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A DATA-DRIVEN FRAMEWORK FOR MULTIDIMENSIONAL URBAN MOBILITY (MUM)

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Abstract

The escalating complexity of global urbanization necessitates a fundamental paradigm shift in how metropolitan transport systems are conceived, modelled, and managed. As terrestrial networks reach their saturation points, the transition towards Multidimensional Urban Mobility (MUM) becomes an operational necessity rather than a speculative ambition. This analysis investigates the architectural requirements for such a transition, specifically focusing on the integration of the "conquest of the air" through Urban Air Mobility (UAM). The research is structured around four primary pillars: the hierarchical levels of decision-making requisite for system deployment; a critical evaluation of the Mobility as a Service (MaaS) paradigm; the proposal of a novel, data-driven reference framework; and an examination of the technical and business interoperability challenges inherent in a multidimensional ecosystem.

The central argument posits that while existing MaaS models have successfully pioneered digital and tariff convergence, their inherent "user-centric" limitation restricts their efficacy in a multidimensional context. To address the constraints of terrestrial networks and the integration of three-dimensional mobility (utilizing drones and helicopters alongside 1D rail and 2D road systems), a transition towards a stakeholder-inclusive, data-driven framework is essential. This framework must move beyond simple trip planning to encompass the strategic requirements of public authorities and service providers. The analysis demonstrates that the success of MUM is contingent upon resolving critical data management hurdles—specifically regarding real-time processing, data heterogeneity, and privacy—while ensuring seamless interoperability across diverse technological and organizational silos. By synthesizing these elements, this report provides a rigorous academic foundation for assessing the feasibility and operational deployment of future urban mobility Cyber-Physical Social Systems (CPSS).

2. INTRODUCTION

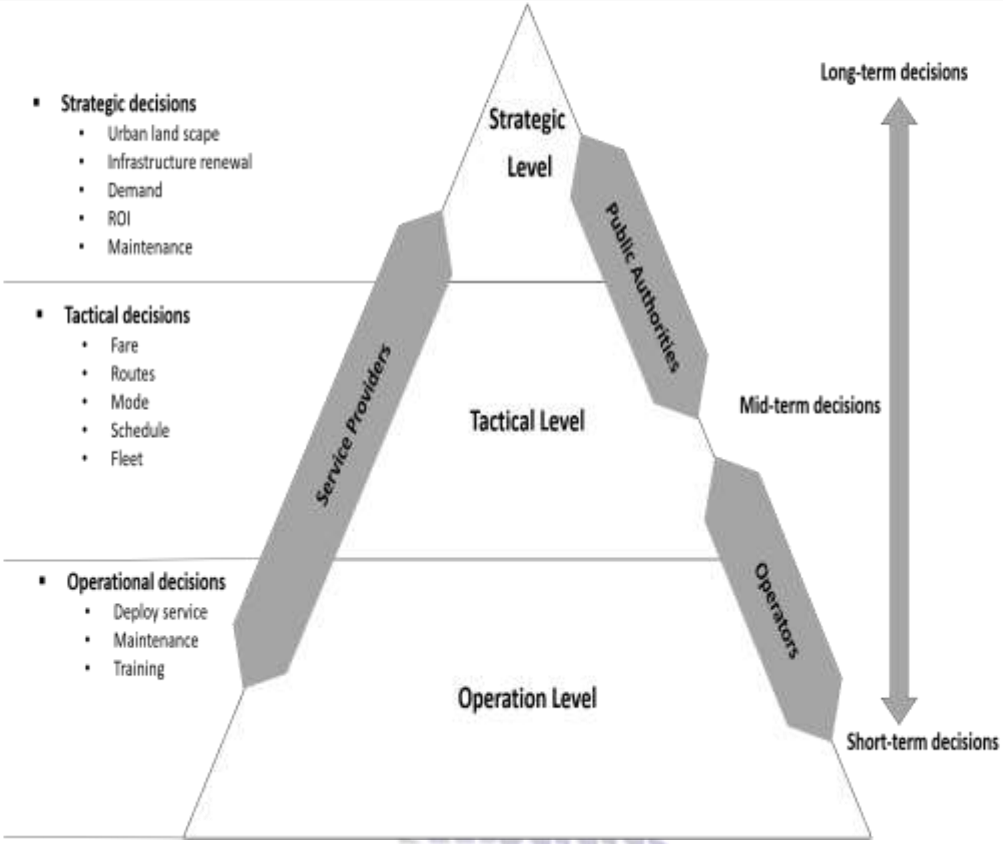
Urban mobility is currently undergoing a period of radical transformation, driven by the dual pressures of increasing population density and the rapid digitization of municipal infrastructure. As regular commutes become more complex due to rising traffic volumes and the expansion of urban peripheries, traditional terrestrial transport networks—historically confined to one-dimensional (1D) fixed-line rail and two-dimensional (2D) road networks—are reaching their physical and operational limits. In response, the industry has witnessed a shift towards "intelligent mobility," which initially manifested as an emphasis on "soft mobility," multi-modality, and the more reasoned use of personal vehicles.

However, the mere optimization of 2D networks is no longer sufficient to meet the demands of modern megacities. The "conquest of the air" represents the next frontier in urban logistics and passenger transport. By introducing a third dimension—Urban Air Mobility (UAM) involving drones, helicopters, and small carriers—cities can diversify their mobility offerings to transport both humans and goods with greater flexibility. This transition requires more than just novel vehicle technology; it demands a deep convergence of digital services and tariff structures to ensure a seamless experience across all dimensions (Jittrapirom et al., 2017).

The deployment of such a multidimensional system is a high-stakes undertaking for urban stakeholders. Prior to significant infrastructure investment, it is imperative that decision-makers can accurately assess the return on investment (ROI) and the operational feasibility of these systems. This report outlines a proposed data-driven framework designed to guide this deployment. By examining the decision-making hierarchies, existing MaaS paradigms, and the technical requirements for data management and interoperability, this analysis provides a structured roadmap for the integration of 1D, 2D, and 3D urban mobility into a unified, efficient, and sustainable ecosystem. The goal is to establish a system where the "physical" processes of transport are perfectly mirrored and managed by "digital" analytical layers.

3. Decision-making in Multidimensional Urban Mobility (MUM)

The implementation of a MUM framework is not a singular event but a series of hierarchically ordered activities. These activities are distinguished by the extent of the issues they address and the timeframe over which they operate. To ensure a successful deployment, decision-making must be synchronized across three distinct levels: Strategic, Tactical, and Operational.



3.1. Strategic Level: Defining Long-term Objectives

The strategic level of decision-making is concerned with the highest level of abstraction, answering the fundamental question: "**What do we wish to achieve?**" At this stage, stakeholders focus on broad objectives that shape the future of the urban landscape. This level determines the fundamental aims of the system, including sustainability goals, profit margins, and the geographic scope of supply and demand areas. Key considerations include:

- **Infrastructure Renewal and Maintenance:** Identifying long-term requirements for physical assets such as vertiports, roads, and digital networks.
- **System Aims:** Defining whether the network prioritizes public service accessibility, environmental mitigation, or commercial viability.
- **Integration and Intramodality:** Determining the extent to which different modes (1D, 2D, and 3D) will be linked.

3.2. Tactical Level: Determining Solutions and Means

Once strategic goals are established, the tactical level addresses the question: "**What solution can assist in achieving these goals?**" This level acts as a bridge, transforming abstract aims into specific service requirements. It establishes the foundation for the actual design of provided services. Key activities include:

- **Acquisition of Means:** Identifying the specific technologies and assets required to deliver the strategic vision.
- **Service Design:** Establishing fare route networks, choosing transport modes, and designing schedules.
- **Fleet Design:** Determining the size, type, and distribution of vehicles (drones, buses, etc.) required to meet predicted demand.

3.3. Operational Level: Execution and Day-to-Day Management

The operational level is the executive phase of the hierarchy, focusing on the question: "**How do you make the product?**" This level ensures the efficient performance of services according to the parameters set by the higher levels. It involves:

- **Day-to-day Practice:** Integrating tactical plans into real-world service delivery.
- **Human Resource Management:** Detailed employee training and staff deployment.
- **Maintenance Execution:** Routine servicing of the system (drones, sensors, tracks) based on objectives specified in the tactical level.

3.4. Stakeholder Roles and Overlapping Involvement

The distribution of these roles depends on the contractual and regulatory framework of the specific city. There is a significant overlap in involvement, particularly where Public Authorities must translate strategic "what" and "with what" (resources) into tactical "how" (plans) and operational deployment.

Table 3.1: Stakeholder Decision-Making Matrix

Stakeholder	Strategic Involvement	Tactical Involvement	Operational Involvement
Public Authorities	**High:** Setting long-term urban policy and landscape goals.	**High:** Translating goals into specific plans and regulatory "how-to".	**Medium:** Supervisory oversight and regulatory enforcement.
Service Providers	**Medium:** Aligning corporate ROI strategies with public policy.	**High:** Designing fare networks, modes, and fleet solutions.	**Medium:** Providing the technical platforms and operational tools.
Operators	**Low:** Influenced by the mandates of the strategic levels.	**Medium:** Specific planning of fleet schedules and maintenance cycles.	**High:** Direct execution, training, and service delivery.

4. Traditional Framework for Urban Mobility: Mobility as a Service (MaaS)

To understand the proposed MUM framework, one must first analyze its predecessor: **Mobility as a Service (MaaS)**. MaaS represents a paradigm shift where diverse mobility providers collaborate within a digital ecosystem to offer a seamless, multimodal transportation service via a single end-user interface (Kamargianni & Matyas, 2017).

4.1. Definition and Vision

The primary vision of MaaS is to structure urban mobility to meet sustainability requirements by discouraging private vehicle use. It leverages digital technology to provide users with access to information and integrated invoicing. By offering a unified interface, MaaS aims to make public and shared transport more convenient and cost-effective than private car ownership, allowing users to find the most efficient route and price quickly through tools like recommender systems.

4.2. The Virtuous Cycle of Stakeholder Priorities

A successful MaaS implementation creates a "virtuous cycle" (Hietanen, 2014) by balancing the priorities of three core stakeholder groups:

1. **End-users:** Prioritize speed, cost, comfort, and reliability.
2. **Transport Authorities:** Focus on city accessibility, reducing public expenditure, and mitigating environmental impacts (pollution and carbon footprint).
3. **Mobility Operators:** Seek profitability to reinvest in service development and innovate in line with user expectations.

When these priorities align, users move from private cars to public modes, relieving city center congestion and reducing the carbon footprint. This shift allows authorities to control costs via high-performance services, while operators secure the revenue needed for further infrastructure investment.

4.3. Core Characteristics of MaaS

According to Jittrapirom et al. (2017), MaaS is defined by eight distinctive features:

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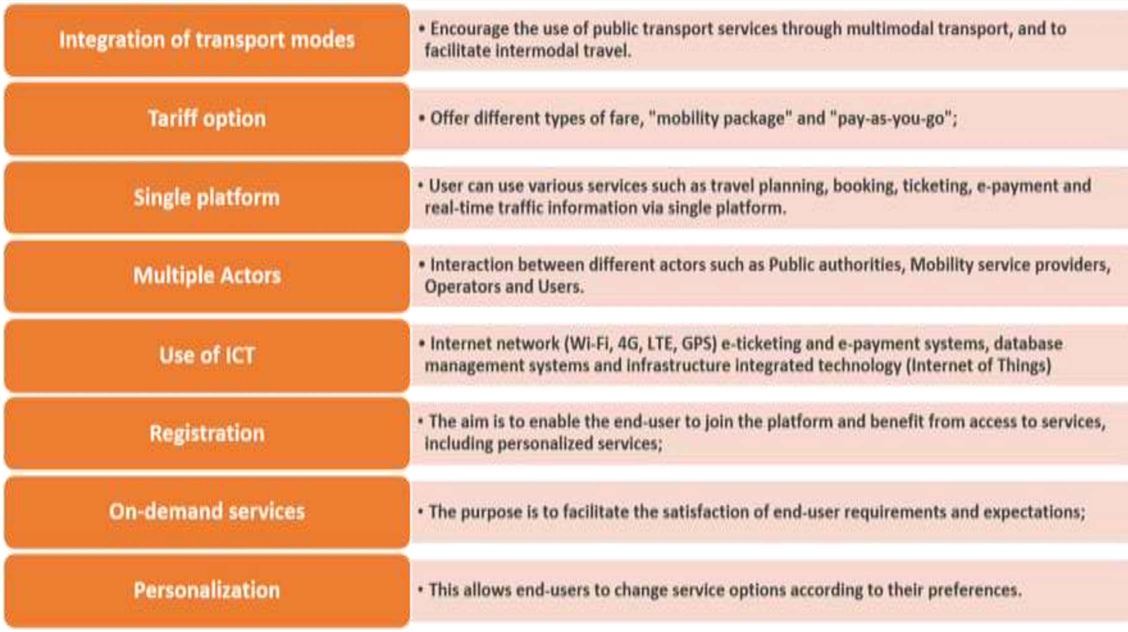


- **Integration of Transport Modes:** Facilitating intermodal travel to make public transport more attractive.
- **Tariff Options:** Offering "mobility packages" (monthly subscriptions) or "pay-as-you-go" models.
- **Single Platform:** Digitalization of content providing booking, planning, and e-payment through a unified interface.
- **Multiple Actors:** A complex ecosystem of public/private providers, platform owners, e-payment firms, and telecommunications companies.
- **Use of Internet Technologies:** Reliance on 4G/5G, GPS, IoT, and robust database management systems.
- **Obligation to Register:** Users must join the platform to access services and enable personalization.
- **On-demand Services:** Focusing on the immediate satisfaction of user requirements.
- **Personalization:** Allowing users to tailor mobility packages and preferences.

4.4. Global Implementation Examples

Various cities have pioneered MaaS platforms, focusing on integrating ticketing and real-time information.

Table 1.1: Well-known MaaS Applications and Services

Application Name	Country	Key Services
Whim	Finland (Helsinki)	Pay-per-ride, bike-sharing, car rental, and public transport.
TransitApp	USA, UK, Global	Car-sharing, bike-sharing, and pay-per-ride for public transport.
Optymod	France (Lyon)	Bike-sharing, parking, transport planner, regional trains.
Mobility2.0	Spain (Palma)	Car-sharing, bike-sharing, and pay-per-ride for public transport.

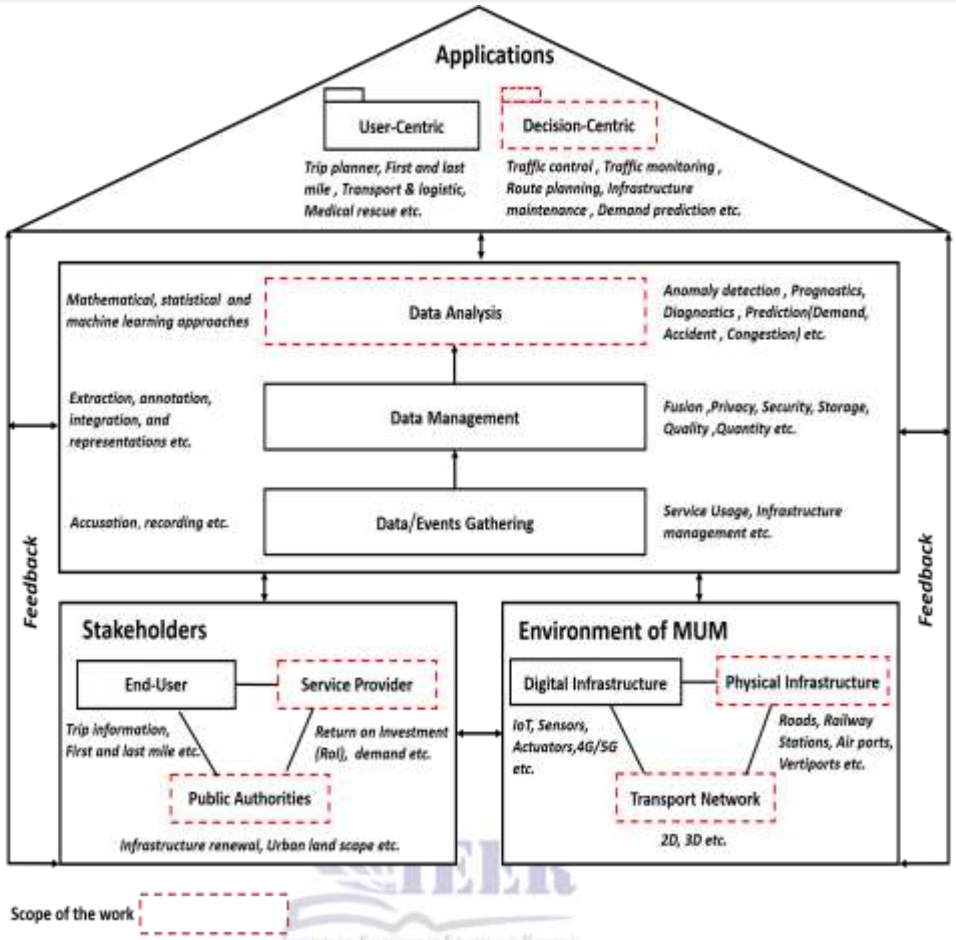
Ustra	Germany (Hannover)	Car-sharing, taxi pre-reservation, and integrated billing.
UbiGo	Sweden (Gothenburg)	Bike-sharing, car rental, monthly budget, and trip planning.
Mobility Mix	Netherlands	Monthly travel budget and comprehensive transport planning.
Moovel	Germany (Berlin)	Pay-per-ride, car-sharing, and bike-sharing.
Smile	Austria (Vienna)	Trip planning, shared modes, service alerts, and real-time info.

4.5. Critical Limitation: From User-Centric to Stakeholder-Centric

Despite its successes, the MaaS framework remains predominantly **user-centric**. It focuses on applications for the individual (e.g., trip planners) while often neglecting the complex data requirements of service providers and government agencies. To support the shift to multidimensional mobility, a broader **stakeholder-centric** approach is required, providing decision-support tools for all parties involved in the ecosystem.

5. Proposed Data-driven Framework for Multidimensional Urban Mobility

The proposed framework for MUM expands upon the MaaS model by integrating the third dimension (UAM) and adopting a data-driven approach that caters to all stakeholders. This framework is designed to gather, manage, and analyze data to generate "decision-centric" insights.



5.1. Framework Pillars: Stakeholders and Environment

The framework is built upon two foundational pillars:

- **Stakeholders:**
  - *End-users:* Input data regarding trip information and usage of first/last-mile solutions.
  - *Public Authorities:* Provide data on urban landscape scarcity, infrastructure renewal, and regulatory constraints.
  - *Service Providers:* Contribute data on operating strategies, ROI, and demand metrics.
- **Environment of MUM:**
  - *Physical Infrastructure:* Roads, bridges, airports, and **vertiports**.
  - *Digital Infrastructure:* IoT sensors, actuators, and 4G/5G telecommunications.
  - *Vehicle Network:* Status and location data from **1D (rail), 2D (ground), and 3D (air)** vehicles.

5.2. Data and Events Gathering

This component involves the continuous collection of events. Public authorities contribute infrastructure management and city footprint data; service providers offer e-ticketing and UAM demand data; end-users generate service usage patterns and complaints.

5.3. Deep Dive: Data Management in Cyber-Physical Social Systems (CPSS)

The transition to a multidimensional system creates a **Cyber-Physical Social System**, where digital analysis must mirror physical reality perfectly. This introduces significant management hurdles (Abbasi et al., 2020).

5.3.1. Real-time Data and Predictive Synchronization

MUM systems are heavily reliant on contextual, time-sensitive data. The challenge lies in the volume and unpredictability of data flows. Because physical processes—such as drone flight paths or emergency medical rescues—must correspond exactly with digital results, computations must be practical and timely. Unlike 2D traffic, which has established patterns, 3D mobility is highly sensitive to environmental flux (e.g., wind speeds, micro-weather). Matching these physical processes with real-time digital analysis is critical to prevent system failure.

5.3.2. Data Heterogeneity and Space-Terrestrial Convergence

The framework must integrate data from heterogeneous sources and formats. This heterogeneity poses a threat to communication integrity. Innovative space communication technologies used in UAM are not naturally compatible with terrestrial IoT sensors. Achieving interoperability between these diverse technologies is difficult; however, the framework must ensure that applications operate without interruption across the entire 1D/2D/3D spectrum.

5.3.3. Data Privacy, Security, and Public Trust

The inclusion of a "social component"—gathering detailed user movement and financial data—increases information sensitivity. Privacy is essential to maintain the user's right to anonymity. Any compromise in security, particularly regarding financial transactions or flight path history, could lead to public rejection of the system. Protecting these systems from cyber-threats is exceptionally difficult but necessary for legal compliance and public trust.

5.4. Data Analysis and Applications: From Raw Data to Prognostics

Data undergoes treatment using analytic techniques like anomaly detection and demand prediction. For example, **city footprints** and **e-ticketing** data are analyzed to identify anomalies in traffic flow or to perform **prognostics** on infrastructure health (Fukuda et al., 2016).

- **User-centric Applications:** Trip planners, medical rescue logistics, and first/last-mile solutions.
- **Decision-centric Applications:** Traffic control, infrastructure maintenance, and demand prediction for policy design.

In this framework, sensors and actuators (Fukuda et al., 2016) interact to impact the environment; for instance, sensors detect a spike in UAM demand, and actuators (digital signals to operators) initiate a response in fleet distribution.

6. Interoperability Concerns and Approaches

Interoperability is the ability of diverse components and stakeholders to communicate and work together effectively. Without standardization, the MUM framework remains a collection of autonomous, siloed solutions.

6.1. Levels of Interoperability

Based on the Framework for Enterprise Interoperability (FEI) (Chen et al., 2017), four levels must be addressed:

- **Data Interoperability:** Ability to access and share information across different databases and operating systems.
- **Service Interoperability:** Concerns services developed by different vendors running in parallel to solve **syntactic conflicts** (data format differences) and **semantic conflicts** (differences in the meaning or definition of data points, such as how "altitude" is calculated by different drone manufacturers).
- **Process Interoperability:** Relates to the sequence of services. For instance, a user must successfully complete the registration-and-payment sequence across two different providers (e.g., a bus and a drone) for a single trip.
- **Business Interoperability:** Harmonizing workflows for consistent business-to-business integration.

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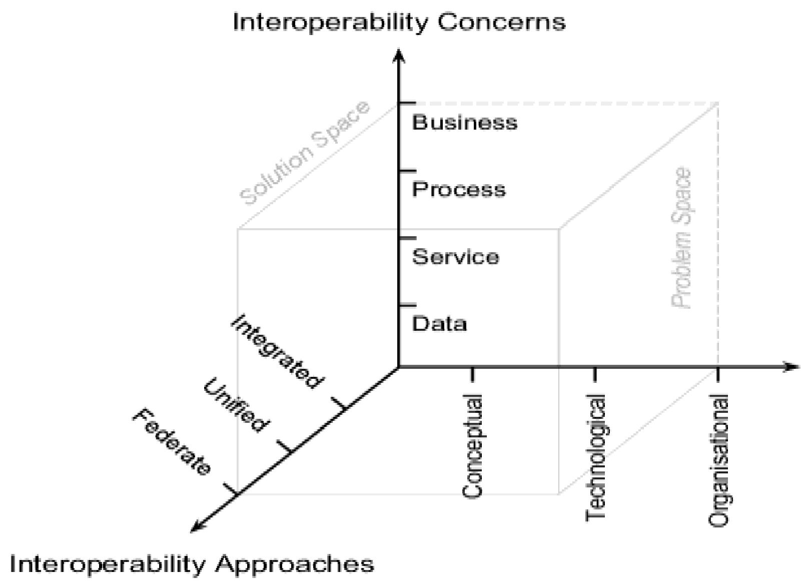

6.2. Implementation Approaches

1. **Integrated Approach:** All stakeholders agree on a common template or format before development. This ensures total compatibility but requires early consensus.
2. **Unified Approach:** A common format exists at a high level of abstraction. It provides a standard "map" for the system but is not directly executable.
3. **Federated Approach:** No shared format is enforced. Instead, stakeholders share a shared ontology—a formal naming and definition of the types, properties, and interrelationships of the entities within the mobility domain. This allows systems to be interoperable at run-time while respecting the autonomy of different partners.
4.

6.3. Business Implications in the MUM Context

Interoperability is critical because the ecosystem involves autonomous solution providers (e.g., drone manufacturers and city rail operators) who must share a single platform. A failure in **process interoperability** has direct business consequences: if a user registers for a multimodal trip but the payment system for the UAM leg fails to communicate with the terrestrial leg's registration, the trip is aborted, leading to lost revenue and decreased public trust. Shared ontologies are the linchpin of the federated approach, ensuring that when an operator says "available vehicle," every other system understands the exact parameters of that availability.

7. Conclusion

The transition toward Multidimensional Urban Mobility (MUM) represents a necessary evolution in urban logistics, necessitated by the exhaustion of terrestrial 1D and 2D networks. This analysis has demonstrated that a successful deployment depends on a synchronized understanding of the three levels of decision-making: Strategic, Tactical, and Operational.

While the MaaS paradigm provided the necessary foundation for integration, its **user-centric** focus is insufficient for the complexities of a 3D environment. The proposed data-driven framework addresses this by incorporating the requirements of all stakeholders and the multidimensional environment into a cohesive Cyber-Physical Social System.

The success of this framework is predicated on overcoming significant challenges in data management and interoperability. Specifically, the management of real-time, heterogeneous data and the protection of user privacy are non-negotiable requirements. Furthermore, establishing clear levels of interoperability—from data to business—is essential to ensure that diverse mobility solutions can function as a single, cohesive ecosystem. By addressing these factors, urban centers can successfully integrate air and ground transport, creating a sustainable, intelligent mobility future.

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