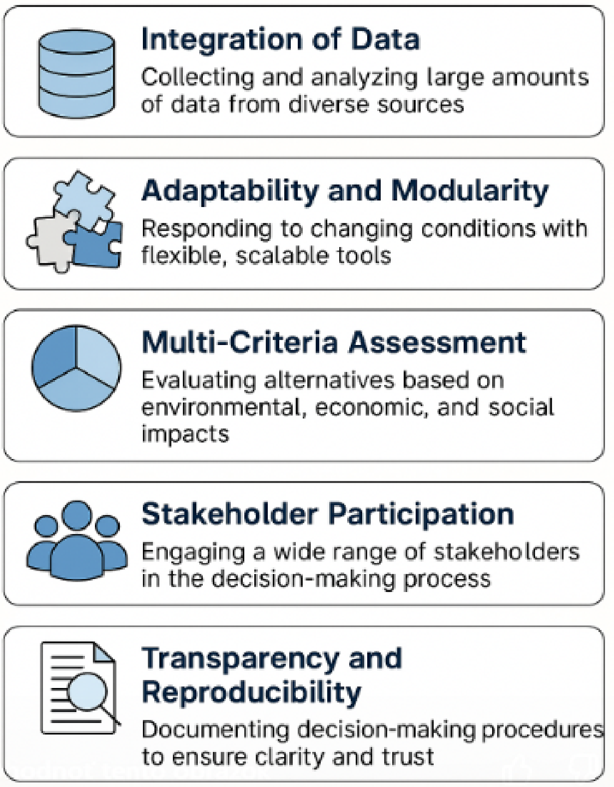

Fig. 1. Concept of the digital decision-making framework.

• **Integration of Data** – The collection, aggregation, and analysis of large volumes of data from diverse sources (sensors, mobile applications, public registries, open data platforms, satellite imagery, traffic detectors) enable a comprehensive understanding of transport phenomena in real time. The digital framework establishes a unified data environment that underpins analytical, simulation, and predictive models. Data integration enhances the system's ability to detect critical situations, identify behavioural patterns, and forecast the future impacts of decisions.

• **Adaptability and Modularity** – Decision-making systems must respond to changing conditions – from peak traffic periods and seasonal fluctuations to extraordinary events (e.g. accidents, climate extremes, social unrest). A modular architecture allows flexible deployment and updating of tools according to the specific needs of the environment or planning phase. This architecture supports system scalability and seamless integration with existing infrastructure.

• **Multi-Criteria Assessment** – In a digital environment, it is possible to simultaneously assess multiple impacts – environmental (e.g. emissions, noise, energy consumption), economic (costs, return on investment, operational efficiency), and social (accessibility, equity, user satisfaction). Models such as AHP (Analytic Hierarchy Process), entropy weighting, fuzzy logic, or the matter-element method enable the combination of subjective preferences and objective data. This results in transparent and quantifiable evaluations of alternatives.

• **Stakeholder Participation** – Digital tools enhance the ability to engage a wide range of actors (municipal governments, transport operators, civil society organizations, the public) in the decision-making process through online consultations, crowdsourcing, feedback mechanisms, visualizations, or participatory simulations. Involving stakeholders not only lends legitimacy to the process but also improves decision quality by incorporating local knowledge, needs, and preferences of different population groups.

• **Transparency and Reproducibility** – One of the advantages of digital systems is their ability to store and document decision-making procedures, model parameters, weighting schemes, analytical outputs, and algorithms used. This facilitates decision validation, simplifies auditing, and strengthens public trust. At the same time, it supports institutional learning and the transfer of best practices between cities and regions.

Therefore, the digital framework is not merely a technical solution but a comprehensive methodological approach to planning. It promotes iterative learning based on data, dynamic impact evaluation, flexibility under uncertainty, and effective management of transport systems in complex urban environments (Faliagka et al. 2024). Its importance is particularly increasing considering the transformation of transport policies toward sustainability, inclusiveness, and digital public governance.

2. Methodology for Developing a Digital Decision-Making Framework

The proposed methodology for developing a digital decision-making framework is based on the integration of systems planning, data analytics, and participatory design. The core principle lies in the creation of a modular system capable of dynamically responding to the needs of transport planning and management across various geographical, technological, and institutional contexts. The methodology consists of three main phases, which are illustrated in Figure 2.

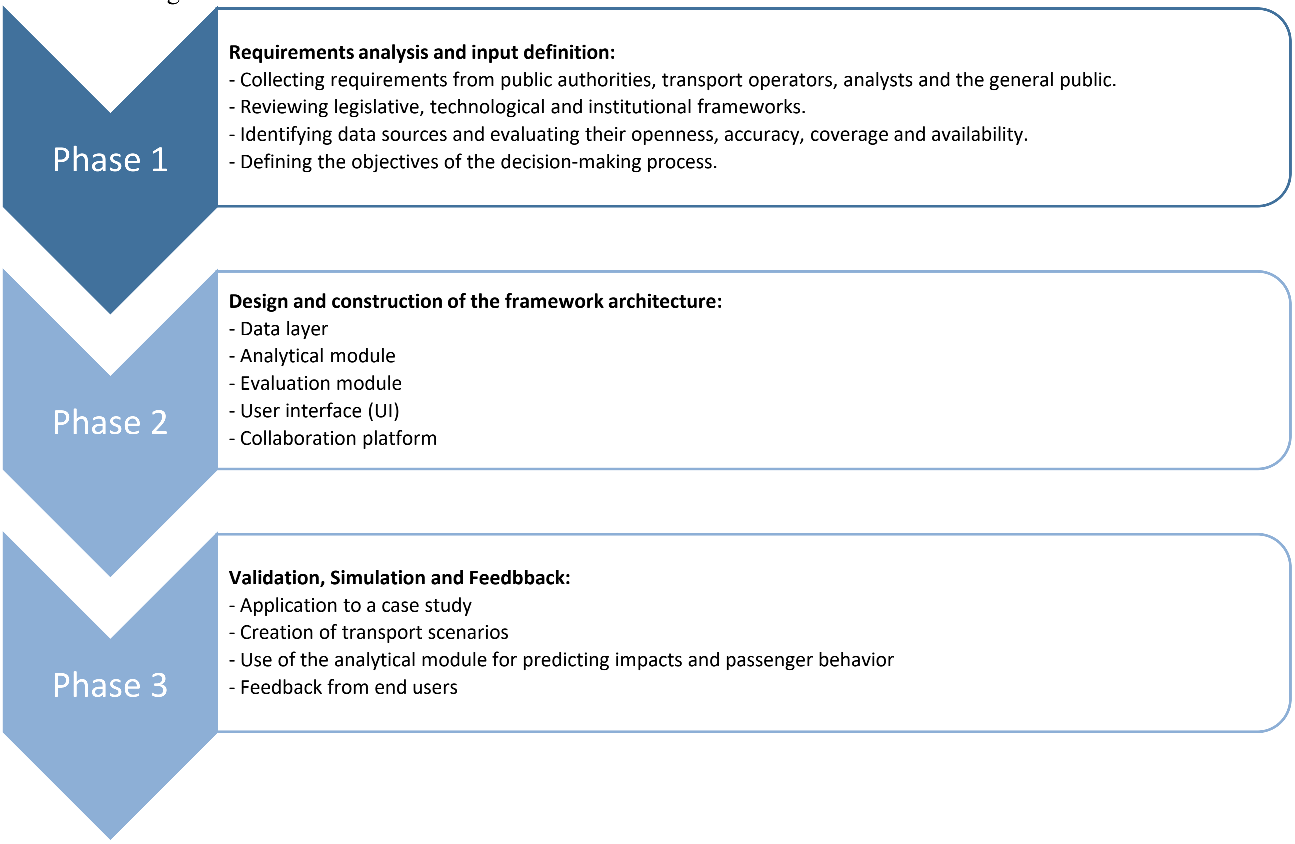

Fig 2. Methodology for Developing a Digital Decision-Making Framework

The proposed methodology consists of the following phases:

Phase 1: Requirements Analysis and Input Definition

The initial phase of the methodology represents a critical step in the design of the digital decision-making framework, as it establishes the fundamental conditions and foundations upon which the system will be built. The aim of this phase is to identify the needs of stakeholders, examine legislative and technical frameworks, define the available data, and establish the main decision-making objectives to which the proposed architecture should be aligned.

At the beginning, a systematic collection of requirements from all key stakeholders is conducted. These include public authorities, which define strategic mobility goals and regulatory frameworks; transport operators, with a focus on integration with their information and tariff systems; analysts and researchers who require accurate and compatible data for evaluation and modelling, and the public, which expresses practical expectations and the need for transparency in decision-making processes. These requirements are gathered through interviews, workshops, online surveys, and public consultations.

This phase also includes a thorough review of the legislative, technological, and institutional context. It is essential to ensure compliance with regulations such as GDPR in handling data, while also assessing the possibilities for integrating the proposed system with existing infrastructure. Consideration is also given to the level of digitalization of local administrations, staff readiness, and the configuration of decision-making processes.

Equally important is the analysis of the availability, quality, and interoperability of data sources. The types of data required for decision-making—static, dynamic, and environmental—are identified, and their accuracy, update frequency, coverage, and compliance with are assessed. If certain data types are not available, alternative methods for acquiring or substituting them are proposed.

At the end of this phase, the main decision-making goals supported by the framework are formulated based on the collected inputs. These may include optimization of public transport routes and schedules, reduction of environmental impacts, improvement of service accessibility for marginalized groups, or enhancement of passenger satisfaction and comfort.

The outcome of this phase is a set of analytical outputs that form the basis for designing the system architecture. These include the requirements specification document, an inventory of data sources, an overview of constraints and opportunities, and a definition of strategic decision-making objectives. These outputs serve as input parameters for the next phase of the system design.

Phase 2: Design and Construction of the Framework Architecture

In this phase, the system architecture is proposed as a response to the requirements defined in the previous stage. The objective is to develop a technologically functional, modular, and scalable framework that connects analytical tools, data flows, visualization components, and participatory mechanisms. The architecture is designed to adapt to various territorial and institutional contexts while supporting transparent decision-making and the evaluation of transport strategies.

1. **Data Layer** – The data layer forms the foundational infrastructure for integrating data from various sources. It ensures the collection, processing, and standardization of data necessary for analytical and decision-making processes. This includes static data such as infrastructure maps, demographic characteristics, or fare systems, as well as dynamic data from sensors, GPS devices, ticketing systems, and environmental monitoring stations. The data are harmonized into standardized formats to ensure compatibility and further processing in other system modules. A critical part of this layer is data quality validation and secure storage.
2. **Analytical Module** – The analytical module is the computational core of the framework. It is used to analyse current transport conditions, forecast future scenarios, and optimize planning. It employs machine learning algorithms to model travel behaviour and predict transport flow trends. It also offers tools for evaluating the impacts of various interventions (e.g., public transport expansion, introduction of low-emission zones, construction of cycling infrastructure). The module works with agent-based behaviour models to simulate the responses of different user groups to changes in the transport system. The analytical layer must be powerful and adaptable to diverse inputs and scenarios.
3. **Evaluation Module** – This component enables multi-criteria assessment of transport solutions. It considers environmental indicators such as greenhouse gas emissions or energy consumption, economic factors like investment and operational costs or return on investment, and social aspects such as transport accessibility, equity of access, and user satisfaction. The assessment is carried out through scoring schemes, weighting matrices (e.g., AHP), entropy weighting, or fuzzy logic. The module allows for the configuration of weightings according to stakeholder preferences, increasing the flexibility and relevance of the results.
4. **User Interface (UI)** – The user interface is designed to be intuitive and accessible to different target groups—from technical planners to the public. It provides map-based visualizations, interactive simulations, and clear dashboards with key performance indicators. Users can visually compare different scenarios, filter outputs by criteria, or export data for further processing. The interface is also optimized for mobile devices, increasing accessibility and supporting participatory use in the field.
5. **Collaboration Platform** – The final component of the framework focuses on involving stakeholders and the public in decision-making processes. It enables the organization of public consultations, collection of feedback via online surveys, idea crowdsourcing, and publication of evaluation results. The platform also serves as an integration hub for communication between cities, regional authorities, transport operators, and analytical teams. Transparent visualization of results enhances the credibility of decisions and supports the consensus-driven formation of transport strategies.

These components collectively form the modular architecture of the framework, interconnected via standardized data channels in a service-oriented architecture (SOA). The framework is designed to support iterative decision-making—meaning that new data or feedback automatically trigger updates to calculations and evaluations. This architecture also provides room for future expansion, such as modules for real-time monitoring of policy impacts, integration of digital twins, or recommendation algorithms. The outcome of Phase 2 is a ready, tested, and conceptually stabilized framework, prepared for validation in a simulated or pilot environment.

Figure 3 illustrates the four fundamental layers that form the proposed digital framework for planning, managing, and evaluating transport systems. The layered model reflects the logical hierarchy and flow of information between infrastructure data, analytical processing, and the user interface.

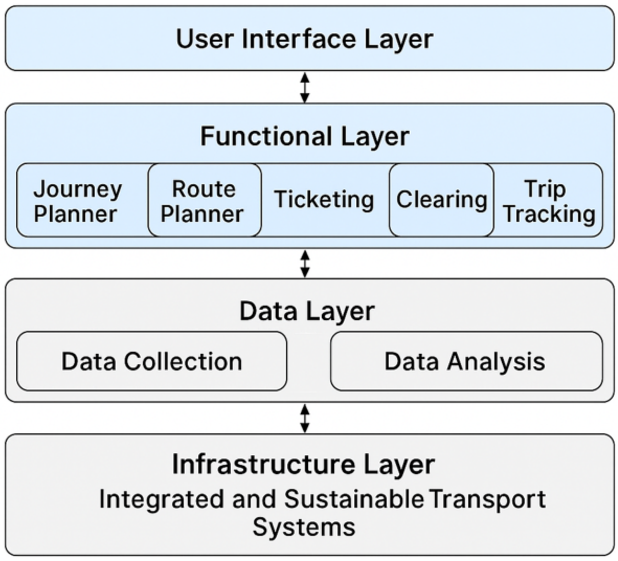

Fig. 3. Architecture of the Digital Framework for Planning and Management of Integrated Transport Systems

This model represents the logical architecture of the system developed in Phase 2 of the methodology and serves as an integrative framework for implementing the individual components of the proposed solution. At the same time, it highlights the interconnection between data, functional, and user dimensions of decision-making in the context of intelligent and sustainable mobility.

The *Infrastructure Layer* (bottom layer) represents the physical and organizational foundation of integrated and sustainable transport systems—namely, the urban and regional transport networks that the framework analyses and optimizes.

The *Data Layer* ensures data collection and processing through two main functional blocks: *Data Collection* (gathering data from sensors, public transport systems, GPS, and ticketing platforms) and *Data Analysis* (preprocessing, validation, and aggregation of data).

The *Functional Layer* contains the core planning and transactional functions of the system. Blocks such as *Journey Planner, Route Planner*, and *Trip Tracking* serve as decision-making and operational tools, while *Ticketing* and *Clearing* handle service and financial operations.

The *User Interface Layer* is the top layer of the system, which delivers the outputs of analytical processes to end users. It enables visualization of results, user interaction with the system, and provides feedback to the lower layers.

Phase 3: Validation, Simulation, and Feedback

The third phase of the methodology focuses on the practical validation of the proposed digital decision-making framework. It serves as a testing stage that evaluates the robustness, accuracy, and practical applicability of the designed architecture under conditions that closely resemble real-world deployment. The aim is to obtain empirical evidence of the system's functionality, identify its strengths and weaknesses, gather user feedback, and calibrate parameters for future implementation.

A key step is the application of the framework to a selected case study—typically an area facing specific mobility challenges, such as a medium-sized urban environment with high traffic congestion, limited accessibility, or increasing pressure to reduce emissions. Within this setting, multiple transport scenarios are proposed and modelled, simulating potential interventions in the transport system. Common examples include the introduction of low-emission zones, expansion of cycling infrastructure, reorganization of public transport routes, integration of shared mobility, or the implementation of intelligent transport systems.

Each scenario is subjected to systematic evaluation using the evaluation module. Through multi-criteria analysis, the environmental, economic, and social impacts are quantified. Simultaneously, the analytical module performs predictive simulations that model passenger behaviour, traffic intensity, potential congestion, time savings, and emission effects. These results are then compared with the objectives defined in the initial phase and serve as a basis for informed decision-making.

Emphasis is also placed on the involvement of end users. Planners, analysts, local authorities, transport operators, and representatives of the public are actively engaged in the assessment process through online platforms, discussion forums, consultations, or surveys. The feedback they provide is crucial for refining the system—it helps to identify shortcomings in usability, clarity of outputs, or insufficient consideration of local specifics.

Based on this feedback, the framework's parameters are calibrated—this may include adjusting the weighting of evaluation criteria, modifying input data, or refining computational models. The result is an optimized, tested framework ready for pilot implementation or broader deployment. Thus, Phase 3 serves as a bridge between tool development and its real-world use in transport planning decision-making. Validating the framework under real or semi-real conditions enhances its credibility, transferability, and acceptance among key stakeholders in public administration and transport.

Conclusion

The proposed digital decision-making framework offers a systematic and methodologically grounded tool for supporting the planning of integrated and sustainable transport systems. Its architecture reflects current requirements for flexibility, transparency, data integration, and stakeholder participation. The framework combines analytical and predictive tools with evaluation models and a user-friendly interface, thereby creating an environment for informed and adaptive decision-making.

This approach to planning contributes to the alignment of strategic mobility goals with the principles of sustainable development and simultaneously creates space for active engagement of stakeholders. The framework can significantly enhance the transparency of decision-making processes, especially in contexts where the impacts of transport strategies must be assessed across multiple dimensions—environmental, economic, and social.

However, successful implementation of the framework requires high-quality input data, digital readiness of institutions, and appropriate legislative and organizational conditions. Identified limitations—such as data incompatibility, limited analytical capacities, and the need for user training—represent challenges that must be systematically addressed.

For future development, we recommend conducting pilot tests of the framework in diverse geographic, institutional, and cultural contexts, expanding its analytical capabilities to include behavioural and microeconomic aspects, and developing a universal methodological guide for practical application. Research should also focus on the development of open data standards, integration of artificial intelligence technologies, and fostering collaboration between academia, local governments, and the technology sector.

Therefore, the proposed framework should not be viewed as a final solution, but rather as an open platform for the continued evolution of digital planning in transport, supporting the transition to sustainable, efficient, and user-cantered mobility.

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