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Digital Twins Facing the Complexity of the City: Some Critical Remarks

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Abstract: The concept of a digital twin (DT), rooted in mid-20th-century ideas, has recently gained significant traction even outside software simulation and engineering modeling. The recent advancements in computational power and the development of model integration methodologies have enabled the creation of virtual replicas of complex physical objects. The success of DTs in engineering has also pushed for the exploration of their use in other domains, especially where complex systems are at stake. One of these cases, which is the focus of this paper, is the modeling of cities and the way they are transformed via technologies into so-called smart cities. In these systems, the huge amount of data that are made accessible and constantly updated via sensor networks suggests that one can use DTs dedicated to the urban scenario as data-driven decision-making devices. However, the concept of a DT was not developed for socio-technical systems and requires careful analysis when applied to urban scenarios. While technologies and information systems have become integrated into city management, this has not reduced the complexity of the city. Relying only on sensory data for city modeling and management seems pretentious since detectable data (what is made accessible via sensor networks) do not seem suitable to inform on all important aspects of the city. Urban DTs hold promise, yet their development necessitates careful consideration of both opportunities and limitations. For this goal, it can be helpful to exploit an ontological analysis due to its neutral and systematic approach and to look at a city as a system of intertwined relationships across its components, such as places, agents, and knowledge. The variety of interactions that the components manifest highlights aspects of the city that the type of data we can collect today leaves unexplored. The paper presents a preliminary example of this issue by studying cases of city squares. The final part of this paper is a call to analyze DTs' potential role in urban contexts and become aware of the intrinsic limitations of the data they rely upon.

Keywords: city planning; digital twin; ontology; ontological analysis; decision-making

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1. Introduction

Over the past decade, artificial intelligence (AI) has made significant strides, leading to increasingly successful applications [1–3]. This progress has sparked a growing interest in the potential for managing and representing knowledge in complex systems such as cities, and more broadly, in territorial and environmental planning and management. In this domain, our group's research line explores the potentialities at the intersection of AI and applied ontology. Ontologies have been developed since the late 1990s to overcome data interoperability problems and make explicit the world model underlying data acquisition [4]. Today, ontology is called to provide a formal and principled structured framework for

knowledge representation, enabling clear communication and information sharing within and even across domains. By integrating the ontological approach into AI methodologies, we aim to enhance the capabilities and interpretability of AI systems. In this way, they can be particularly effective for disambiguation and knowledge sharing among different agents (both human and non-human), transcending the nuances of natural and technical languages. Ontology plays a crucial role in facilitating interactions between humans and machines by explicitly identifying the involved types of entities, their characteristics, and the connections among them, including how they change over time, which are essential elements for operating a system in real time. In this study, we work within the framework of the foundational ontology called DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering), developed as part of the European project WonderWeb [5–9].

Given the exploratory nature of this study, we adopt a conceptual and ontological analysis approach, rather than a structured methodology. Our discussion is mostly grounded in methodological insights and case-based reasoning, using literature reviews and ontological modeling to examine urban complexity and digital twins (DTs). The paper follows an explorative structure, aiming to outline critical reflections and propose a conceptual framework.

The methodological approach of this paper is rooted in applied ontology, specifically leveraging the DOLCE framework. This framework provides a formal and systematic way to analyze and represent the complex relationships between urban components, such as places, agents, and knowledge. By employing an ontological analysis, we aim to capture the multifaceted nature of cities, including both tangible and intangible elements, and to explore how these elements interact within urban systems. This approach allows us to critically evaluate the potential and limitations of digital twins in modeling urban complexity while also providing a foundation for future research in this area.

In this context, the concept of a digital twin has emerged as a powerful tool for simulating and managing complex systems [10–14]. Traditionally, DTs have been used in engineering and manufacturing to create virtual replicas of physical objects, enabling real-time monitoring, predictive maintenance, and performance optimization. These traditional DTs are typically focused on tangible, mechanical systems in which the physical and digital counterparts are tightly synchronized. However, when applied to urban environments, the concept of a DT must be expanded to account for the unique complexities of cities. Unlike engineered systems, cities are dynamic, socio-technical systems characterized by a multitude of interacting agents, both human and non-human, as well as tangible and intangible elements. An urban digital twin (UDT) must, therefore, go beyond the physical replication of infrastructure to incorporate social, behavioral, and environmental dimensions, reflecting the multifaceted nature of urban life.

The long-term target of our research is to characterize and develop a cognitively transparent and formally robust decision-support model oriented to city planning and managing. A city, particularly a smart city is a complex system whose knowledge and data are multifarious in nature and gathered by and exchanged among a variety of agent types, which has suggested organizing it through semantic approaches and, more specifically, via ontologies [15]. Such diffused knowledge is critical today for the development of effectively sustainable spatial plans, policies, and decisions [16,17]. The adoption of a DT approach, originally developed in manufacturing, has recently been proposed to address the complexity of city modeling. Yet this proposal necessitates careful reflection about the possible implications of employing a UDT, considering the specificities of the knowledge involved (for collection, representation, and exchange), as well as the adaptability that this approach provides in engaging with urban socio-technical systems.

While traditional DTs focus on the synchronization of physical and digital models, a UDT must address the additional challenge of integrating socio-technical complexities.

Cities are not merely physical infrastructures; they are living systems shaped by the interactions of their inhabitants, the flow of information, and the evolving needs of communities. A UDT must, therefore, incorporate not only the physical layout of the city but also the behaviors, intentions, and cognitive representations of its agents. This requires a shift from a purely engineering-based approach to one that embraces the dynamic, emergent properties of urban systems. By leveraging ontologies, a UDT can provide a structured framework for representing these complexities, enabling more informed decision-making and sustainable urban planning.

There has recently been an emerging literature regarding twin models of (or applied to) the city. Often, however, the citation of UDTs refers explicitly to applications in the so-called smart city, that is, subordinated to a 'smart-type' organization of the city. There are criticisms of this approach that overemphasize digitalizable features, advanced levels of interaction that are not the management standard of the vast majority of urban settlements on Earth [18–20]. Therefore, a UDT model focused on the 'smart city' appears difficult to generalize since it tends to marginalize the role of digitally under-connected agents or of digitally hard-to-detect relationships and, for this reason, tends not to include aspects of socio-environmental complexity that are instead typical characteristics of cities [21]. It also excludes aspects of agents' spatial cognition from the structure of the twin model, thus excluding the role of the different individual representations of urban spaces in (dynamically) influencing individual behaviors. This inevitably tends to frustrate the emerging and most characterizing properties of the system that the twin model should represent [22,23]. The rich dimension of the city thus appears to be drastically limited to physical–infrastructural features that are easier to handle, thereby reducing the systemic complexity to a complexity of the artificial, which is more manageable but not very geminal to the real city.

Indeed, some literature also refers to urban scenarios with models of agents aggregated or, at most, disaggregated into very simplified categories. Frequently, collective agents are considered (e.g., the 'crowd'), essentially characterized by predefined typologies that are often binary—e.g., the elderly and the young. In these studies, agents are not built on the basis of their individual characteristics of cognition and representation of urban spaces. Therefore, the dynamism associated with the evolution of the city is not affected in a complex way by the constructive contribution of its inhabiting agents (who are instead decisive in characterizing the very essence of the city) [24]. Some works reflect on the possibility of integrating the role of active agents through occasional digital feedback without, however, integrating the agentive dimension structurally into the model. This approach certainly allows an increase in the memory of the options and available data, but the lack of dynamic structuring drastically reduces the urban similarity (and effectiveness) of the twin model [24,25].

A significant UDT should model essential components of the city, like the communities of human and non-human entities, and the artificial urban environment. It should provide the capability to comprehend and assess the needs, intentions, visions, and strategies peculiarizing a sustainable city.

To explore these ideas, this paper's structure after the present introduction is as follows. Section 2 presents an ontological perspective on cities, introducing the foundational framework used in our analysis. Section 3 discusses the digital twin concept and its relevance in urban contexts. Section 4 critically examines the limitations of DT applications in city modeling, supported by real-world examples. Section 5 explores the participatory dimension of technology adoption in urban decision-making. Section 6 discusses the constraints of current city models, emphasizing the challenges of incorporating complexity

into urban DTs. Finally, Section 7 provides a case study of a city square to illustrate our approach, followed by concluding reflections in Section 8.

2. What Is a City from an Ontological Viewpoint?

An ontology is particularly effective in disambiguating and facilitating knowledge exchange among diverse agents, including humans, non-human entities, and artificial systems. As previously established, this study is grounded in the foundational ontology DOLCE. In recent decades, ontologies have experienced increasing application across numerous disciplines, including the humanities, medicine, social sciences, archaeology, environmental planning, geography, urban studies, and architecture. Figure 1 presents DOLCE's taxonomic structure, illustrating its relational hierarchy. Beginning with particulars, the taxonomy delineates the classification of *endurants* (concerning physical entities), *perdurants* (addressing temporal phenomena), qualities (encompassing temporal, physical, and abstract attributes), and finally, the abstract category pertaining to regions.

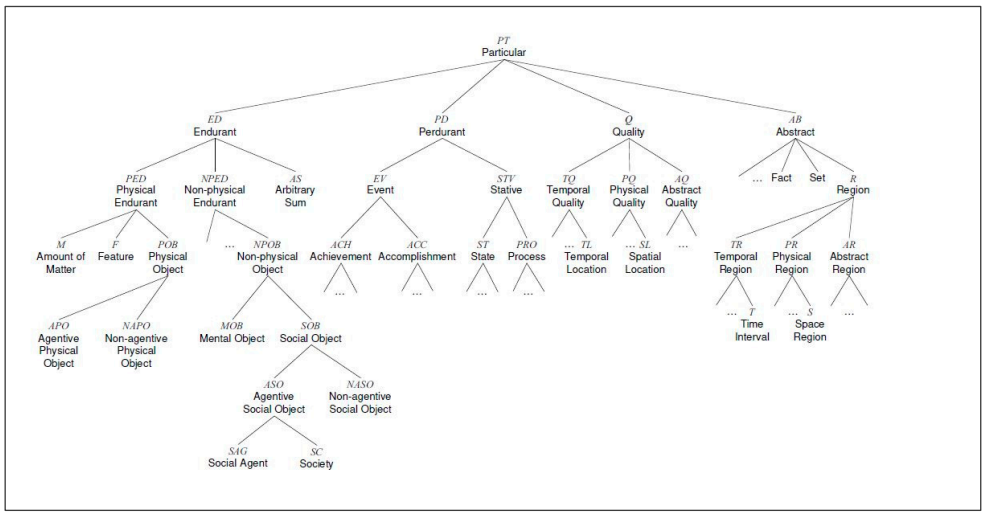


Figure 1. DOLCE's taxonomy [6].

This section explores the concept of the city, particularly focusing on the smart city concept, using an ontological perspective [26]. It goes without saying that no single representation may claim to fully describe a city as such, yet numerous descriptions might capture, to some satisfactory level, its different facets. Cities are dynamic systems with frequently polycentric layouts [27], where their current 'smart' feature aims at enhancing the city's capacity to organize and oversee relationships, services, and network connections via the automatic exploitation of different kinds of data. In smart cities, data are commonly gathered by distributed sensing devices and individuals who share information, either intentionally or unintentionally—and so posing risk issues in data aggregation and interpretation processes. The smart city concept has significantly influenced the historical understanding of cities and is likely to remain a key component in their future evolution [26]. Urban complexity encompasses many dimensions, making the city an open, dynamic, and varied system where agents exhibit unique traits that emerge as distinct properties, integrating into the city diverse behaviors [17,28]. Modern technologies aid in interpreting complex environmental and cognitive issues by tracking their features and interconnections, aiming to manage these emergent properties [29,30]. Thus, the concept of a smart city reflects a new city's abilities to persist, sustain itself, and advance both as an interconnected system of diverse agents and as a unified entity.

Conducting an ontological analysis to identify the fundamental components of a city reveals interactions between ontologically distinct elements. These interactions are

as crucial as the components themselves, indicating that the presence of components alone is insufficient for a city's existence [26]. Therefore, we performed an analysis of the city's components, recognizing that the city does not emerge from simply juxtaposing them but from their interactions and practical entanglements [26]. Cities are complex systems characterized by diverse, interacting elements and heterogeneous interactions. We identified three components of the city [26]: (i) city-place; (ii) city-agent; and (iii) city-knowledge (Figure 2).

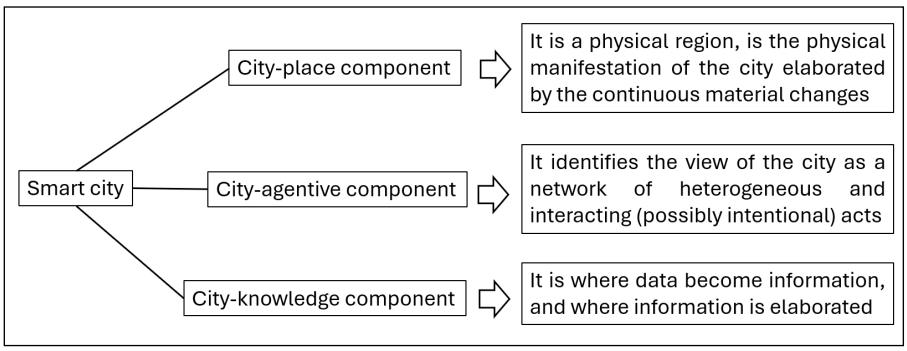


Figure 2. A schematization of city components [26].

In this paper, the term 'agent' refers to any active component of the city, including both human and non-human entities that interact within the urban environment, influencing and being influenced by it. Agents can include individuals, groups, organizations, or even technological systems that perform actions and contribute to urban dynamics. Conversely, 'entity' is used in a broader sense to denote any component of the city, whether tangible (such as buildings, streets, and infrastructure) or intangible (such as regulations, cultural norms, and data structures). The distinction between agents and entities helps structure the ontological framework, ensuring a systematic representation of the complex interactions within the urban system.

Throughout this section, we have emphasized the inherent complexity of cities, which arises from the dynamic interactions between diverse components such as physical infrastructure, human and non-human agents, and knowledge systems. Cities are not merely physical spaces but are also shaped by intertwined social, cultural, and cognitive dimensions that evolve over time. This complexity poses significant challenges for urban modeling, particularly when attempting to create digital twins that accurately reflect the multifaceted nature of urban systems. By adopting an ontological approach, we have sought to capture this complexity and highlight the need for models that go beyond simplistic representations of cities.

The *city-place* component represents the physical expression of the city, shaped by minor and/or major, constant changes, with different levels of coordination and mutual interferences. The dynamic development of the city through interactions between humans, non-humans, and communities is described as the *city-agent* component. The *city-knowledge* component encompasses the data and knowledge produced via the city, enhancing its ability to represent and understand itself, its external environment, and the relationships and potential evolutions of its parts [26]. The relationships and interactions among these components are rich and multifaced, and while some have been discussed, we still lack a comprehensive analysis of these aspects.

Starting from the above conceptual framework, we can easily envision that 'smartifying' the city can foster the evolution process of communities, adding self-awareness and intentionality. This should occur alongside the creation of new systems and networks that bring significant transformations to the city's social fabric. Questions arise about how we

can represent the level that emerges from this kind of knowledge. DT technology seems to be a useful instrument for representing and communicating (possibly in real time) the emergence of individual and communal intentions, feelings, and decisions. For instance, it is natural to imagine that the knowledge component will be encoded in the UDT, serving as a tool for the agentive component (e.g., collective agents, administrating agents, or simple inhabitants) to decide on actions, interventions, or preservation efforts in physical spaces or in response to events. These actions would lead to changes in reality, which would then be fed back into the UDT model, modifying the knowledge component and producing new data with their suitable interpretations offered to individuals and communities. This vision could be carried out for a smart city or a section of it, taking advantage of the socio-technical systems' structure and the sensors' capacity available today.

At this stage of our research, the ontological representation of a city object, as an example, has not yet been fully developed. However, we can outline some steps that are useful for this 'translation'. If we intend to refer to the city components previously described, we should 'unpack' them, following the model depicted in Figure 2, which explores an extension of DOLCE with new elements. Table 1 is a possible schematic map aligning city components with DOLCE's taxonomy in Figure 1, while preserving its foundational hierarchy.

Table 1. City components vs. DOLCE's taxonomy *.

DOLCE Core Layer	Category	Subcategory	City Component	Examplified Urban Elements
Endurant	Physical object	Non-agentive	City-place	Buildings, roads, infrastructure
		Agentive	City-agent	Humans, organizations, sensing devices
Perdurant	Process/event	–	(Emergent)	Traffic flows, crowd dynamics
Quality	Abstract	Information object	City-knowledge	Sensor data, cultural norms
Region	Spatial	–	–	Districts, neighborhoods

* Please note: *Perdurants* (temporal entities) interact with city components but are not standalone urban elements. The dashed line (–) indicates dynamic processes that emerge from component interactions.

In accordance with the general paper's approach, this conceptual mapping reflects our exploratory focus on foundational relationships, rather than exhaustive technical specifications. The mapping shows how DOLCE's stratified structure could accommodate aspects of urban complexity, as further elaborated within this study. Specifically, while *endurants* are aimed at capturing physical and agentive elements, *perdurants* model their temporal interactions—a distinction of critical significance for future digital twin implementations, as discussed in Section 3.

3. The DT Vision and the Actuality of DTs

The DT concept appeared and was repeatedly used in the mid- and last part of the 1900s, driven by the evolution of computing proficiency and of widespread interest in digitalization. The early 2000s saw it become a major area of research, especially in the manufacturing sector, where DTs were intended to be virtual assistants for the duration of a product's lifecycle [12].

At its core, the idea of a DT is straightforward: engineers utilize product models that are structural, process-based, and functional. By integrating these models, the product's condition and behavior can be effectively simulated in real time, at least in principle. This simulation can anticipate potential critical situations, as well as possible failures, and provide information to enhance the product's performance. Achieving this objective necessitates maintaining synchronization between the development of the physical item and the simulation provided via the DT. Given the distinct characteristics of these two elements, it is usually accepted that their conditions will drift apart as time progresses.

This divergence can be reduced through a (potentially continuous) data alignment between the product and the DT, ensuring that the DT simulates over verified data. In turn, the DT simulates the product's behavior, allowing managing agents to anticipate possible problems, adjust parameters and schedule maintenance to reduce the risk of failure.

The appeal of a DT lies in its ability to comprehensively describe, remotely control, and predict the behavior of a physical system. The meaning of "physical" here refers to an object with a spatial location, composed of material but also non-material parts. The latter can be holes, cavities, signals, etc., which are essential constituents in many cases, from mechanical to civil objects such as engines, buildings, pipelines, and the like. The related computational capabilities needed to run a DT in these cases are achieved at a relatively low cost compared to fixed maintenance scheduling, repairing physical objects after failure, and costs due to production interruptions. As a matter of fact, reliability has been a key engineering feature since the 1950s, with methodologies like scheduled maintenance and regular inspections developed to address it [31]. Yet, traditional maintenance methods remain costly and do cover all failure types.

The application of DTs represents a groundbreaking strategy for enhancing reliability. However, creating a DT involves addressing existing challenges and introducing new ones. Certain product representations are static, such as structural models, whereas others are dynamic, like process models. Additionally, some representations are discrete, as exemplified by the Bill of Materials (BOM), while others are continuous, as seen in operational models (e.g., in processes like pumping). Furthermore, some models follow a linear pattern, like input–output configurations in a fluid container, whereas others are inherently non-linear, such as turbulence phenomena in fluid dynamics (air, water, etc.). This diversity complicates achieving a global, integrated product view. Integration is part of the DT vision, but significant differences across models pose obstacles. Aligning models without full integration—sharing data between models without merging them—faces challenges like dealing with different granularities, modeling assumptions, and required data. In this context, applied ontology highlights which implicit modeling assumptions can hinder integration, even for seemingly similar models. Additionally, the concept of DT necessitates establishing a robust interdependence between the physical and digital realms, which inherently differ, even when focusing solely on the information they naturally handle and utilize [32–34]. Recent studies emphasize the importance of integrating social dimensions into urban digital twins. For instance, Qanazi et al. [35] propose a framework for social digital twins, highlighting the need to model human behaviors and community interactions alongside physical infrastructure. Similarly, Ruohomäki et al. [36] argue that urban digital twins should be viewed as socio-technical constructs, blending technological capabilities with social dynamics to better reflect urban complexity.

To address the socio-technical complexities inherent in urban systems, the integration of applied ontologies could represent structured frameworks for urban DTs. A relevant example could be in DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering), whose distinction between *endurants* (entities that persist through time, such as buildings) and *perdurants* (processes or events, such as traffic flows) allows for a more nuanced representation of urban dynamics. In it, the *city-place* component can be modeled using the *physical object* category, while the city-agent component, encompassing human and non-human actors, can be represented through *agent* and *social object* categories. Similarly, the *city-knowledge* component, which includes data and information flows, can be modeled using the *information object* category. Using ontological, urban DTs could better represent the interplay between physical infrastructure, human behavior, and environmental factors, enabling a more systemic and inclusive representation of urban systems. To date, the intrinsic complexity of urban systems has played a significant role in limiting

the adoption of ontological approaches in this context [26,37]. Recent interest has been in research on the management of the smart city, where the situational configuration in terms of components is traditionally more structural [38]. However, this ontological approach can not only enhance the possible accuracy of urban DTs but also support more informed decision-making in urban planning and management, particularly in addressing the emergent properties of cities that are often overlooked in traditional DT frameworks.

Based on earlier observations, a significant number of DT initiatives tend to construct mostly simplified models of DT. In practice, many of these efforts resemble data integration projects. However, the aim of merging extensive datasets with diverse types of information stimulates advancements and potentially innovative strategies for service optimization. Specifically focusing on urban studies, the DT concept provides opportunities to implement new methodologies for enhancing infrastructure (such as water and power distribution) and for minimizing service-availability challenges, including issues like traffic congestion and the monitoring of recharging stations, as exemplified by the Snap4City project (https://www.snap4city.org)

The field of DTs in urban settings is still in its early stages, particularly when it comes to integrating agent-based and socio-technical complexities. The dynamic and multifaceted nature of urban systems requires flexibility and adaptability, calling for an open exploration of methodological possibilities, rather than the proposal of structured methodologies that are still too premature. This exploratory approach seeks to lay the groundwork for future research to better reflect the evolving realities of urban environments.

4. DT Failing in Modeling Cities: The Cases of Indore and Toronto

Aside from the theoretical and technical challenges of developing suitable DTs, the application of DTs is increasing. Previous discussions explain why such applications often target specific aspects of the urban environment, particularly the ones that are readily measurable using the currently accessible and affordable sensing devices and that ensure significant social impact [10]. A common example is the enhancement of closed-circuit television (CCTV) systems to combat crime in urban areas. The idea is that the automated recording and data analysis of videos can create a positive feedback loop that discourages criminal activities. Law enforcement agencies and political figures have frequently supported the perspective that AI tools may play a role in lowering crime rates. This viewpoint is pertinent to previous arguments, as it supports the data-gathering methodology used in developing DTs. However, despite the presence of extensive CCTV systems in many large cities today, analysis shows that there is no correlation between a decrease in crime and more camera surveillance; in fact, in some cases, the opposite is true (broader analyses reported in https://restofworld.org/2023/cctv-crime-surveillance-india/, accessed on 1 April 2025) [39,40].

Conversely, relying on digital-based models can introduce unforeseen challenges on a larger scale. For instance, in Toronto, a digital infrastructure established to oversee various city services, including autonomous waste collection, pedestrian crossings, and park-bench activity led to new issues associated with viewing the city as something to quantify and control (https://www.technologyreview.com/2022/06/29/1054005/toronto-kill-the-smart-city/, accessed on 1 April 2025) [41,42]. Where some perceive disorder, others see engaging and surprising interactions; where some see confusion and a lack of regulation, others experience a sense of enriching diversity and closeness. This, coupled with concerns about data privacy and behavior monitoring (as seen in the case of Marseille (https://www.technologyreview.com/2022/06/13/1053650/marseille-fight-surveillance-state/, accessed on 1 April 2025)) [43], has led to a series of issues that have disrupted technology-based initiatives targeting urban environments.

Such cases as Indore and Toronto aim to illustrate some challenges of applying traditional DT models to urban environments, particularly in terms of socio-technical complexities and data limitations. These limitations align with critiques from Missikoff [44], who advocates for a human-centric approach to digital twin ecosystems, emphasizing that local contexts and community participation are often overlooked in favor of technocratic solutions. Such perspectives underscore the need for UDTs to incorporate both tangible and intangible urban dimensions. These challenges align with the aforementioned ontological approach, which emphasizes the need to consider the city as a system of intertwined relationships between places, agents, and knowledge. In this context, it is suggested that an ontological approach can help identify gaps in current DT models toward more inclusive and adaptive UDT designs.

5. The Participatory Adoption of Technology: What Does It Mean for DT and How Can It Be Done?

Community participation in spatial planning has a long history, but it has never been straightforward. The challenge lies in creating and managing a complex knowledge framework, which ensures the active involvement of communities for a sustainable development process. Initially, the concept of participation was driven by ethical–democratic values, mainly leaving aside cognitive issues because of management difficulties. However, these problems have been somewhat lessened by the economic deregulation of data networks and the increasing use of smartphones, at least for certain age groups. This progress has benefited inclusive planning processes in two main ways: enabling the precise recording of cognitive interactions and facilitating the real-time dynamic construction of cognitive databases [45]. Nonetheless, challenges persist, particularly for digital non-natives like the elderly and those less skilled with technology, who often show reluctance towards these approaches. These groups, however, are crucial, as they represent essential voices and perspectives needed for an effective planning process and sustainable development [16,46]. Also, recent advancements in participatory modeling explore how feedback loops between digital twins and communities can enhance equity in urban planning [35]. However, as Ruohomäki et al. [36] note, achieving this requires reconciling top-down technological frameworks with bottom-up social processes.

The building up of an inclusive UDT is even more technologically demanding. It calls for specialized skills and advanced technology resources from individual knowledge agents and may demand a detailed cognitive framework for the entire system. The interpretation of the 'twin' concept is crucial for defining goals and shaping the UDT model. The ongoing debate about the model's adherence to real-world contexts is significant, as different levels of adherence (physical, social, and behavioral) impact the model's effectiveness and sustainability. Recent studies suggest that the ontological analysis of complexity levels is relevant for practical applications [47].

After the phase of participatory knowledge building, the model enters a stage where it is used for inclusive decision support. The problems here still include the complexity features that characterized the previous phase. Furthermore, significant aspects related to knowledge, its forms, and its contents prove to be crucial in the decision-making processes. Like traditional DT applications, a UDT should facilitate decisions in urban contexts, allowing their setting up, the dynamic simulation of actions, control, and possible adjustments in a manner that is more informed, context-aware, responsive, and adaptive [11,48]. However, even mechanical digital models often struggle with data consistency when associated with physical, tangible elements. These models allow for mechanical simulations that can compare and verify impacts on real products. Participation must include relevant agents whose cognitive inputs support operational decisions, such as experts from various

knowledge domains [49]. Initially, UDT debates focused on the perceivable configuration of city representations, with GIS models providing early examples [50].

Subsequently, integrating building information modeling (BIM) approaches further explored the potential for more explicitly functional features, particularly in built spaces [51]. Yet, as previously said, real urban areas are complex manifestations of multifarious ontological levels. Therefore, such models built at most a very partial UDT, not comparable to DT in more traditional domains. Nonetheless, the participatory decision-support process within this framework, guided by that specific type of UDT, features some intriguing characteristics. Basically, a noteworthy use of this approach is to aid in simulating various scenarios and spatial impacts related to urban developments. Such simulations essentially target physical aspects but can also encompass socio-economic factors more indirectly. Within this framework, *geodesign* research has gained attention, initially focusing on the collaborative possibilities offered via a public-participation geographical information system (PPGIS) [52]. During knowledge gathering, the model facilitates cognitive exchanges among diverse participants, who contribute insights that refine the *geodesign* model, fostering the development of decision-support scenarios. Nevertheless, incorporating content that is informal, highly complex, or frequently changing remains challenging and has demonstrated limited effectiveness in these models so far [53]. Other research avenues have been explored within specific, often contained settings like exhibition halls and museums. Here, technology-based virtual spatial reproductions have been used to study spatial decision-making in evolving scenarios. Despite involving multi-agent cognitive interactions in their creation, these models primarily support individual decision-making activities only, even when informed by digital-twin-inspired technologies [54]. Applied ontology is also frequently employed to represent and handle spatial complexities, particularly in these cases [55]. Such an ontological approach offers valuable frameworks for articulated spatial representation, addressing the complexity of real environments—which should undergo the development of any DT oriented to sustainable city planning and management.

6. Limits of City Models

Significant challenges are associated with the participatory adoption of urban DTs (Section 5). They also stem from the inherent limitations of existing city representation models. Predominantly grounded in metric-rational methodologies, these models often fail to effectively account for the socio-technical complexity of urban environments, as underscored by the technical challenges of DTs (Section 4). In the following discussion, we examine these limitations in detail to elucidate how an ontological approach can address and overcome them.

Research focusing on city modeling evolves alongside our understanding of cities. This parallel development stems from the need to organize and manage a complex and multifaceted entity. In this study, we focus on contemporary cities. In the 20th century, marked by world wars, there was a growing need to address the well-being of human communities. Planning increasingly aimed to meet public interest objectives, driven by the need to support demand. The Pareto principles of economic rationality that underpinned market-led city models were challenged by the need to cater to diverse and individualized people's needs [56]. Urban decision-making models based on rationality are increasingly challenged by the complexity of diverse agents involved in city governance. The limitations of a rational approach become apparent when addressing the varied social, political, and economic distortions present in multiple communities, as opposed to a straightforward, metric-based organizational model [57]. Additionally, the rise in environmental awareness following significant urban transformations reshapes community needs and expectations. The quest for environmental sustainability makes the urban system still more complex,

if possible, leaving the quest for a thoroughly effective management and organizational model still unsolved.

As a matter of fact, traditional models based on orthogonal metrics and economic rationalities persist in this picture. Urban spatial planning rules still refer to these models today, making them more manageable, but ultimately moving toward a more abstract and simplified reality than the complex one they aim to represent [58]. GIS-based models have evolved following just the same perspective to become more sophisticated physical representations of natural and anthropized contexts, plants, and infrastructures. These models, therefore, still tend to keep a low profile on relations, behavioral attitudes, and cognitive exchanges that are difficult to formalize geographically using traditional Euclidean metrics [59]. In such contexts, GIS best expresses its current potential—as shown by its suitability for physical-based simulations, such as climate forecasting models [60].

In this scenario, UDT models can aim to become faithful replicas of the real physical characteristics, drawing from the GIS's representative metric system. However, this alone is needed but not enough to classify such models as UDT. A DT, according to its original definition and purpose, is designed to enable thorough simulations, assess behaviors and cognitive processes, comprehend interactions, validate systemic impacts, etc. It should incorporate intrinsic features of the system it represents, such as cognitive elements or individual needs, as essential components of the system's mechanics—complying with the very concept of DT [11,61]. Therefore, a UDT should, according to this concept, attempt to reflect the complexity of the represented system, rather than simplifying it to allow an apparently easier management.

The comprehensiveness aims of a socio-spatial decision-support model have long been a contentious topic in decision theory. In the 20th century, the rational approach to planning gave rise to the rational-comprehensive plan model, which proved to be an abstract ideal when confronted with the multidimensional complexity of decision-making environments [56]. Recognizing its inherent limitations paved the way to a period of significant methodological innovation, which now informs the quest for, and development of, decision-support architectures. Unlike in the past, in fact, advancements in technology and IT capabilities may now suggest the possibility of addressing this complexity with similarly complex descriptive and semantic models—with applied ontologies offering intriguing perspectives [55].

In this context, recent studies have suggested that BIM models can evolve towards BIM-DT as partial models of DTs. It should be noted that the logic of BIM is inherently aligned with the individual physical building entity it represents. Yet, in this sense, it seems hard to legitimate the representation of the built organism by modeling just its physical attributes without compromising the functional efficacy of the representation. Indeed, even structurally similar buildings can exhibit significantly different performance dynamics based on the behavior of the occupants. Research about the energy attitudes of housing residents has highlighted, for instance, the importance of different behaviors in worsening or soothing the urban heat island effect [62]. Additionally, the study of individual urban elements (such as buildings) often overlooks the dynamic nature of behavioral interactions beyond the building as such, due to its integration within a neighborhood, district, or entire city system. Therefore, this partial model should ensure explicit relational links with the broader environment to preserve the essential complexity that defines it.

Traditional urban models, perhaps useful for representing physical structures, yet inherently tend to overlook immaterial, behavioral, and cognitive, interactions. An ontological approach, as outlined in Section 2, is suited for structuring static and dynamic relationships between material and immaterial components (e.g., agent perceptions and intentionality), integrating heterogeneous data into a more coherent framework. This

approach reduces the risk of excessive simplifications and can integrate both dynamic and non-physical into urban models, aligning with the appropriate systemic perspective on urban digital twins discussed in Section 3. In the end, creating an effective DT model for cities involves investigating their complex structural and operational features and trying to avoid unnecessary simplifications.

The adoption of an ontological framework, as proposed in this study, can offer perspectives to develop urban DTs that integrate physical, cognitive, and relational components, aligning with the systemic vision introduced in Sections 2 and 3.

In the next section, we explore an ontology-oriented approach applied to a specific context (i.e., an urban square) to reflect on the extent to which it can incorporate both sensory data and cognitive and social aspects in order to mitigate the limitations discussed in this section.

7. A Use Case: A City Square

7.1. An Ontology-Oriented Experimentation

Building on previous discussions, a UDT should be able to integrate its various components: the *city-place*, city-agency, and *city-knowledge*. These elements must coexist, interact, and integrate within the DT model. What types of knowledge should a city's DT incorporate? Ideally, it should encompass the city as a whole, acknowledging its full complexity. However, using a smaller, representative model could also provide valuable insights—without implying that a DT is limited to isolated parts. A notable example is the urban square, which is measurable, symbolic, and reflective of citizens' social habits and customs. Historically, urban squares have characterized cities, especially in the West, reflecting social customs from ancient times, like the Greek *agora*. This square represents a specific "type", comprised of fundamental elements (such as basic geometric forms) and specific requirements (like intended functions). These elements and needs serve as generative dynamism, connecting with more complex concepts. Thus, the square's shape emerges from these foundational elements and the functional demands placed upon it.

In sum, the example of the urban square serves as a microcosm of the broader challenges facing urban models, particularly in capturing the dynamic interactions between physical spaces, human agents, and knowledge flows. This case study is not presented here to offer a comprehensive methodology for constructing UDTs but, rather, to explore how ontological approaches can facilitate the integration of diverse, complex urban elements. By focusing on a smaller, more representative model, the aim is to highlight the potential of UDTs in addressing some of the limitations inherent in traditional urban models.

In 1570, Palladio classified public spaces into two categories: solids (buildings) and voids (like squares). Two centuries later, Durand also categorized squares within a broader set of urban types. This can allow us to apply the same ontological framework used for architectural types to analyze squares. Consequently, a UDT of an urban square should include key dimensions to evaluate these types: objective constraints (such as form, surrounding context, functionality, potential uses, and social status) and subjective constraints (like personal and collective interpretations, memory, intentionality, creativity, and perceptions of livability). This framework captures both collective and individual experiences [63,64].

This analysis can help us explain and organize some complex elements of references, constraints, and functional objectives while also defining connections between expert and common-sense knowledge. This is crucial for developing a UDT that considers the interconnections among its components (such as place, agency, and knowledge) and their mutual transformations and developments over time. These considerations form the foundation of the UDT. When applied to a city square, the UDT should encompass data

relevant to the agency aspect within the urban context. From its initial development, the UDT should include characteristics of use, behaviors, and customs that change along with the spatial layout of the square based on the day/night cycle, the progress of days, and occasional events. It should also incorporate different individual or collective agents present in the square who use the space either alternatively or jointly, as outlined in the literature [65]. Additionally, it should encompass the observation of occurrences that impact behaviors, either enhancing, reducing, or solidifying them: new equipment, a subtle shift in color, new seating, and established flower beds. Achieving this involves careful analysis and observation, incorporating sociological and anthropological perspectives to understand how agents interact with their surroundings, all enhanced through aware interaction.

Superimposed on this is a second layer of case knowledge related to the square. This knowledge emerges from translating and integrating data gathered from sensing instruments, communication networks, and possible tailored actions if needed. The data flow from sensors contributes to this knowledge, tracking both people/agents and the material components of the place. These sensors monitor ambient factors impacting the square, such as light/shade trends, wind direction and intensity, pollen presence, pollution levels (e.g., !0-micrometer particulate matter—PM10, or carbon dioxide—CO_2), humidity, temperature, and other dynamic events.

The knowledge integrated into a UDT of an urban square extends beyond this. It can also include insights from literary works, such as essays, novels, or poems. For instance, two of the authors have previously analyzed the square by integrating knowledge from literary works like poems through applied ontology: this project is here recalled because it helps exemplify some points of our previous analysis [66]. Such work originated from a collaborative exercise conducted with students. An internet survey, distributed via Google Drive, asked students to choose three literary excerpts from their usual readings that referenced the city. The responses from 160 students resulted in a database of 480 literary passages. Of these, 90 included at least a minimal mention of the square, though many students selected the same passages, indicating a similarity in their reading choices. After removing duplicate entries and disregarding excerpts that mentioned squares without any context or description, we identified seven key selections: four from tales and scientific papers, and three from poetry. Relational visual diagrams were developed for all seven pieces to emphasize the key concepts that emerged. An example of maps coming from two famous Italian poems on Piazza Sarzano [67] and Piazza San Petronio [68] is shown in Figure 3.

A taxonomy was then developed using DOLCE Lite ontology, to achieve some ontological representation of the square as represented in literary works [66]. This framework was selected because it is recognized in the literature as the most appropriate to be applied in engineering sectors and capable of capturing concrete, as well as abstract elements. Because of such flexibility, the inclusion of various characters of both materiality and immateriality, as well as conceptual features, can be involved—including dynamic aspects that are inherent to literary representations. The mechanism of integrating literary data with other data into formal ontological classes was performed manually through a loose multi-step approach, such as the following: (1) identifying recurring themes and spatial relations from the literary excerpts via relational mapping, (2) identifying frequent and redundant terms, (3) aligning these elements with DOLCE's founding categories of classes, subclasses and relations, and (4) validating the classifications via consensus among the research team. This was a purely manual approach at this stage. It was deliberately chosen for this proof-of-concept study to maintain some control over how qualitative narrative elements were formalized within the ontology. Future implementations could use natural language processing techniques to automate parts of this process, once the founding onto-

logical framework has been sufficiently validated through studies such as this one. The structure was represented using the Protégé 5.6.3 software from Stanford University, and an excerpt from the taxonomy based on all seven literary maps is shown in Figure 4.

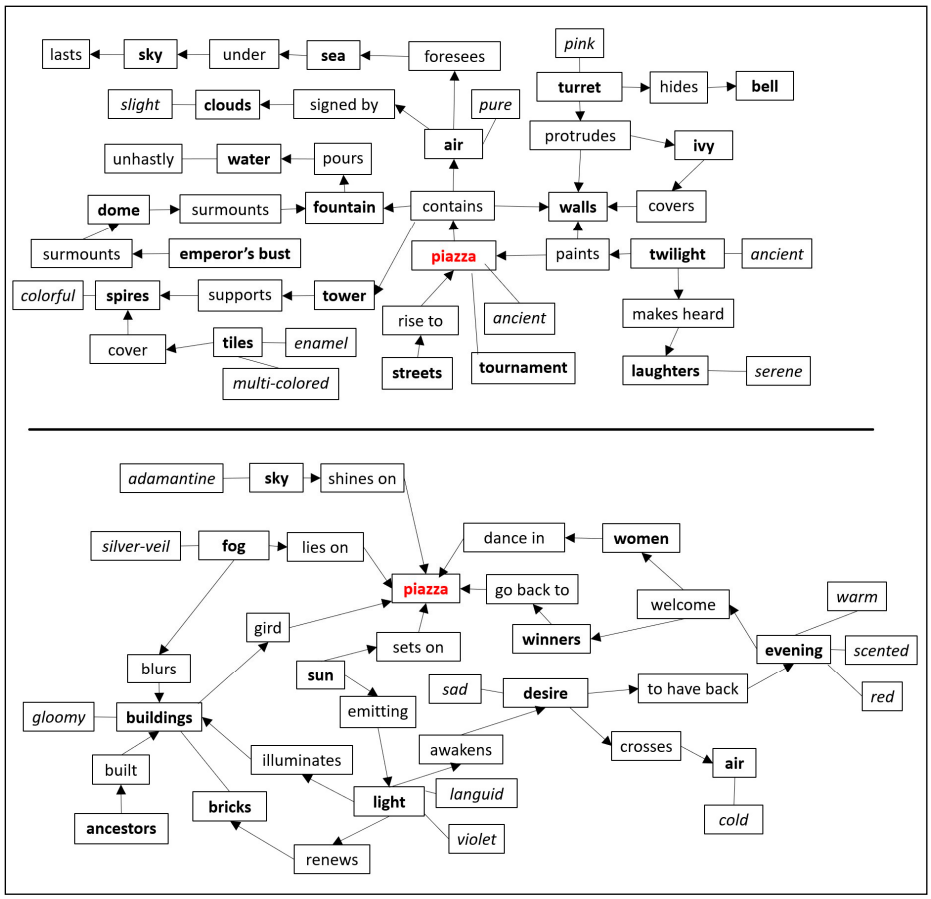


Figure 3. The relational maps of Piazza Sarzano (up) and Piazza San Petronio (down) [66]. Terms are translated by the current authors: bold = nouns and locutions; italic = adjectives; other = verbs.

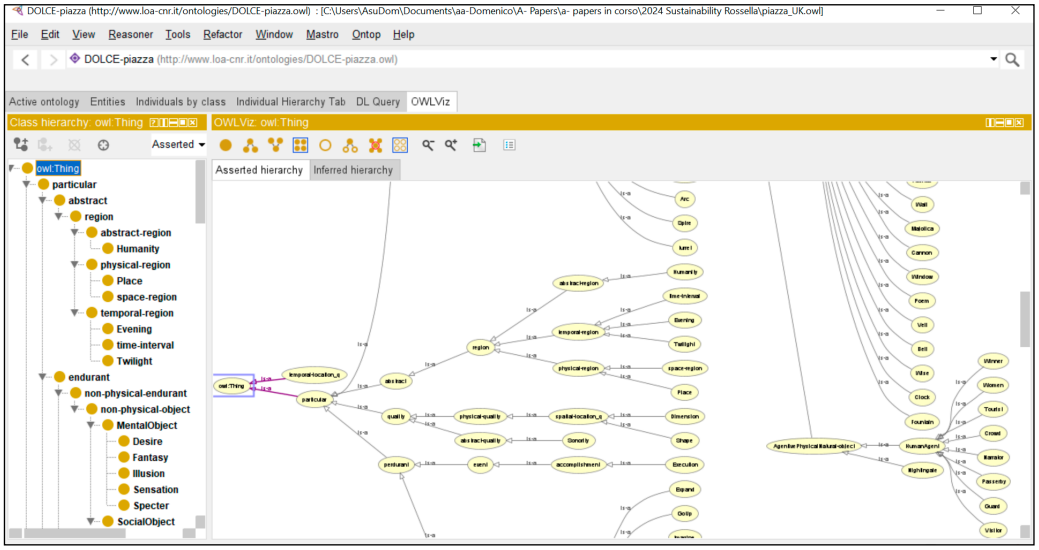


Figure 4. Excerpt of an ontology-oriented taxonomy of the urban square from literary works (Protégé 5.6.3) [66].

It should be noted that the Protege excerpt here is not meant to provide complete details of all classes and subclasses, it is just shown as an exemplary snapshot. In fact,

at this stage, the DOLCE lite structure does not yet include every individual element's property. Yet the current taxonomy effectively captures and emphasizes the complexity of the square's conceptualization. The taxonomy already includes subclasses specified with DOLCE ontology-formal definitions, and it organizes 121 subclasses, of which 63 are classified as *endurant*. These are entities that exist in their entirety at each moment of their existence [69]. The remaining 51 subclasses are classified as *perdurant*, i.e., entities composed of temporal parts that may be present now but not in the future. As we said, *endurant* entities are those that exist in their entirety at each moment of their existence (e.g., a building or a tree), while *perdurant* entities are composed of temporal parts that may change over time (e.g., an event or a process) [70]. These distinctions help in capturing both the static and dynamic aspects of urban spaces. The significant presence of both *endurant* and *perdurant* subclasses seems to suggest that the dynamic square elements, particularly *perdurant* aspects, are central to the urban square conceptualization. This is consistent with the square's role in a city's organization.

In this context, Protege is not being used as a structured methodology for building UDTs. As a matter of fact, it is just one of the most widely used tools for ontological representation. Its role is to serve as an analytical tool for examining the potential of ontological frameworks to help organize and represent the complex interactions within urban spaces. This approach enables us to identify unconventional areas and uncover potential technical challenges, such as the integration of dynamic and static data, ultimately guiding the development of more structured modeling perspectives.

In summary, a UDT of an urban square should be a comprehensive model that integrates physical, social, and cognitive dimensions, reflecting the complexity and dynamism of urban life. A UDT of an urban square could be envisioned as a dynamic, three-dimensional model that brings space to life. This model would not only capture the physical layout of the square but also incorporate the behaviors and interactions of the people and elements within it. For instance, the model could visualize real-time data streams, such as wind patterns, heat islands, or even the emotions of the crowd—perhaps inferred from social media activity or sensor-based mood detection. Additionally, it could track and display crowd density, providing insights into how people move and gather in space. It should also allow inclusivity for non-human elements, with sensors that identify the presence of bees, birds, or swallows. It could also feature popup windows, whether for advertisements or information sharing, either intentionally or unintentionally, and so on. Informative data flows, such as updates on events or environmental conditions, could also be integrated, offering a comprehensive view of the square's activity and atmosphere. This approach would allow urban planners and decision-makers to better understand and respond to the complex, ever-changing dynamics of urban spaces.

7.2. Brief Discussion

The above reflections have led us to say that a UDT, to be meaningful, should model essential components of the city, communities of both human and non-human entities, as well as the artificial urban environment. It should provide the ability to understand and evaluate needs, intentions, visions, and strategies that characterize a sustainable city.

Such a UDT should effectively integrate its various components, namely the city as place, the city as agency, and the city as knowledge. This means that those elements should coexist, interact, and integrate within the DT model, which should encompass the city as a whole, fully representing its structural complexity.

Admittedly, a smaller yet representative model would be useful to conceptually navigate such complexity, providing valuable insights without necessarily implying that a DT is limited to isolated parts. Indeed, the example of the urban square has proven to be

useful and poignant, being historically representative of, and reflecting, citizens' habits and social mores towards spaces—a small proxy for urban complexity.

In this light, using a poem, a piece of poetry, allowed us to show how tangible and intangible, static and dynamic, structural, and transitory elements can be relevant in building a representation of an urban square—and, more broadly, of a representation of a complex city. The analysis helped us explain and organize some complex elements of references, constraints, and functional objectives, also defining connections between expert and common-sense knowledge. This cannot but be crucial to develop a UDT that considers the interconnections between its components (such as place, agency, and knowledge) and their mutual transformations and developments over time.

Modeled and managed through an ontological approach, the resulting layout seems to show an interesting potential to improve as much as possible the preservation of the original complexity. In other words, a model of an urban square, built with an ontological approach and possibly managed through ad hoc tools (e.g., Protégé), seems to open good perspectives to support high-level knowledge exchanges and more informed decisions (e.g., design, planning, etc.).

These observations suggest that a UDT for an urban square can be effective, provided it is both comprehensive and inclusive. As our examples show, the UDT should accurately reflect the urban system's full complexity, incorporating all elements that make up the city, with nuanced but structural cross-border interactions across these components.

8. Conclusions

The challenge of grasping and representing the essence of the city remains an open problem. It seems we still do not agree on what a city is beyond a mere place in space. Geddes talks of the city as "a drama in time" [71], suggesting that we need to move beyond standard approaches in modeling. Today's simulations via DTs are valuable improvements especially for management, problem anticipation, and information sharing. Yet, DTs have significant limitations and add new risks, such as the possibility of creating an Orwellian scenario through observation [61].

This paper has explored the application of DTs in urban contexts as an aid for cognitively transparent decision-making and planning models. While urban models based on DTs have great potential, they tend to oversimplify complex systems. Important facets of complex systems, like the sudden emergence of novel components and properties, or the changes in behavioral and evolutionary dynamics, may remain undetected, notwithstanding the use of large sensor networks. A UDT, similarly to other urban models, should account for these elements to be truly effective in terms of equity, sustainability, and cognitive transparency.

Our analysis has revealed several critical issues in applying digital twins to urban contexts. First, reliance on sensor data and measurable features often leads to a reduction in urban complexity, neglecting important socio-environmental and cognitive dimensions. Second, the participatory adoption of technology, while promising, faces challenges in ensuring inclusivity and addressing the needs of digitally underrepresented groups. Third, the current models of urban DTs tend to focus on physical and infrastructural aspects, failing to account for the dynamic and emergent properties of urban systems. These limitations underscore the need for more systemic and inclusive approaches to urban modeling, grounded in ontological frameworks that prioritize cognitive transparency.

Originally, DTs were proposed as virtual copies of engineering devices. Within the urban organization, there is little evidence that this materialistic view remains reliable when applied to urban scenarios since the latter are much richer than the tangible structures we can detect in them. Cities have components that are tangible and intangible, living

and non-living, behavioral and interactive, fixed and evolving, transient and lasting. The concept of DT needs to be expanded to address this multidimensional complexity, ensuring that cognitive and agentive dimensions are explicitly represented to achieve transparency in decision-making.

In this paper, we have tried to contribute to the field of urban planning/decision-making and DTs by leveraging an ontological approach to address the complexity of cities. At its core, this ontological perspective allows for a more nuanced understanding of the interactions between physical infrastructure, human and non-human agents, and knowledge systems, which are often under-considered in traditional urban models. By formalizing these interactions through frameworks like DOLCE, our approach enhances cognitive transparency, enabling decision-makers to trace how data, assumptions, and agent behaviors influence model outcomes. The paper has also critically reflected on the application of DTs in urban contexts, identifying both their potential and limitations. Furthermore, the paper calls for future research to develop more robust and inclusive UDT frameworks. Our use case of an urban square suggests that future work should focus on creating scalable and adaptable models that can be applied across diverse urban contexts, including both smart and non-smart cities. Practical applications of this research could include pilot projects where ontologically structured UDTs are used to simulate planning scenarios, with explicit documentation of how agent behaviors and intangible factors (e.g., cultural narratives and individual perceptions) are integrated into the model. Together, these contributions can pave the way for more systemic and representative urban planning approaches.

Finally, while urban DTs have primarily been developed for smart cities with advanced technological infrastructures, their potential application in less technologically advanced cities should not be overlooked. In such contexts, the challenge lies in adapting DTs to environments with limited digital connectivity and resources. Low-cost sensor networks, participatory data collection methods, and community-driven input could serve as foundational elements for creating inclusive and scalable DTs. By leveraging these approaches, urban DTs can be tailored to reflect the socio-technical realities of non-smart cities, ensuring that they remain relevant and accessible across diverse urban landscapes. To operationalize cognitive transparency, such adaptations must include mechanisms for stakeholders to interrogate the model's assumptions, such as visualizations of how agent interactions or cultural values are weighted in decision outputs. Future research should explore these adaptive strategies further, focusing on practical implementation and the integration of local knowledge to foster equitable and sustainable urban development.

To realize the full potential of urban DTs, future research should focus on developing scalable and adaptable frameworks that can be applied across diverse urban contexts, including both smart and non-smart cities. This includes exploring how DTs can integrate data from under-connected agents, such as marginalized communities or informal settlements, to ensure that urban models are truly representative of the entire population. Additionally, there is a need for interdisciplinary collaboration between urban planners, data scientists, and social scientists to refine the ontological structures that underpin DTs, ensuring they capture the full spectrum of urban complexity. Pilot projects in specific urban areas, such as city squares or neighborhoods, could serve as testbeds for these frameworks, providing valuable insights into their practical implementation and scalability.

As urban DTs become more prevalent, it is essential to address the ethical implications of their use, particularly concerning data privacy, surveillance, and equity. The development of urban DTs should be guided by principles of transparency, inclusivity, and accountability to avoid reinforcing existing inequalities or creating new forms of exclusion. By embedding these principles into the design and deployment of urban DTs, their role

as decision-supporting architecture for empowerment and sustainable development can be enhanced.

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