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Formalizing Sustainable Urban Mobility Management: An Innovative Approach with Digital Twin and Integrated Modeling

Andrea Grotto [1,2,*], Pau Fonseca i Casas [1], Alyona Zubaryeva [2] and Wolfram Sparber [2]

[1] Department of Statistics and Operations Research, Universitat Politècnica de Catalunya (UPC), Campus Nord, C/Jordi Girona 1-3, 08034 Barcelona, Spain
[2] Institute of Renewable Energies, Eurac Research, Viale Druso 1, 39100 Bolzano, Italy; pau@fib.upc.edu (P.F.i.C.); alyona.zubaryeva@eurac.edu (A.Z.); wolfram.sparber@eurac.edu (W.S.)
* Correspondence: andrea.grotto@eurac.edu

Abstract: *Background*: Urban mobility management faces growing challenges that require the analysis and optimization of sustainable solutions. Digital twins (DTs) have emerged as innovative tools for this assessment, but their implementation requires standardized procedures and languages; *Methods*: As part of a broader methodology for continuous DT validation, this study focuses on the conceptual validation phase, presenting a conceptualization approach through formalization using Specification and Description Language (SDL), agnostic to simulation tools. The conceptual validation was achieved through stakeholder engagement in the Bolzano context, producing 41 SDL diagrams that define both elements common to different urban realities and specific local data collection procedures; *Results*: The feasibility of implementing this stakeholder-validated conceptualization was demonstrated using Simulation of Urban MObility (SUMO) for traffic simulation and optimization criteria calculation, and its framework SUMO Activity GenerAtion (SAGA) for generating an Activity-Based Modeling (ABM) mobility demand that can be improved through real sensor data; *Conclusions*: The SDL approach, through its graphical representation (SDL/GR), enables conceptual validation by enhancing stakeholder communication while defining a framework that, while adapting to the monitoring specificities of different urban realities, maintains a common and rigorous structure, independent of the chosen implementation tools and programming languages.

Keywords: urban mobility; digital twin; SDL; formalization; SUMO; SAGA

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1. Introduction

In cities worldwide, effective urban mobility management has become a crucial challenge in the context of growing urbanization [1]. With approximately 55% of the world's population residing in urban areas [2], covering nearly 11% [3] of the Earth's land area, understanding and planning for urban growth becomes increasingly critical. In many high-income countries, such as in Western Europe, the Americas, Australia, Japan, and the Middle East, over 80% of the population resides in urban areas [4].

Transportation systems play a vital role in modern cities, intricately linked with essential services such as healthcare, education, and utilities. Referred to as a 'subsystem' rather than an isolated entity, their efficiency holds paramount importance for the overall functioning of the urban ecosystem. Current challenges, including rising road traffic, highlight the need for sustainable urban transport solutions [5]. Issues such as traffic congestion [6], air pollution [7], and energy consumption [8] are just a few of the problems plaguing modern cities. Embracing technology and forecasting methods becomes essential for effective policy planning in the ever-evolving urban landscape [5].

In response to these challenges, digital twins have emerged as an innovative solution [9]. A DT is a virtual replica of a physical system that enables the simulation, monitoring, and optimization of real-world processes [10]. The primary objective of this research is to formalize the process of creating a DT for urban mobility management. Within the scope of this research, the focus is placed on creating a DT to address the challenges of urban mobility and assess the environmental and socio-economic sustainability of mobility scenarios, promoting the improvement in air quality, mitigating traffic congestion, reducing travel times and optimizing energy consumption. Specifically, we aim to develop a novel approach that expands the scope of the conceptual model to include not only the definition of the system but also the procedures for validating and executing the model.

The process of constructing a DT necessitates the validation of assumptions made by the various stakeholders who will be involved in the process. This validation is not a one-time event, but rather an ongoing process that must be carried out continuously before and once the digital twin is deployed in a production environment. A comprehensive validation and verification process for modeling can be found in [11]. One of the key aspects of this process is Solution Validation. This is a continuous process that must be carried out once the digital twin is used in production. The purpose of Solution Validation is to ensure that the digital twin continues to perform accurately and reliably under changing conditions and over time. It involves regularly checking the digital twin against its physical counterpart and updating the model as necessary to reflect any changes in the physical system. It is also essential to ensure that all stakeholders understand and accept the different assumptions that the models of the digital twin hold. This is because these assumptions can significantly impact the performance and accuracy of the digital twin. Therefore, it is crucial that these assumptions are clearly communicated to all stakeholders and that they are fully understood and accepted. In this regard, stakeholder engagement and communication are key. All stakeholders should be involved in the validation process and should have a clear understanding of the assumptions and limitations of the digital twin model. This will help to ensure that the digital twin is accepted and trusted by all stakeholders, and that it can effectively support decision-making and operational processes.

Moreover, a digital twin is a comprehensive system that typically encompasses several distinct components (see Figure 1). These components include the digital shadows, which encapsulate both synthetic data derived from the models and real-world data often obtained from sensors. The digital twin also includes conceptual models and their respective implementations, aligning with the principles of Industry 4.0 (I40 in Figure 1). The digital shadows serve as a bridge between the physical system and its digital counterpart, embodying a key aspect of I40's cyber–physical systems. They contain synthetic data generated by the models, which simulate the behavior of the physical system under various conditions. Additionally, they also contain real-world data collected from the physical system, often through sensors. This combination of synthetic and real-world data allows the digital twin to accurately represent and predict the behavior of the physical system, often through sensors, reflecting I40's emphasis on data-driven decision-making and interconnectivity. This combination of synthetic and real-world data allows the digital twin to accurately represent and predict the behavior of the physical system, enabling the smart factories and systems central to I40.

Conceptual models form the theoretical foundation of the digital twin, often named Digital Master. They represent abstract concepts and relationships that define the behavior and characteristics of the physical system, incorporating I40 principles such as interoperability and decentralized decision-making [12]. These conceptual models are then implemented in the digital twin, translating the abstract concepts into concrete algorithms and data structures that can simulate the behavior of the physical system.

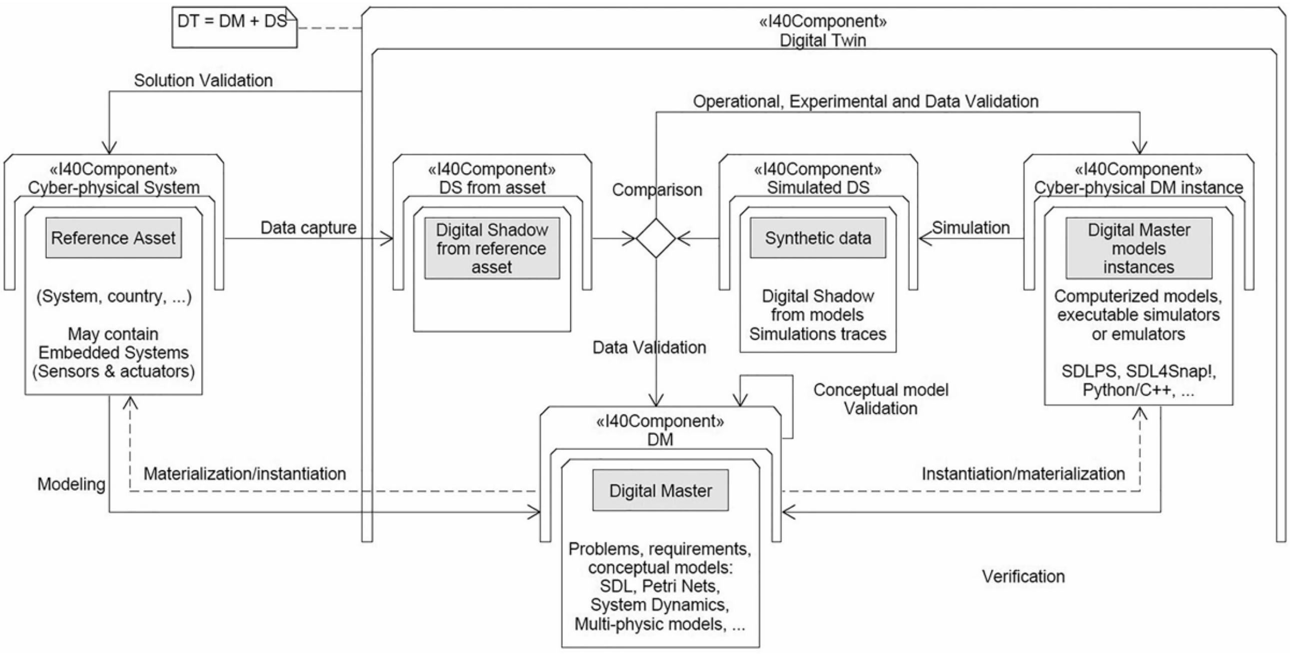

Figure 1. Digital twin architecture, from [13].

However, it is important to note that the validation and experimental aspects of the models are key to the success of the digital twin. Therefore, a primary objective of this research is to propose a novel approach that includes these aspects in the conceptual model. This is a novel approach that expands the scope of the conceptual model to include not only the definition of the system but also the procedures for validating and executing the model. This approach has been similarly proposed in [14], though not for the validation and execution procedures, but for the representation of the models.

With this novel approach, the conceptual model becomes a comprehensive framework that includes the definition of the system, the validation procedures to ensure the accuracy of the model, and the execution procedures to simulate the behavior of the system. The aim is to ensure that the digital twin is not only an accurate representation of the physical system but also a reliable tool for predicting its behavior and supporting decision-making processes.

Specifically for our area of research, we aim to develop a methodology that combines activity-based modeling (ABM), traffic microsimulation, and optimization techniques to achieve these goals. The innovation is based on the use of integration techniques through the SDL language: this research compares data from various sources, including real-time flows from IoT traffic sensors, historical data, and static information (such as schedules of local public transportation), with traffic simulation results generated by SUMO [15]. These simulations are based on an Activity-Based Model (ABM), which, in turn, is generated by SAGA [16], an internal framework within SUMO specialized in creating ABM models from OpenStreetMap files. This comparison leads to a continuous validation process, ensuring constant improvement and alignment of the model with the dynamics of the urban mobility system. In this way, a DT is generated that, in addition to monitoring real-time data, can perform predictive analyses and optimizations for future mobility scenarios.

Structure of This Research

The structure of this research is organized as follows: Section 2 reviews the relevant literature, with a focus on urban environmental modeling and innovative aspects of mobility modeling and formal languages. Section 3 describes the methodology, including the phased approach, data collection, and the sources of data used in this study. Section 4 presents the case study used for testing the proposed framework. Section 5 outlines the results, focusing on the conceptual validation and the implementation of the conceptual model. Section 6 provides a discussion of the findings, including an analysis of the results, limitations, and future research directions. Finally, Section 7 concludes this study by summarizing the key insights and suggesting areas for further investigation.

2. Literature Review

2.1. Urban Environmental Modeling

Urban environmental modeling is a process through which representations or simulations of cities or urban areas are created for the purposes of analysis, planning, design, and evaluation. These models are crucial for understanding the functioning of the city and predicting urban development, assessing the impact of planning and design decisions. They also serve as a testing ground for various urban strategies and policies and can be divided into various categories or subfields, each focusing on specific aspects of the urban ecosystem. Here, are some of the main subdivisions:

1. Land use models focus on representing the distribution and land use within an urban area. They can be used to predict how urban land will change over time, such as identifying areas for residential, commercial, or industrial development [17,18];
2. Transportation models concentrate on urban mobility, studying how people and goods move through a city. They are useful for optimizing public transportation systems, managing traffic congestion, and improving connectivity [19];
3. Environmental impact models assess the impact of human activities on air, water, and soil quality in urban areas. They can help evaluate environmental risks and design mitigation measures [20];
4. Urban resilience models are oriented toward preparing cities for extreme events such as natural disasters or economic crises. They help assess a city's capacity to cope with and recover from such events [21];
5. Urban growth models have been created and widely embraced for examining the growth of cities and its consequences on the surrounding environment. These models find application in urban policy formulation and the analysis of various developmental scenarios;
6. Socio-economic models analyze the economic and social aspects of a city, including factors like employment, income, access to services, and residents' quality of life [22];
7. Visualization models provide visual representations of cities or projects, allowing stakeholders to have a clear view of proposed changes [23].

Urban modeling analysis employs various combinations of the illustrated models. Taking SUMO as an example, it not only models' traffic within the examined city but also facilitates the visualization and calculation of emissions or energy consumption related to different mobility technologies.

2.2. Existing Mobility Modeling and Formal Languages

In this section, the analysis will explore both the mobility model and the specific languages employed to generate a digital twin through a formalism and standardization process. This understanding is critical for the next steps, such as methodology and data collection, as it lays the foundation for the research process. In the field of simulations, several tools have emerged to facilitate modeling and analysis of complex systems:

1. Demand models are used in the fields of transportation to predict and understand the demand for trips between different origins and destinations in a specific geographical area. These models provide a mathematical or statistical representation of the factors influencing travelers' choices, such as demographic characteristics, transportation accessibility, economic conditions, and individual preferences through a synthetic population [24]. The mobility demand can be calculated through two main approaches [25]: the traditional four-step method and Activity-Based Modeling (ABM). The first is a conventional approach and it is divided into four stages: trip generation, trip distribution, mode choice, and traffic assignment. The second is based on the daily activities of individuals and models travelers' behavior [26];

2. Microsimulations models [27] are traffic models that simulate the behavior of each individual vehicle (including the powertrain and the interactions with pedestrians, cyclists, public transport, etc.), which are evaluated at intervals of less than a second. Their journeys through the network are derived from the analysis of their interactions with the road network (lanes, speeds, signage, toll areas, etc.), traffic control systems (like traffic lights), and other vehicles on the network. These models are often used to analyze a small area in detail. Some tools that use microscopic simulations are SUMO [15], PTV Vissim [28], Citilab Cube [29], and TransModeler SE [30];
3. Macrosimulation models [31] deal with the overall traffic flow and consider aggregated variables such as traffic density, average speed, and vehicular flow. They are often used to assess the performance of road networks on a large scale. Traveler demand is analyzed at the flow level (sets of users moving between different origin–destination pairs throughout the environment) on a map-based network. The network has features such as capacity, directional speeds, turning restrictions, and generally, the models operate with cost equilibrium functions. Some tools that use macroscopic simulations are Transmodeler [32], PTV Visum [33], and EMME [34];
4. Traffic assignment models [35] allocate traffic flows to a road network based on traffic conditions, travel costs, and capacity constraints. They are useful for optimizing traffic flow and evaluating the impact of infrastructure changes. Based on the consideration of the temporal dimension, traffic assignment models are classified into three categories: dynamic traffic assignment (DTA), semi-dynamic traffic assignment, and static traffic assignment (STA) models [36]. A tool that uses traffic assignment models is DYNAMEQ [37];
5. Modal choice models [38] focus on individuals' decisions regarding the choice of transportation mode. They consider factors such as travel time, costs, convenience, and personal preferences to predict how people choose to commute. A tool that uses modal choice model is Biogeme [39]. In addition, there are tools such as Adopt [40] that allow for the evaluation of large-scale media choice without considering the road network;
6. Agent-based models [41] represent individual "agents" (vehicles, people) and simulate their behavior based on local rules and interactions. They are particularly useful for studying emerging behaviors and chain effects. Some tools that use agent-based simulations are Matsim [42], and SUMO [15].

Given the digital twin's objective to conduct an energy analysis for seamless integration, for example, with urban energy subsystems, the recent classification of mobility models based on a broader understanding of energy systems is introduced into the literature. In accordance with [43], simulation models of mobility can be categorized in the following manner:

1. Economy-wide energy scenario models are typically used to evaluate costs, energy use, and emissions impacts over broad geographic (national or global) and temporal (decades to centuries) scales under various assumptions about future technology evolution and policy;
2. Accounting and exploratory tools are often used to investigate the implications of "what if?" scenarios on energy use and emissions, typically without explicit representation of the effects of costs or other factors in consumer decision-making. Some tools in this category include representations of all end-use demand sectors, while others focus on specific sectors;
3. Vehicle choice models are typically used to project the evolution of the vehicle stock based on assumptions about consumer preferences and future technology cost and performance;
4. Transportation system simulators are primarily used for detailed analyses of the traffic and energy use implications of local infrastructure projects and policies;

5. Refueling infrastructure models are used to assess optimal network design (station location) and use for the alternative fuel production centers and refueling stations needed to meet specified levels of demand.

In the following section, a literature review of various formalization languages is presented. Formalism must be independent of simulation tools and models, allowing for the execution of analyses to determine relationships among different components comprising the urban mobility demand model. This approach facilitates clear and specific communication of how the integration has occurred, ensuring an understanding of the system.

1. SDL language: The Specification and Description Language (SDL) is an object-oriented formal language used in the field of computer science and engineering and standardized by ITU-T (Comité Consultatif International Télégraphique et Téléphonique) [CCITT]), established in 1968. SDL is primarily employed to model and describe the behavior of complex systems, including those related to communication protocols, distributed systems, and real-time systems. It provides a standardized way to define system components, their interactions, and their states;
2. The Discrete Event System Specification (DEVS) is a formal modeling and simulation language used to describe and analyze discrete-event systems, introduced by Bernard Zeigler in 1976 [44]. DEVS provides a structured framework for modeling complex systems where events occur at distinct points in time and where system states change in response to these events. Key features of DEVS include its ability to model systems with discrete events, concurrency, and hierarchical organization. DEVS models consist of atomic models (representing individual system components) and coupled models (describing the interactions between these components);
3. Petri nets (also known as place/transition nets: PTNs) are a formal mathematical modeling language used to represent and analyze systems with concurrent and distributed processes. PTNs were introduced by Carl Adam Petri in the 1960s [45] and have since found applications in various fields, including manufacturing, discrete event systems and networks, specification, simulation and validation of software. Petri nets consist of two main components: places and transitions. Places are represented as circles, while transitions are represented as rectangles. Tokens, usually depicted as dots, move between places and trigger transitions when certain conditions are met. The interactions between places, transitions, and tokens allow Petri nets to model dynamic and concurrent processes. Petri nets provide an effective approach in modeling dynamic systems, capturing relationships and interactions precisely. Their graphical representation simplifies the understanding of complex systems, offering an integrated environment for formal analysis. The ability to explicitly represent states and events, coupled with their practical applicability in scenarios like real-time control systems, underscores their utility in addressing complex challenges [46].

Innovative Aspects

While many studies have delved into exploring the use of digital twins in urban mobility [47,48], this research in Bolzano introduces an innovative approach focused on two key components: the formalization of the DT creation process and the optimization of mobility technologies through a multicriteria analysis (MCA).

The first innovative element in this research lies in the formalization process, facilitated by the Specification and Description Language (SDL). Formalization transforms intricate concepts into a clear structure, ensuring a comprehensive understanding for stakeholders in the urban mobility system. Additionally, formalization enables the standardization of digital twin creation, ensuring analysis repeatability over time and extending its applicability to other facets like urban utilities, energy systems, education, and health, thereby contributing to the development of a comprehensive urban digital twin.

The second key element of innovation involves the optimization of mobility technologies through a multicriteria analysis. This analysis considers crucial parameters such as air quality, traffic congestion, travel time reduction, and energy consumption. This approach allows for a comprehensive and integrated consideration of all aspects of urban sustainability, leading to tangible improvements in urban mobility management and the quality of life for citizens.

3. Materials and Methods

3.1. Continuous Validation Process

This research adopts a phased methodology for continuously developing and validating a digital twin for urban mobility. The methodology consists of several sequential validation phases, as illustrated in Figure 2, where each phase builds upon the results of the previous one, ensuring a systematic and comprehensive approach to digital twin development.

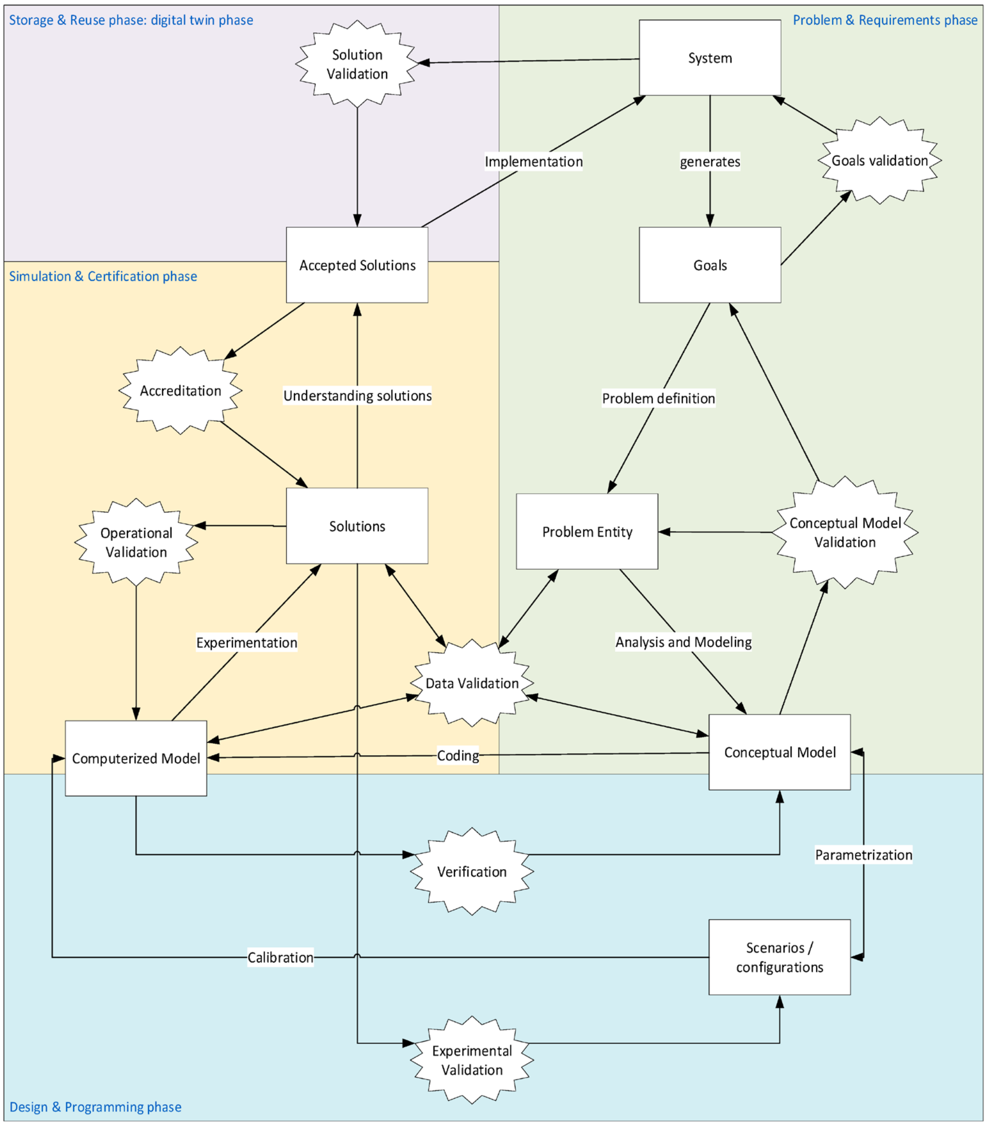

Figure 2. Phased methodology for continuous validation process [11].

The current work focuses on the Conceptual Model Validation, which is part of the Problem and Requirements phase (green part in Figure 2). This phase is crucial as it establishes the theoretical foundation upon which subsequent validations will build. The validation process integrates various components including the Problem Entity (System), Goals, Conceptual Model, Computerized Model, and Solutions, connected through different validation and verification activities in distinct phases (Problem and Requirements, Design and Programming, Simulation and Certification, and Storage and Reuse), as shown in Figure 2:

1. Goals' Validation (carried out): verified the system objectives and requirements, which are typically defined by stakeholders as city managers and mobility planners as part of their strategic planning process;
2. Conceptual Model Validation (current phase): validates the theoretical framework against the real system, ensuring that assumptions, theories, and mathematical representations adequately capture the Problem Entity's characteristics;
3. Computerized Model Verification (future phase): will verify that the computer programming and implementation accurately represent the Conceptual Model's specifications;
4. Operational Validation (future phase): will involve comparing the simulation results with the actual system behavior, ensuring the model's predictions align with real-world observations;
5. Experimental Validation (future phase): To validate the model's results, sound experimental procedures are necessary. This includes verifying the design of experiments, the number of replications, and the methods used to obtain them.
6. Data Validity (continuous process): ensures the quality and appropriateness of data used throughout all validation phases;
7. Solution Validation (future phase): will verify the effectiveness of implemented solutions in production environment, ensuring continuous alignment with real-world conditions;
8. Accreditation (future phase): will establish the formal acceptance of the model for its intended use, certifying its fitness for purpose.

3.2. Data Collection

The authors propose an innovative approach centered around data collection for real-time validation of urban mobility demand calculations. This phase involves a synergistic blend of data sourced from IoT traffic sensors and information integrated from online platforms. The process unfolds in two complementary modalities: utilizing static information such as public transportation schedules and the location of bus stops and leveraging dynamic data from IoT systems embedded in the streets to monitor real-time vehicle flows.

Data collection is facilitated using the Specification and Description Language for Graphical Representation (SDL/GR), detailing the integration process. As a formal language, SDL/GR provides a clear representation of system specifications, enabling efficient communication among different components. Integrating data from various sources becomes a structured and coherent process through SDL/GR, defining specifications and requirements related to data collection. This includes outlining information flows, synchronizing static and dynamic data, and configuring acquisition parameters.

Being a language commonly used in the telecommunications sector, SDL/GR can be successfully extended to the collection of data from signals generated by IoT sensors. In this way, the adoption of SDL/GR, as proposed by the authors, represents a significant step in the strategy to implement a digital twin of urban mobility, becoming a tool for analysis based on real information.

3.3. Source of the Data

As described in the previous paragraph, data are acquired from both static and dynamic perspectives, with each contributing crucial insight. Static data primarily encompass information extracted from online platforms, such as public transportation schedules, forming a fundamental element for assessing baseline mobility demand. On the other hand, dynamic data originate from real-time monitoring systems, including road sensors and embedded IoT devices. These sensors capture and transmit immediate information on vehicular movements, enhancing the understanding of current traffic patterns and mobility trends.

In the case of the Bolzano study, dynamic data are obtained from an open data platform directly connected to traffic sensors. This platform, named Analytics [49], collects traffic data through Bluetooth sensors embedded in the streets and cycling lanes. The sampling frequency is approximately every ten minutes for vehicular traffic and extends to about one hour for bicycles passing through the city's cycling lanes. The flows detected by the sensors do not directly represent actual traffic but instead signify the number of Bluetooth-enabled devices (smartphones) passing over the sensor.

The company managing these devices has validated that these flows account for approximately 15% of the total traffic, with this value continuously rising over time due to an increasing number of people passing over the sensors with Bluetooth enabled.

3.4. Methodology

The methodology is grounded in the process of formalization, facilitated by the structure of SDL/GR (Specification and Description Language/Graphical Representation). This approach concentrates on systematically formalizing various aspects, empowering the implementation of the conceptual model [50]. As specified by [51], the construction of the model sometimes reveals essential lacunae in the understanding of the model before its implementation.

The formalization approach leverages SDL/GR to create a comprehensive and unambiguous representation of the digital twin for urban mobility. This choice was made for these reasons:

1. SDL/GR provides a clear and non-ambiguous representation of system specifications, including both formal elements (such as states, transitions, events, variables, and processes) and a graphical representation that enhances comprehension through diagrams;
2. The visual aspect of SDL/GR promotes effective information exchange among diverse model components, facilitating communication among stakeholders with varying levels of technical expertise;
3. The graphical nature of SDL/GR enhances the clarity and accessibility of the specified system, making it an asset in the design and communication of complex systems in urban mobility applications;

The use of SDL/GR specifically enhances data communication and synchronization in the digital twin through its signal-based architecture. SDL treats different data streams as signals with varying priorities, enabling:

1. Dynamic triggering of specific model components or procedures when signals (data) arrive from different sources;
2. Prioritized handling of different data streams (sensors, historical data, static information);
3. Automated synchronization of model components based on signal reception and processing.

The methodology integrates various tools and techniques within the SDL/GR framework:

1. A traffic simulator for urban vehicular flow micro-simulation;
2. A trip generator for creating Activity-Based Models (ABMs) from OSM (Open Street Map);
3. IoT traffic sensors for real-time data collection;
4. Historical data and static information (such as public transportation schedules) for comprehensive model development.

This integration of diverse tools within the SDL/GR framework allows for a comprehensive and flexible representation of the urban mobility system. The specific details of the implementation, including the tools used, will be described in Section 5.2.

The formalization process in the methodology follows these steps:

1. Initial system analysis and requirement gathering;
2. Development of high-level SDL/GR diagrams representing the overall system structure;
3. Detailed modeling of individual components and their interactions;
4. Integration of various data sources and simulation tools within the SDL/GR framework;

5. Iterative refinement based on stakeholder feedback and validation results.

The agnostic approach in the formalization phase enables greater adaptability of the model to different urban and technological realities, ensuring that the framework remains valid regardless of the specific tools used in the implementation.

Formalization not only provides guidance for implementing the conceptual model but also creates a tangible outcome in the form of formalized documentation. This documentation can be considered a product itself because it comprehensively represents the structure and behavior of the simulations system [52]. In other words, the formalization itself, using a language like SDL/GR, becomes an output that can be shared, understood, and utilized by the stakeholders involved in the urban mobility project.

The approach goes beyond traditional modeling by incorporating validation procedures directly into the conceptual model. This novel aspect ensures that the digital twin remains accurate and reliable throughout its lifecycle, adapting to changing urban conditions.

As mentioned in Section 2.2, the history of SDL dates to the mid-1970s when it was developed under the ITU's guidance, a specialized agency of the United Nations [53] dealing with telecommunications and information technologies. SDL underwent a standardization process, resulting in its formalization as Z.100 in the 1980s. Since then, it has evolved to meet the changing needs many times the applications of telecommunications, distributed systems, and embedded systems. The language is currently described in ITU-T Recommendations Z.100–Z.109, playing a crucial role in specifying and describing complex systems in various sectors.

Before delving into the application of urban mobility demand, let us provide a sequential overview of the SDL language. SDL is composed of two distinct components: a static part and a dynamic part. The static aspect focuses on outlining the system's structure by defining stable elements such as states, transitions, and variables. In contrast, the dynamic facet models the system's behavior, encompassing events, processes, and dynamic interactions among static elements. This dual nature enables SDL to offer a comprehensive and well-defined perspective for specifying and describing intricate systems. Communication among components is facilitated through signals and communication channels. In summary, SDL can be categorized into three fundamental parts: structure, behavior, and communication.

In SDL, agents represent entities within the system that have a defined role or responsibility. These entities could be components, subsystems, or other functional units that play specific roles in the overall system architecture. The structure of SDL involves defining and organizing these agents, along with specifying their interactions and relationships. In SDL, designating the system as a top-level agent underscores its central role, representing the highest organizational entity that encompasses various components. It is crucial to note that the system, as a top-level agent, contains everything within its scope but cannot be contained by any other entity. Outside the system, there is the environment, which may or may not communicate with the system. In this sense, we can say that the environment is a bottom-level agent since it cannot contain other blocks or processes.

In Figure 3, there is a depiction of the urban mobility system and its communication channels with the external environment. The system is represented by a rectangle, while the input and output channels are depicted with arrows. Signal names are enclosed in square brackets. Specifically:

- [Technologies] indicates the types of mobility technology to be integrated into various scenarios;
- [Optimiz_tech] represents the quantification of technologies through optimization;
- [Real_Flow] shows traffic flows monitored by sensors;
- [FirstPop] contains information about the characteristics of individuals;
- [OSM] indicates an OpenStreetMap file for simulations;
- [GTFS] provides public transport schedules.

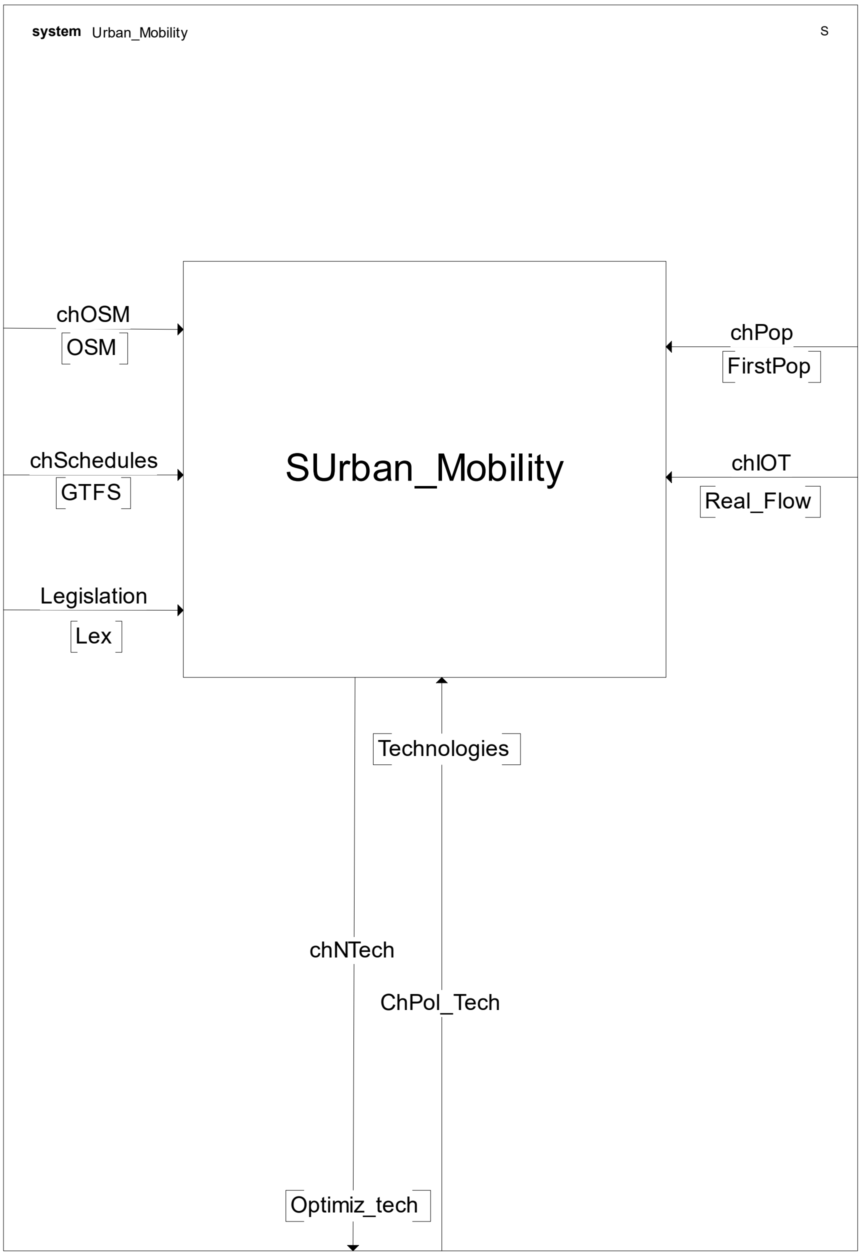

Figure 3. Urban mobility system.

Upon entering the system, a division into blocks is represented in Figure 4, representing different modules. These modules include the mobility demand model and the block dedicated to the optimization process. This optimization involves quantifying selected technologies for different scenarios based on a specific objective function. The objective function considers results obtained in the simulation block in terms of emissions, traffic, and energy consumption.

As evident from Figure 2, there are five blocks:

- Bmap_Net: This block involves representing the network on a discrete basis with nodes V (1, 2, 3, 4, . . .) and arcs N (2-3, 3-2, . . .), reflecting the physical structure of the network. The network encompasses various elements such as roads, bike lanes, railways, and traffic flow influencers like traffic lights, intersections, and road signs. Each node in this network is treated as an agent capable of generating (node 1-2) and/or regulating traffic flow. Additionally, each connection is assigned a weight corresponding to the imposed speed limit, a characteristic typical of discrete networks. The data are sourced from OpenStreetMap. Furthermore, this block is responsible for extracting points of interest on the map, subsequently passed to the activity block to evaluate the attractiveness of different areas of the city. This assessment aids in quantifying the flows between these areas;

- BPop_ABM: This block generates activities classified as primary, secondary, and home activities based on population characteristics such as population size and information received from the map block regarding the attractiveness of different areas of the city. Consequently, the city is divided into multiple areas, and an origin–destination matrix is generated. Using this matrix, trips are assigned to activities in space and time. These activity data are then provided to the simulator, which determines the most suitable routes to connect the various activities, thus generating the routes that each city inhabitant will take. Additionally, it creates a simplified synthetic population of street users who undertake various journeys within the city. Everyone in this population can be considered an agent, and the resulting model is referred to as Activity-Based Modeling (ABM);
- BTraff_Sim: In this block, routing, mode choice modeling, and traffic simulation operations are integrated. Routing involves selecting the most optimal path for each vehicle, while mode choice modeling models individuals' decision-making behaviors using a utility function to optimize their selections from multiple options. Subsequently, traffic simulation through microsimulation models simulates individual vehicles and their movements within a road system over a 24 h period. Each vehicle (or agent) is represented as an individual entity, considering specific behaviors such as acceleration, deceleration, lane changing, and interaction with other vehicles. Additionally, this simulation evaluates emissions, energy consumption, and traffic dynamics;
- BComp_Val: This block contributes to validating mobility demand before quantifying the different technologies associated with various scenarios. Routing involves selecting the most optimal path for each vehicle, while mode choice analysis models individuals' decision-making behaviors using a utility function to optimize their selections from multiple options. As depicted in Figure 4, a comparison is made between the actual monitored data of traffic flow and the results obtained from simulations. Real-time validation is essential, enhancing the overall accuracy and reliability of the digital twin. It offers several benefits, including the timely detection of problems and anomalies, ensuring the digital twin remains aligned with changes and updates in the mobility system, and supporting real-time decision-making;
- BSc: This block systematically adjusts the experimental factors for technologies within each scenario. Its role encompasses creating technology scenarios, with some of these technologies being quantified and optimized based on an objective function considering simulation results in terms of emissions, energy consumption, and traffic outcomes. The aim is to provide qualitative scenarios that can be quantified and optimized based on various criteria, such as emissions reduction, cost-effectiveness, energy efficiency, and traffic flow optimization, thereby facilitating informed decision-making.

In this article, not all graphs are presented. However, for illustrative purposes, the graph related to the modeling of transport infrastructures is included as an example. Entering the BPop_ABM block, the corresponding processes, channels and signals are shown (Figure 5).

Entering the processes PBuilding, P_Weight_TAZ, PDef_TAZ, POD_Matrix, PActivity_Gen SDL is utilized to explicitly outline the various phases involved in obtaining the activities for conducting simulations.

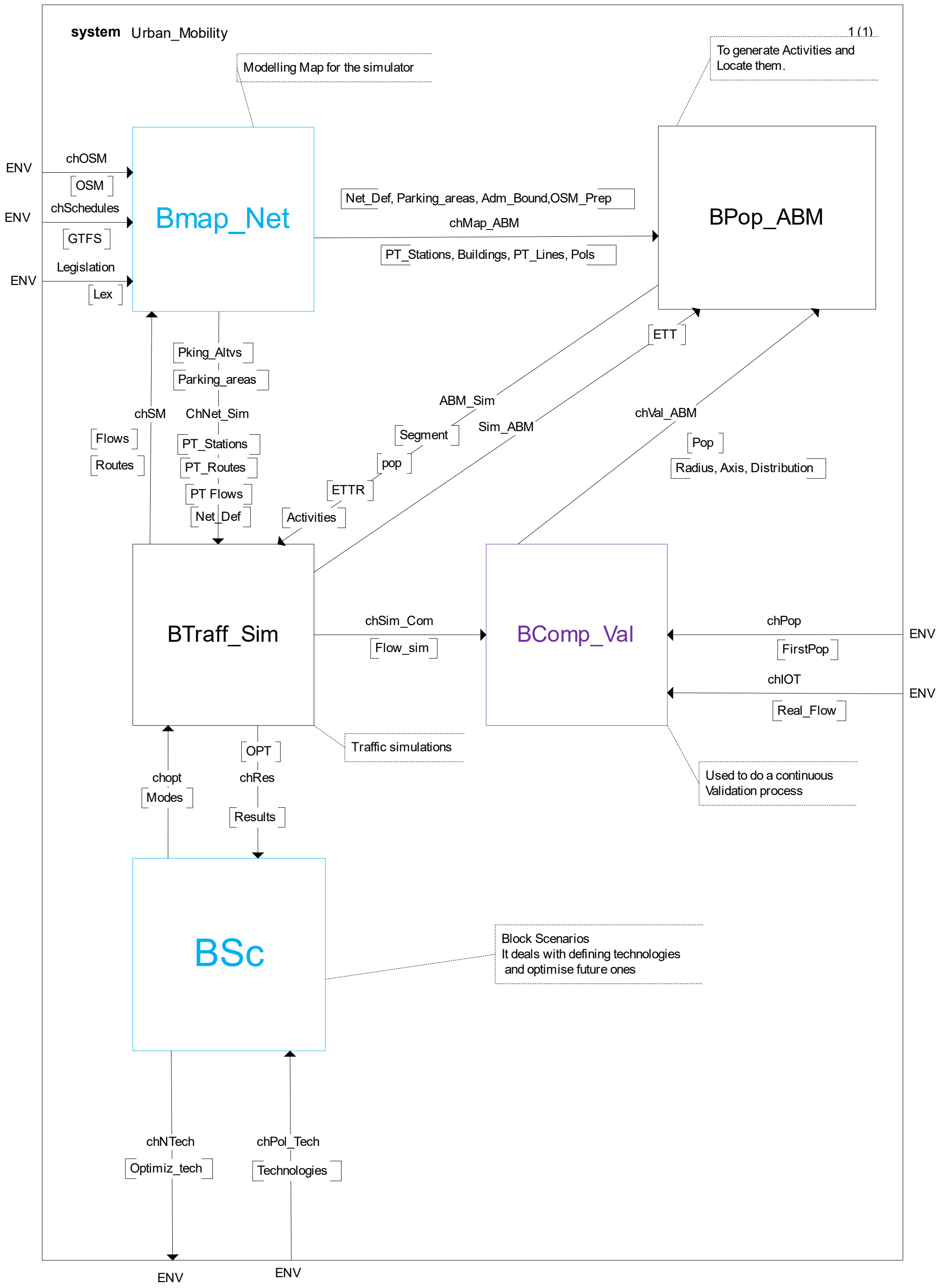

Figure 4. Inside an urban mobility system.

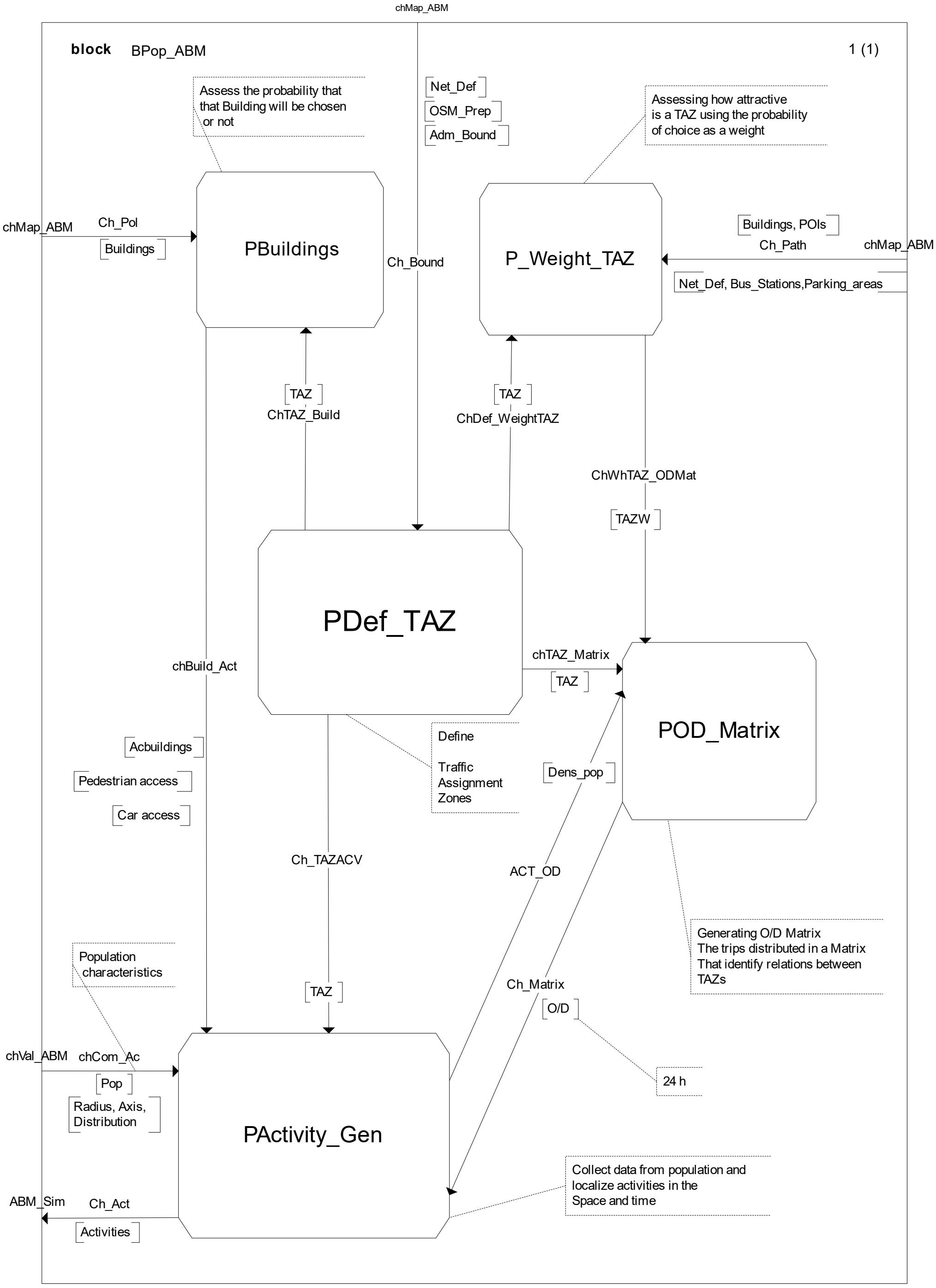

Figure 5. Block BPop_ABM.

4. Case Study

To demonstrate how the formalized process can be applied in a real urban context, this study focuses on the city of Bolzano. Located in northern Italy, Bolzano represents an interesting case study for several reasons. First, its size (106,107 inhabitants, 52.34 square kilometers) is representative of many medium-sized European cities. Second, the city demonstrates a strong commitment to sustainable mobility through its extensive transportation infrastructure, including 269.3 km of roads, 70.7 km of bike paths, and an innovative public transport system operating 115 buses (70 electric/hybrid and 12 hydrogen-powered).

Following the digital twin blocks structure presented in Section 3.3 of the methodology, the formalization process has been applied as follows:

1. Bmap_Net block: formalization of road networks structure, exemplified by elements such as public transport lines (14 lines, 348 stops) and limited traffic zones (351,715 square meters);
2. BPop_ABM block: formalization of mobility behavior patterns, characterized in Bolzano's case by specific modal splits (29% walking, 26% cycling, 10% public transport, 29% cars, 5% motorcycles/other);
3. BTraff_Sim block: formalization of traffic dynamics elements, including geographical features (valley location, confluence of Isarco, Sarentino, and Adige rivers), infrastructure (A22 motorway), and public transport usage (8,327,107 annual passengers);
4. BSc block: formalization of future scenarios focused on sustainable transport modes, exemplified through planned expansions of electric/hydrogen fleet and bike paths;
5. BComp_Val block: formalization of the validation process structure, implemented using data streams from the Analytics Open Data Hub and Bluetooth sensors on major roads and bicycle lanes.

The data above were provided by [54]. As described in Sections 3.2 and 3.3, the city monitors traffic flows on major roads and bicycle lanes through the open platform Analytics Open Data Hub. This platform can visualize the Bluetooth sensors present in the city (the simulation system) and those in the surrounding areas.

5. Results

The presented work focuses on the conceptual formalization of the urban mobility DT, using SDL as formal language and validating an ABM model, with a case study in Bolzano. This approach is extendable to other urban contexts where mobile phone data for activity tracking are limited and in situations where a DT based on road sensors is crucial for validating simulation results.

5.1. Conceptual Validation

Constructing a DT requires effective collaboration among stakeholders involved in the process. Validation, as specified in the introduction, is not an isolated event but a continuous process that must be carried out before and after the implementation of the DT in the operational environment. Unlike verification, which focuses on the correctness of the model and its software, ensuring they are built and function properly, validation aims to ensure that the model accurately reflects the observed reality. The combination of continuous validation and verification is crucial to ensure that the DT is accurate, reliable, and useful for making informed decisions and supporting operational processes. This article deals only with validation and not verification, which will be addressed separately in a subsequent analysis. Urban Resilience SL [55] (UR) has taken on the role of validating the assumptions of the DT conceptual model, collaborating closely with local authorities and other public and private stakeholders. Their involvement has ensured the validity and acceptance of the model assumptions, which are articulated through SDL diagrams. UR's specific interest lies in the deployment of SUMOSU charging stations. This infrastructure is designed not only as a charging point for electric vehicles but also as a comprehensive hub for urban mobility services, supporting the needs of electric buses, private electric vehicles, shared electric vehicles, and e-taxis.

For example, through the analysis of the SDL/GR model, UR was able to understand that the digital twin could perform energy-related calculations and emissions evaluations. This realization led UR to recognize that the model could be used to assess the impact of their SUMOSU charging stations on the wider urban environment. Specifically, UR could use the model to:

1. Evaluate the energy demand of the charging stations;
2. Estimate potential reductions in emissions due to increased use of electric vehicles;
3. Analyze the effects on traffic flow in the areas surrounding the charging stations.

This comprehensive understanding would not have been possible by simply reviewing code or running an isolated simulation. The SDL/GR model provided UR with a visual and interconnected representation of the urban mobility system, allowing them to see how their charging stations fit into the larger picture of urban transportation and energy use.

This integration aims to bridge the gap between public and private mobility sectors through inter-modality, making the hub a space for exchange. Given the diversity of users involved, it is crucial for UR to collaborate with various stakeholders, both public and private, to ensure the success and efficiency of these hub operations.

The use of the DT conceptualized model, as formalized in this article, can effectively assess the impact that an infrastructure can have on an urban level through the Scenario Block (BSc) and the Simulation Block (BTraff_Sim), as shown in Figure 4. However, to ensure that the model is accurate and meets the diverse needs and competencies of stakeholders, it is essential that the underlying assumptions of the conceptual model are validated by all involved parties, each with different interests and expertise.

The SDL diagrams, which provide a visual approach, facilitated explicit representation of the diverse logical relationships and assumptions within the model while also promoting communication among all stakeholders. For example, a public administration might be particularly interested in assessing the infrastructure's impact in terms of traffic and pollution. Conversely, a public transport company might focus more on reducing operational costs or optimizing fleet management. However, there are common assumptions regarding public transport management that can unite both stakeholders. A hypothesis could be, for example, that both stakeholders could validate that local citizens will adopt electric public transportation at a behavioral level in block BPop_ABM.

The formalization led to the creation of 41 diagrams, divided into 16 processes and 5 blocks, highlighting a combination of procedural and model-related aspects. During the development of SDL diagrams for urban mobility modeling, a significant distinction emerged between procedural and model-related components. In particular, the Bmap_Net and Bsc blocks, highlighted in light blue (as shown in Figure 4), exhibit a combination of both features. The highlighted blocks, Bmap_Net and Bsc, show this fusion of procedural and model-related aspects. Within these blocks, SDL diagrams are outlined with partial coloring: those in black refer to the pure model, while those in light blue indicate procedural aspects. In Figure 4, the Bcom_val diagram responsible for the validation of the DT is also colored in purple. In this case, it is intended to explicitly state that this block is aimed at improving the model but does not represent the actual model itself. In addition, once the SUMOSU station is implemented, it could provide real-time data from their monitoring devices to the DT necessary for the Solution Validation described in the introduction. Solution Validation is essential for verifying the effectiveness of proposed or implemented solutions in achieving their goals, meeting the needs of end users, and addressing identified challenges.

In contrast, Experimental Validation occurs before the implementation of new infrastructure, using, for example, existing data from road sensors to test and refine the DT conceptual model. This step ensures that the initial assumptions and predictions are accurate and reliable based on historical data. The BComp_Val block performs experimental validation by comparing real data from road sensors with simulated data and improving the ABM Block by modifying some parameters.

Since Solution Validation is the final step in the validation cycle, the real-time data from SUMOSU enable continuous validation, which is an essential ongoing process once the DT is operational. This validation process verifies that the DT remains accurate and reliable over time, adapting to changing conditions in the physical system. By regularly comparing the DT's simulations with real-world data from SUMOSU, stakeholders can assess performance metrics such as traffic flow, energy consumption, and environmental impact based on increasingly accurate forecasts owing to continuous interaction with the real world.

5.2. Implementation Tools: Identification and Initial Testing

SUMO and its SAGA framework have been identified as key tools for implementing the conceptualization developed with SDL, representing the component Digital Master models instances, as illustrated in Figure 1. These tools have been tested only to verify their basic capabilities in line with our conceptual model requirements. This testing phase represents an initial verification of their suitability, while the actual implementation of a digital twin, which requires continuous validation through real-time data integration and repeated simulations, has not yet been performed and remains for future development phases.

SUMO can assess emissions, energy consumption, and traffic effects in detail through microscopic simulation (as conceptualized in block BTraff_Sim), providing a criterion for the block BSc, where the different technologies identified qualitatively in each scenario are quantified. SAGA, on the other hand, can implement ABM represented by the block BPop_ABM using information extracted from the map generated as explicated in block Bmap_Net, thus enriching the understanding and predictive capacity of the DT. This integration combines SUMO's microscopic simulation capabilities, which calculate emissions and energy consumption using the Handbook of Emission Factors [56], with SAGA's ability to generate trips based on real traffic volume data. This complementary approach enhances the digital twin's predictive capabilities: SUMO provides accurate environmental impact calculations at the individual vehicle level, while SAGA ensures that the simulated mobility patterns reflect real-world traffic conditions.

Such data are synthetic, meaning activities and trips are created in the BPop_ABM and have not been collected, as described previously, from mobile phones.

Owing to its ability to simulate the behavior of individual vehicles and agents on the road based on social parameters, SUMO allows for a detailed representation of traffic flow in an urban context. This approach enables a more nuanced understanding of mobility patterns influenced by social factors.

As evident in Figure 6, the visualization output of the SUMO-SAGA simulation captures the road network of Bolzano, including major arteries and secondary roads as in the block Bmap_Net. The trips of individuals are evaluated based on the activities they perform, which have been calculated using data from Open Street Map (see block BPop_ABM. The distribution of the several vehicles (colored rectangles) across the city provides insight into traffic flow patterns, potential congestion areas, and the impact of the city's topography on mobility. This visualization not only demonstrates the practical implementation of the conceptual model but also serves as a tool for urban planners and policymakers to assess real-time traffic conditions, analyze road congestion, and identify critical points in the city's transportation network.

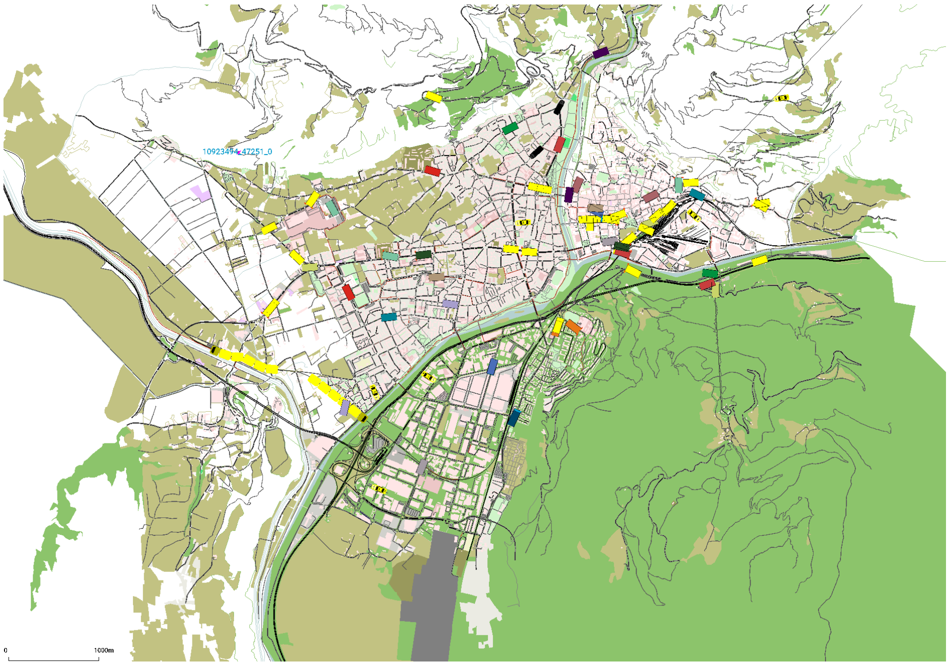

Figure 6. Bolzano's urban mobility visualization through SUMO-SAGA implementation.

To further test SUMO's capabilities in line with the conceptual model, the authors conducted additional tests on a smaller scale. Specifically, SUMO was applied to a particular scenario in a small neighborhood of Bolzano (Figure 7) to assess its ability to calculate energy consumption and emissions (block BSc).

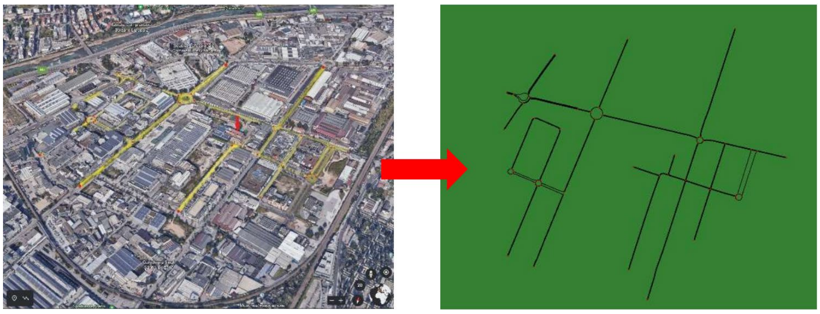

Figure 7. Road network discretization form OSM to test SUMO in a Bolzano district.

On this network, the authors simulated two basic scenarios to demonstrate SUMO's capabilities in analyzing different vehicle types. The first scenario involved a traditional internal combustion bus, while the second featured an electric vehicle. These simple, contrasting scenarios were chosen to illustrate SUMO's ability to model and compare different propulsion technologies.

As shown in Figures 8 and 9, the following charts present the results of these simulations, showcasing key performance metrics for each bus type:

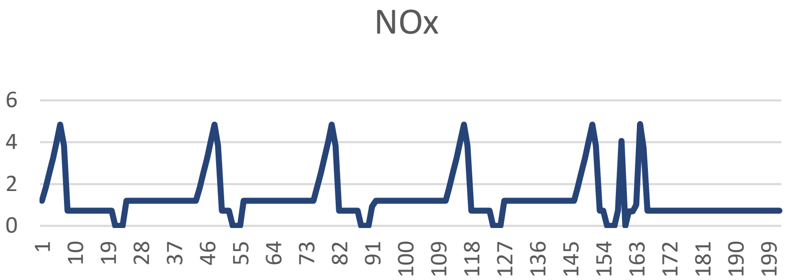

Figure 8. Bus NOx emissions (mg/s) over time (s).

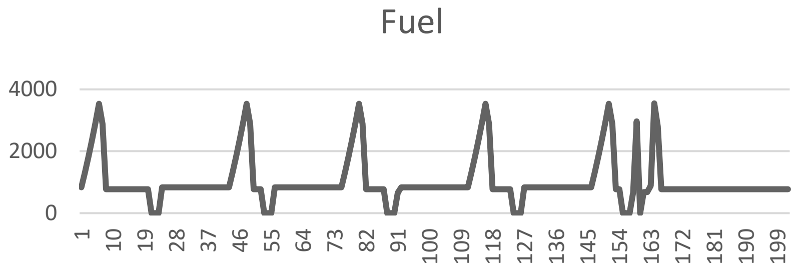

Figure 9. Bus fuel consumption (mg/s) over time (s).

It is important to note that these charts represent instantaneous values from microscopic simulations, capturing moment-to-moment variations in vehicle performance. To optimize different technologies (as conceptualized in BSc) and assess their overall impact, it is necessary to integrate these curves over time and aggregate the contributions from multiple vehicles. Figure 10 demonstrates SUMO's capability to model complex aspects of electric mobility, specifically showcasing an electric car's energy consumption pattern. The graph's positive values indicate power consumption during acceleration and cruising, while the negative values represent regenerative braking (the electric motor acts as a generator to recharge the battery during deceleration).

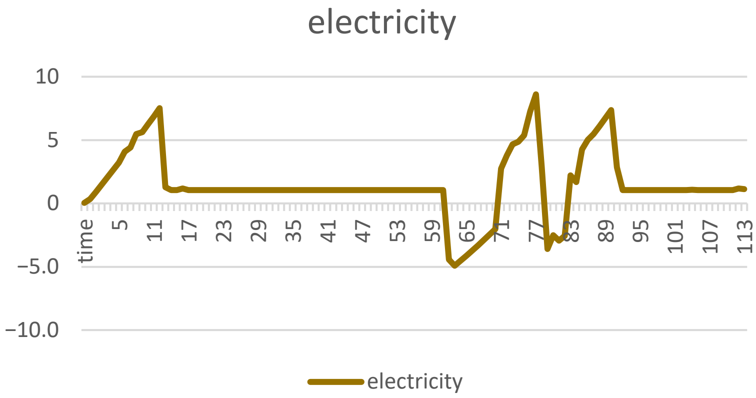

Figure 10. Electricity consumption (kW) of electric vehicle over time (s).

The comparison of real traffic data with simulated and synthetic data—crucial for refining the mobility demand generated in the BPop_ABM block—is handled within the BComp_Val block. Unlike SUMO and SAGA, which focus on specific aspects of simulation and modeling, BComp_Val is responsible for the integration and evaluation of real-time traffic conditions and simulated scenarios. This comprehensive assessment enables iterative refinement of the mobility demand model, a process beyond the capabilities of SUMO and SAGA alone.

6. Discussion

6.1. Analysis of Results and Strengths

The outcomes of this study derive from the formalization of the process of constructing a DT for urban mobility, with Bolzano as a case study. As demonstrated through the 41 SDL diagrams presented in Section 3.4, and particularly evident in the formalization of the validation process (Figure 3), the success of this approach is based on the use of the language SDL, which standardizes the DT through appropriate graphical symbols, making the process clear and independent of the simulation tools used. This standardization, following the principles established by [51], and demonstrated in our case study through stakeholder engagement (Section 5.1), facilitates understanding and communication among the involved parties, as described in the previous chapter.

Although SUMO and SAGA demonstrate capabilities in simulating urban mobility and calculating emissions and energy consumption, as shown in Section 5.2, it is important to note that they implement an Activity-Based Modeling approach but do not constitute a true DT. As defined in Section 3.1, a true DT requires real data to continuously improve simulations through an ongoing validation process. In line with this requirement, the proposed DT relies on real data from traffic sensors to continuously improve and update the activity model. This continuous improvement process, formalized in the model through the BComp_Val block (Section 3.4), constitutes a key difference from traditional simulation approaches. These relationships, which constitute a process of continuous improvement or ongoing validation, are explicitly detailed in the conceptual model but are not directly implemented by SUMO and SAGA. This requires the repeated use of the SUMO simulator and thus the ability to use it multiple times to compare real data with simulated data. Based on this distinction between traditional simulation tools and true DTs (Section 2), a crucial element in bridging this gap and enabling true DT functionality is TraCI (Traffic Control Interface for SUMO). TraCI uses a TCP-based client/server architecture to provide access to SUMO, allowing for dynamic interaction with the simulator. As demonstrated in our implementation (Section 5.2), this interface enables the integration of real data into the simulation process and continuous validation of the model, thus improving responsiveness while maintaining the standardization provided by SDL.

The approach presented in this study offers several key strengths that set it apart from traditional urban mobility modeling techniques:

1. Real-time integration: Unlike conventional simulation tools, as evidenced by Section 3.4, the method continuously incorporates live data from traffic sensors and other sources. This real-time integration enables a true digital twin representation of the urban environment, allowing the model to accurately reflect current conditions and adapt to changes as they occur;
2. Flexibility and adaptability: As shown by Section 3.4, the approach offers remarkable responsiveness to changing urban conditions through its SDL-based formalization. The modular structure of SDL diagrams enables the integration with other digital twins (such as weather monitoring systems) and allows for the expansion of the model through new blocks and processes to analyze specific phenomena. This adaptability makes it possible to study less frequent events, such as traffic congestion due to accidents or behavioral changes during adverse weather conditions, by capturing real data when these events occur. While SUMO and TraCI serve as implementation tools, it is the extensible nature of the SDL formalization that provides the true flexibility, allowing the model to evolve and incorporate new components as needed in the ever-changing landscape of urban mobility;
3. Balanced standardization and dynamism: Following established digital twin principles process [11], the approach strikes a careful balance between structure and flexibility. On the one hand, the use of SDL provides a standardized framework for representing the digital twin, ensuring consistency and clarity in the model's structure. On the other hand, the dynamic interactions enabled by the operational validation (Section 3.1) that reside in the block BComp_Val (Section 3.4) allow for real-time adjustments and updates. This combination creates a robust yet flexible approach to urban mobility modeling, capable of maintaining a standardized structure while adapting to the dynamic nature of urban traffic systems. The present study leverages TraCI to enable a dynamic interaction between real-world traffic data and the simulated environment. This feedback mechanism, as shown in Figure 5, demonstrates that as new data are collected from traffic sensors and other sources, these can be incorporated into the ongoing simulation, helping to keep the model current. As highlighted in recent DT research [57], this updating process aligns with the concept of a digital twin, as it allows the virtual representation to evolve alongside the physical system it represents.

6.2. Technical Limitations and Challenges

Despite its strengths, the approach presented in this study faces limitations and challenges that warrant consideration:

1. Computational intensity: As evidenced in the block BSc (see Supplementary Materials), the method's reliance on continuous validation through repeated use of SUMO simulations could present a significant computational challenge. While this aspect will be fully assessed during the implementation phase, considering that this computational intensity would apply even to a medium-sized city like Bolzano, this process may require substantial computing resources, potentially limiting the model's scalability or real-time performance in larger urban settings or when dealing with more complex scenarios;
2. Data dependency: Consistent with findings from other urban digital twin studies [58], while the integration of real-time sensor data is a key strength, it also introduces a notable dependency. The approach's effectiveness is closely tied to the availability and quality of real-time data from traffic sensors and other urban monitoring systems. This dependency may limit the model's applicability in areas with less developed data infrastructure or in cities where comprehensive sensor networks are not yet in place;
3. Potential for expanded use of synthetic data: As explained in Section 3.4, the digital twin uses only synthetic traffic volume data to compare with real data. In the future, this setup will allow for operational validation during implementation. Additionally, given the presence of air quality sensors in Bolzano, these data could also be used

to achieve a more comprehensive operational validation. Both synthetic and real traffic volume data are generated by the simulator, though other synthetic data from different simulators could also be integrated to assess extreme traffic conditions, such as catastrophic natural events [59].

6.3. Study Limitations

In addition to these technical challenges, this study presents broader limitations that warrant acknowledgment:

1. Focus on conceptual validation: This study focuses specifically on the conceptual validation of the digital twin formalization process. Other forms of validation, such as operational validation and technical implementation validation, will be addressed in subsequent studies;
2. Single urban context: The formalization process has been developed considering Bolzano's characteristics. Its applicability to cities with different scales, mobility patterns, and infrastructure will be investigated in future validations;
3. Stakeholder scope: The current validation process involved a specific set of stakeholders (Section 5.2) in the Bolzano context. Future validation phases will need to consider different stakeholder groups and institutional frameworks;
4. Validation process scope: while this study establishes the foundation for Digital Twin formalization, additional validation aspects including economic feasibility and organizational integration will be explored in future research;
5. Mobility patterns influenced by social factors (Block BComp_Val): The synthetic population's activities in the model are limited to primary, secondary, and domestic categories, lacking differentiation for specific types like shopping or business. This reduces the model's precision in capturing true mobility patterns. Furthermore, journeys rely on polylines from Open Street Map (OSM), which connect to building areas. While this avoids using mobile phone data, the assumption that travel volume correlates with building area may lead to inaccuracies, especially in urban environments with many skyscrapers.

6.4. Future Research Directions

Building on the validation framework presented in Section 3.1, future research will address the subsequent phases of the validation process. While this study has focused on the Conceptual Model Validation phase, the next steps will involve the Computerized Model Verification and Operational Validation phases. These phases will include the development and verification of computer implementation to ensure it accurately represents the formalized conceptual model, followed by validation of the digital twin in a real urban environment. This progression will also concentrate on enhancing the continuous data validation processes, focusing on real-time data integration and quality assurance. Moreover, the measurements of environmental impacts, such as NOx emissions and fuel consumption, will be extended to consider seasonal variations (summer/winter), providing a more comprehensive understanding of how temporal factors affect urban mobility patterns and environmental impacts. Through these validation phases, we aim to address the technical and methodological challenges identified in this study, working towards the development of a fully operational DT for urban mobility management.

7. Conclusions

This research has focused on the conceptual validation phase of developing a DT for urban mobility. Through SDL formalization, we have established a theoretical framework that has been validated with stakeholders, particularly Urban Resilience, ensuring that our assumptions and theoretical representations adequately capture the characteristics of the urban mobility system.

While identifying SUMO and SAGA as potential implementation tools, this study has primarily focused on validating the conceptual model structure and relationships.

Initial tests with these tools in Bolzano have demonstrated their basic capabilities, but their actual implementation as part of a Digital Twin—which requires continuous validation and real-time data integration—remains for future phases.

The SDL formalization has also identified TraCI as a key component for future implementation, as its architecture aligns with the conceptual model's requirements for enabling real-time data integration and continuous validation. However, this integration, like the actual implementation of continuous simulation and validation processes, is a part of future development phases.

While the conceptual validation has proven effective with a moderately sized city like Bolzano, the integration of digital twins into broader urban systems can enhance the overall efficiency and sustainability of urban management. The technologies considered in this study primarily focus on replacing traditional technologies, such as cars, with alternative technologies. However, technologies like connectivity and intramodality have not been considered. Future research should aim to include these technologies to obtain a more comprehensive and integrated view of urban mobility.

Future research should also aim to extend the SDL-based formalization process to encompass a more extensive range of urban services, ensuring that the digital twin framework remains scalable and adaptable to different city sizes and configurations. By focusing on a holistic approach to urban planning and management, the potential benefits of digital twins can be fully realized, contributing to smarter, more resilient, and sustainable urban environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/logistics8040117/s1, This supplementary material contains SDL (Specification and Description Language) diagrams formalizing the concept of the digital twin. These diagrams provide a graphical representation of the structure and interactions of the digital twin, offering a detailed overview of its functioning and features. Figures 3–5 in the main text are derived from it.

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