Smart, dynamic, programmable, composable, and scalable Urban Environment

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Abstract

This paper explores the concept of urban environments, their hierarchical organization, and the principle of nesting and composition. Urban environments encompass a spectrum of human settlements, from isolated dwellings to sprawling mega-cities. They are characterized by high population density, a dominance of human-made structures, and a complex network of infrastructure systems. This paper proposes a framework for understanding these environments through a hierarchical lens, where settlements are categorized based on size, complexity, and population density. Higher levels in this hierarchy are composed of elements from lower levels, reflecting the natural growth patterns of settlements. The concept of nesting further emphasizes the interconnectedness of different settlement levels within the urban environment. The basic concepts and entities of this hierarchical-compositional approach in the specification of urban environments are defined into the UEOnto ontology, also addressing the interoperability, dynamicity, programmability and scalability challenges. This paper introduces this vision and approach, describing the UEOnto ontology. Analyzing urban environments through this hierarchical and nested perspective offers several advantages. It fosters a deeper understanding of how these environments function as interconnected systems, informs urban planning and development strategies, and encourages a more holistic approach to urban sustainability.

Introduction

The human story is intricately woven with the story of our settlements. From the first rudimentary shelters huddled against the elements to the towering metropolises of today, the way we build and organize our living spaces reflects not only our technological advancements but also our evolving social, economic, and cultural needs. Understanding the structure and organization of these urban environments is crucial for effective planning and sustainable development. This paper delves into the concept of urban environments, exploring their hierarchical organization and the principle of nesting.

Imagine a journey across a vast landscape, dotted with human settlements of various sizes and complexities. At the most basic level, you might encounter solitary dwellings – a single family home or an apartment building standing alone. These isolated structures represent the foundation of the urban hierarchy. As we move on, the landscape transforms. Small clusters of dwellings coalesce, forming hamlets nestled in rural settings. Here, the rudiments of infrastructure begin to emerge, with shared resources like wells and rudimentary roads hinting at the beginnings of a more organized community.

Continuing our exploration, we encounter villages, representing a significant step up in complexity. These settlements boast a centralized water source and perhaps even basic waste collection services, indicative of a developing infrastructure. The presence of shops and a school underscores the evolving social fabric of these communities.

Further along the path, we arrive at small towns, bustling hubs with a wider range of amenities and services. Established municipal water and sewer systems replace individual solutions, and paved roads connect dwellings and facilitate access to surrounding areas. The introduction of basic public transportation, like buses, signifies a growing need for efficient movement within the town and potentially to connect with nearby settlements.

As we progress, the urban landscape takes on a more prominent character. Large towns establish central business districts, attracting residents and businesses alike. The infrastructure becomes more advanced, with expanded public transportation networks and dedicated waste management services ensuring efficient sanitation. The potential for specialized services like recycling emerges, reflecting a growing awareness of environmental concerns.

Finally, we reach the pinnacle of the hierarchy – the sprawling metropolis. Here, major urban centers boast a complex and extensive infrastructure. A vibrant mix of residential areas, commercial districts, and industrial zones pulsates with life. Complex transportation networks keep the city moving, while advanced waste management systems ensure efficient sanitation. Diverse utilities, catering to the varied needs of a large population, are an integral part of the metropolitan landscape.

This journey highlights the fascinating progression of human settlements, each level a testament to our ingenuity and our desire to build communities that cater to our ever-evolving needs. The following sections of this paper will explore this hierarchical structure in greater detail, examining the concept of nesting and its significance in understanding the interconnectedness of urban environments. We will delve into the practical implications of this framework, considering its role in informing urban planning and development strategies that promote sustainability and well-being for all. This effort will result and be formalized into an ontology of smart, dynamic, composable and scalable urban environment, UEOnto, detailed in the paper.

Urban environment, Settlement hierarchy and nesting

An urban environment is an area characterized by a high density of human population and human-made structures. This includes a range of settlements from small villages to sprawling mega-cities. Some key aspects of urban environments are:

- **Population Density -** many people live in a relatively small area compared to rural environments.
- **Built Environment -** buildings, roads, sidewalks, and other infrastructure dominate the landscape.
- **Infrastructure systems and services -** developed systems and related services for transportation, communication, water, sanitation, health and energy are essential.
- **Social Complexity -** a diverse range of people from different backgrounds live and interact in close proximity.
- **Economic Activity -** urban environments are centers of commerce, trade, and industry.

Urban environments are constantly evolving as populations grow and technologies advance. On this premise, the concept of urban environment has been characterized into a hierarchy providing a framework for understanding how settlements of various sizes and complexities are interrelated, shown in Figure 1.

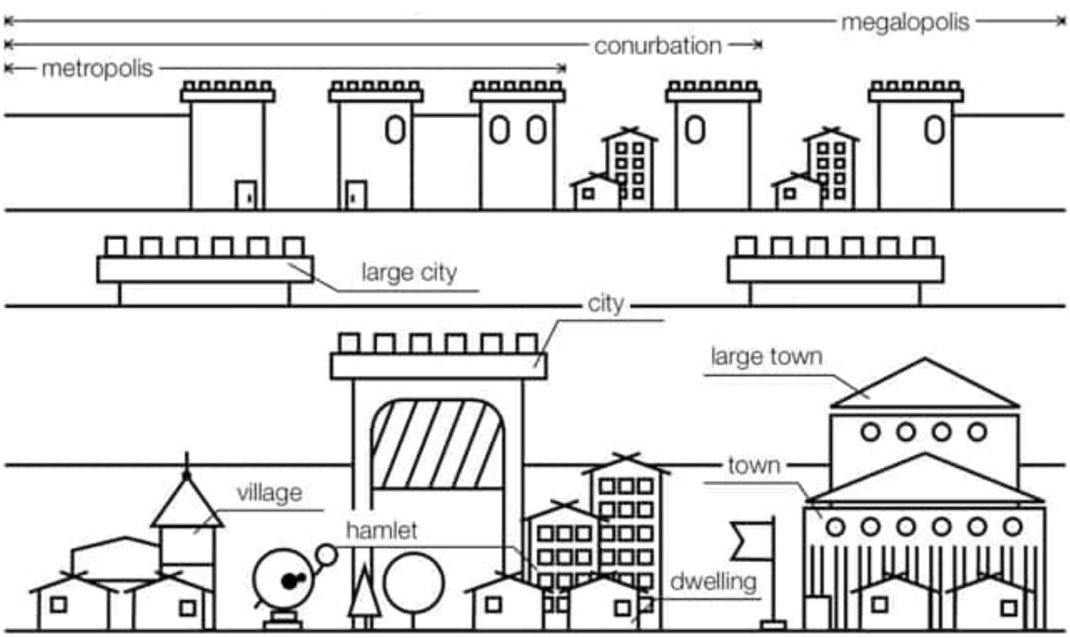

Figure 1: Urban Environment hierarchy and nesting

Each level in the hierarchy represents a settlement type with increasing population density, infrastructure development, and social complexity. As you move up the hierarchy, settlements grow in size and complexity, and may even be composed of elements from the levels below, thus identifying a recursive, composable pattern. For example, a village might be composed of hamlets, and a city might be composed of large towns and districts. This hierarchical structure reflects the natural growth patterns of settlements. Smaller settlements often cluster together to form larger ones, creating a nested structure.

Urban environment nesting builds upon the concept of hierarchy. It emphasizes the interconnectedness of different settlement levels within the urban environment. Imagine a set of Russian nesting dolls, where each doll fits inside the next larger one. Similarly, smaller settlements can be seen as nested within larger ones. This highlights the fact that urban environments are not isolated entities. They interact with each other, exchange resources, and influence each other's development. For example, a village might rely on a nearby city for specialized services or job opportunities. This concept is generalized by the composition one, which allows to bring together multiple urban environments at the same or different levels into higher level ones.

The Hierarchical and Nested View offers different benefits. By analyzing settlements within a hierarchy and nesting framework, we can gain a better understanding of how urban environments function as interconnected systems. The hierarchical-compositional approach for urban environment supports urban planning and development strategies. For example, planners can consider how a new development in a small town might impact the surrounding city or region. Furthermore**,** a hierarchical and nested view encourages a more holistic approach to urban sustainability. By considering the interconnectedness of settlements, strategies that benefit the entire urban ecosystem can be developed.

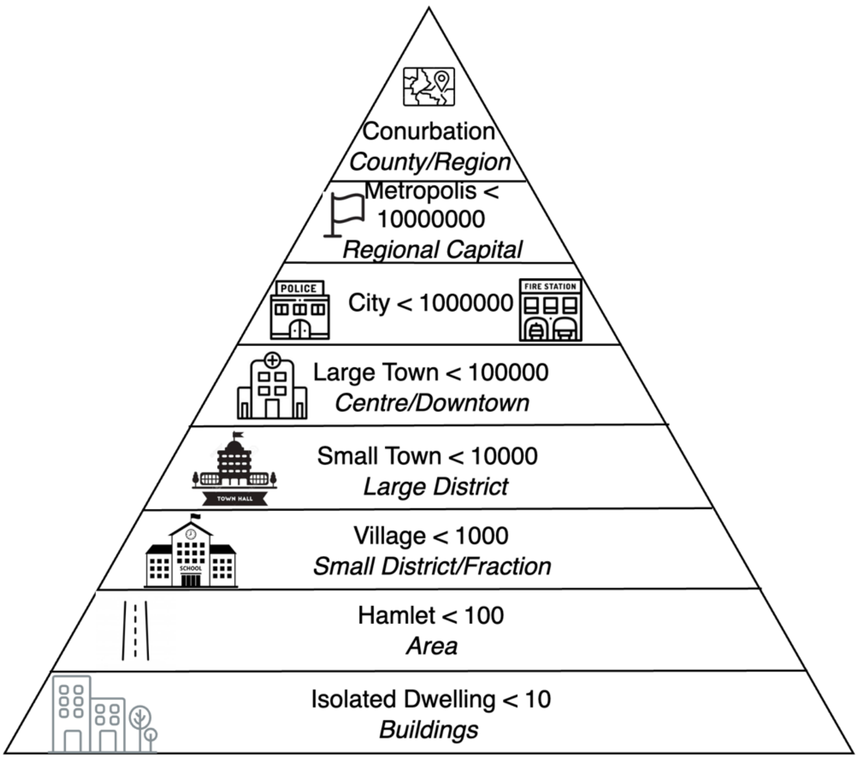

Figure 2: Urban Environment hierarchy layered model

The hierarchical-compositional view of Urban Environment is depicted in the pyramid structure of Figure 2, representing a spectrum of human settlements, each with its own unique character. Let's embark on a journey through the urban environment hierarchy, composed of 8 layers, bottom-up in ascending order of inhabitants (descending order of multiplicity):

1. **Isolated Dwellings / Buildings:** at the bottom of the settlement hierarchy there is the most basic unit - a single-family home or an apartment building. These stand alone, with limited infrastructure needs. Individual utilities like water and electricity are typically provided by on-site systems or connections to local grids.
2. **Hamlet:** Here, we encounter a small cluster of isolated dwellings, often nestled in a rural setting. Infrastructure is basic, with shared resources like wells and septic systems being common. Dirt roads might provide rudimentary access.
3. **Village / Small District-Fraction:** As we move on, the settlements become more complex and require a developing infrastructure. Villages typically have a centralized water source, perhaps a well or a treatment plant, and may have limited waste collection services. Gravel roads start to connect dwellings and essential locations.
4. **Small Town / Large District:** Small towns represent a significant step up in development. They boast a wider range of infrastructure facilities. Municipal water and sewer systems become established, replacing individual or shared solutions. Paved roads provide better access within the town and potentially connect it to surrounding areas. Basic public transportation, like buses, might be introduced.
5. **Large Town / Centre-Downtown:** These towns establish a central business district (downtown) as a focal point. The infrastructure becomes more advanced, with expanded public transportation networks like buses and trams. Dedicated waste management services ensure proper collection and disposal. Additionally, potential for specialized services like recycling emerges.
6. **City / Municipality:** Cities are major urban centers with a complex and extensive infrastructure. They offer a vibrant mix of residential areas, commercial districts, and industrial zones. Complex transportation networks, including subways, buses, and even light rail systems, keep the city moving. Advanced waste management systems ensure efficient sanitation. Diverse utilities, like gas and potentially district heating/cooling systems, cater to the varied needs of a large population.
7. **Metropolis / Regional Capital:** Metropolises are large, influential cities that often serve as regional hubs. Their infrastructure is highly developed, featuring extensive public transportation networks with options like subways, commuter trains, and comprehensive bus systems. Sophisticated waste management systems handle the large volumes of waste generated by a dense urban population. Additionally, specialized utilities like district heating/cooling systems may be used to improve efficiency and sustainability.
8. **Conurbation / County-Region:** At the pinnacle of our hierarchy lies the conurbation - an extensive urban area formed by the merging of multiple cities. These vast regions boast interconnected infrastructure. Integrated transportation networks like subways, commuter rail, and extensive bus systems seamlessly connect the constituent cities. Regional-scale utilities and waste management systems ensure efficient operation across the entire conurbation.

This journey highlights the fascinating progression of human settlements and the crucial role infrastructure plays in supporting their growth and development. From the simple beginnings of isolated dwellings with limited utilities to the sprawling conurbations with interconnected networks, each level reflects the evolving needs and aspirations of society. The 8 levels of the UE hierarchy and related main characteristics are summarized in Table 1.

Settlement Level	***Composed of -> into***	***Typical Population***	***Description***	***Infrastructure Facilities***
Isolated dwelling	Buildings -> Compounds	1-10	Single family homes, apartments	Limited - Individual utilities (water, electricity)
Hamlet	Buildings, Compounds -> Area	10-100	Small cluster of dwellings, often rural	Basic - Shared wells, septic systems, dirt roads
Village	* before + Areas -> Small district, fraction	100-1000	Cluster of dwellings with basic amenities (shops, school)	Developing - Centralized water source, limited waste collection, gravel roads

Small town	* before + Small district-fraction -> Large district	1000-10000	Developed town with wider range of amenities and services	Established - Municipal water and sewer systems, paved roads, basic public transportation
Large town	* before + District -> Centre-downtown	10000-100000	More prominent town with central business district	Advanced - Expanded public transportation, dedicated waste management, potential for specialized services (e.g., recycling)
City	* before + District -> Municipality	100000 – 1M	Major urban center with diverse economic activity and infrastructure	Extensive - Complex transportation networks (subways, buses, train, airport), advanced waste management systems, diverse utilities (e.g., gas)
Metropolis	* before + Municipality -> Regional capital	1M+	Large, influential city, often a regional hub	Highly Developed - Extensive public transportation networks, sophisticated waste management systems, specialized utilities (e.g., district heating/cooling)
Conurbation	* before + Regional capital -> County-State	Millions	Extensive urban area formed by merging multiple cities	Interconnected - Integrated transportation networks across constituent cities, regional-scale utilities and waste management

Table 1: Urban Environment hierarchy level characteristics.

From theory to practice

To implement the hierarchical-compositional view of Urban Environments, specific methodologies, techniques, mechanisms and tools are required. In particular, in the following this vision, model and approach is specified by a proper ontology defining the basic concepts and terms, after introducing the main requirements.

Challenges, issues and requirements

Specifically, the main challenges, requirements and characteristics of a Urban Environment to be considered in the implementation of this approach are summarized in the following five features.

- **Smart:** An urban environment may use sensors and data analytics to gather information about everything from traffic flow to energy consumption control, from emergency to utility management. This information is used to optimize systems and improve efficiency. Urban environments must be therefore considered as "smart entities" or things in the IoT landscape, able to interact and interoperate each other to further improve and optimize the urban environment management (e.g. traffic, emergency, utility, etc.). This envisions an Internet of Urban Environments
- **Dynamic:** An urban environment is dynamic, since it can change morphology, extension and other spatial and urban features, usually expanding (urbanization) or shrinking its area. An UE must thus react and adjust to changing conditions. For example, new buildings and infrastructures have to be included in the UE administration and management (e.g. municipality), or two (or more) UE can merge into bigger UE, or even an UE can split into smaller UE for e.g. administrative/management purposes (new areas or districts).
- **Programmable:** Residents and UE planners can define how the city functions. The infrastructure has to thus be easy configurable and adaptable to the UE changing conditions by e.g. adjusting lighting schedules for local events or programming street signs to display targeted information. Programmable facilities, mechanisms and API for the UE domain management have to also be provided by the system.
- **Composable:** An UE can be considered as a set of modular units that can be easily added, removed, or reconfigured. Basic urban elements can be composed into more complex ones in the UE hierarchy, and even further nested/composable into higher level UE. This allows for flexible development and adaptation to changing needs.

- **Scalable:** The UE can grow and shrink as needed. Buildings could have modular floors that can be added or removed, and infrastructure could be designed to easily accommodate expansion. The concept of smart UE can be thus scaled up to smart counties, region, country, till even smart continent or world. Similarly, it could scale down to smart village, district or even hamlet.

UE ontology

Based on the hierarchical-composable view and on the above requirements a proper ontology that describes and implements them altogether is required. Existing ontologies mainly deal with semantic interoperability among smart cities, but mostly at infrastructural device level for Topology, Administrative Area and City Object modeling [9], and for context information exchange [10]. Ontologies have been used to support smart city services, addressing problems related to data and process interoperability, big data management, and automated reasoning on knowledge [1]. Challenges in developing city ontologies include the need for multidisciplinary analysis, decision making for city sustainability, and the integration of data from different sources [1] [2] [3]. The development of city ontologies is hindered by the difficulty of representing the transport domain and the obsolescence or specificity of some proposed ontologies [2] [4] .
However, ontologies have been demonstrated to be effective in enhancing the smart city concept, providing efficient management solutions, operation, and sustainable development of cities [5]. City ontologies can be used to provide services to commuters via specific applications in intelligent transportation systems, aiding in traffic planning and policy-making purposes [6] even harmonizing data exchanges between municipalities and service providers [7]. Ontology-based semantic approaches can improve interoperability between IoT-generated data and complementary data needed for smart city applications [8].
In this light, most of the core view and ideas behind hierarchical and composable Urban Environment is not covered by existing ontologies and need specific efforts to fill this gap. To such a purpose the UEOnto ontology is proposed, as reported

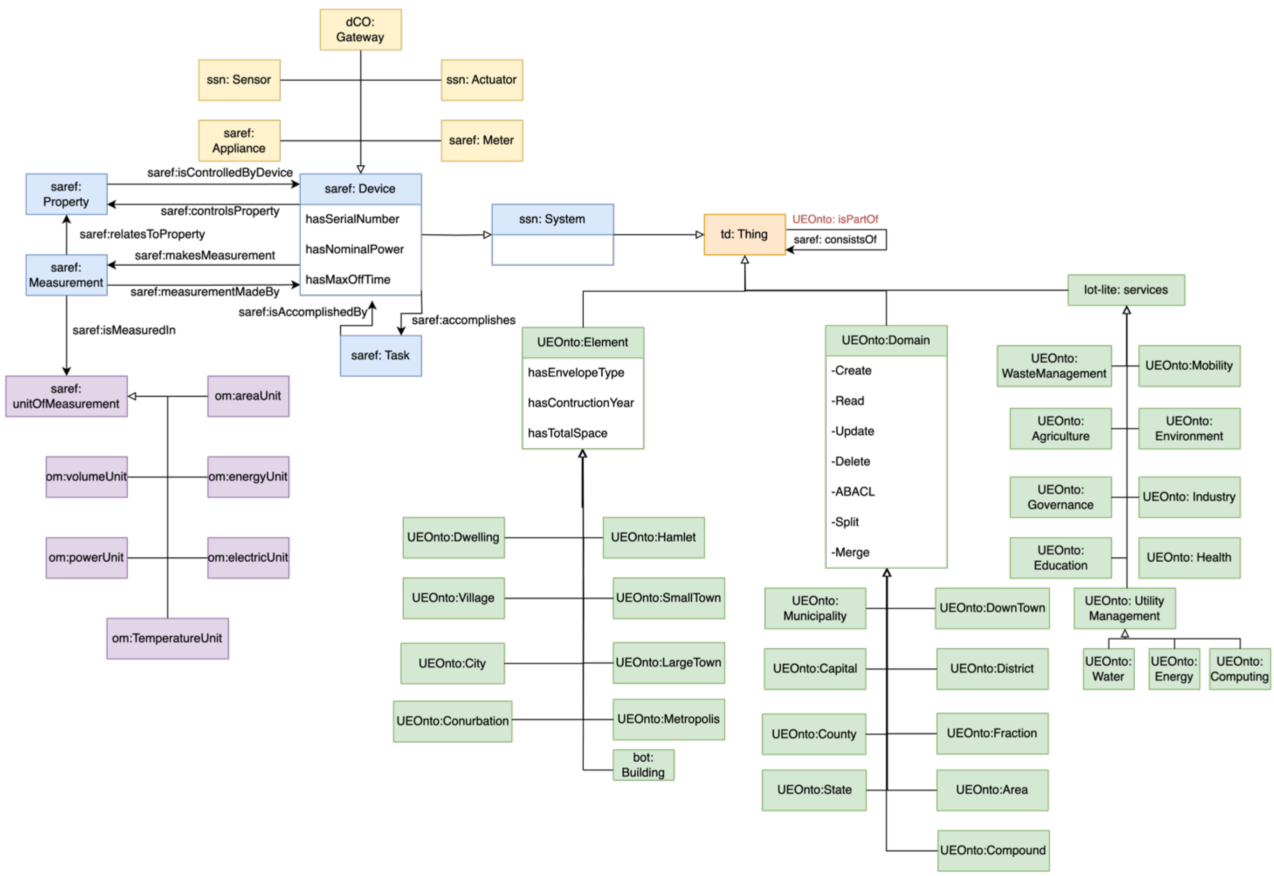

Figure 3: Urban Environment Ontology - UEOnto

Staring from well known ontologies such as iotlite [11], thing description [12], saref [13], ssn [14], and dCO [15], the UE ontology *UEOnto* has been specified by extending them as follows. The main idea is to define Urban Environment *UEOnto* concept *(Element* and *Domain)* as things, as well as devices and services. This allows that any UEOnto concept is discoverable, interoperable and also inherits all the properties of smart object and things, i.e. is a live entity in the IoT with which interact to. The hierarchical composability of UE is implemented by adding the *consistOf* and *isPartOf* properties to the *td:Thing* entity, allowing to include in any thing and subclasses' objects other objects of the class hierarchy (i.e. Device, Element, Domain and Service).
The *UEOnto* is designed to properly address and meet all the above challenges and requirements of UE, specifically:

- **Smart:** An urban environment is mainly represented by *Element* and *Domain* classes, specializing the *Thing* class. Thereby, they are able to interact and interoperate each other directly, allowing interoperability and federations towards the Internet of Urban Environments (IoUE). In particular, an *Element* is a physical space (a village, town city etc.) while the *Domain* represents a logical, administrative domain (a district, county, state) reflecting the UE management organization.
- **Dynamic:** Any structural/infrastructural or logical/administrative change to the UE can be easily addressed by the *Element* and *Domain* classes-instances, respectively. In the case of new infrastructure new *Element* objects will be instantiated and connected with the UE (*consistOf*, *isPartOf*) while in the case of changes in the UE management, the *Domain* class provides all methods to create, destroy and modify UE *Domains*.
- **Programmable:** in the UEOnto, all UE entities are *Things* that can recursively include other *Thing* and subclasses' objects. In particular *Services* (*IoT-Lite:service*) can be includes and nested within UE *Elements* and *Domains*, as well as to *Devices*, thus achieving customizability, reconficurability and programmability at all levels.
- **Composable:** As discussed above, UE composability is achieved by nesting withing an UE *Element* and/or *Domain* other Things, thus including *Element, Domain* and *Device*. This allows to implement the full UE hierarchy and even more, a degree of freedom far beyond the latter.
- **Scalable:** The UEOnto, by exploiting the IoT/WoT interoperability of *Element* and *Domain* classes, specializing the *td:Thing* class, allows interactions among multiple UE domains. This is the basic mechanisms for scaling up and down an UE domain, allowing to share resources among multiple entities.

Conclusions

By examining urban environments through a hierarchical and nested lens, we gain valuable insights into their interconnectedness and how they function as complex systems. This framework offers a foundation for informed urban planning and development strategies, ensuring that decisions consider the impact on surrounding areas and promote long-term sustainability. Furthermore, the concept of a hierarchical and compositional view paves the way for the development of smart and adaptable urban environments that can respond to changing needs and demands. As technology continues to advance, the ability to manage and optimize urban environments at different scales will be essential for ensuring the well-being of their inhabitants and the overall health of our planet.

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