The Needs and Trends of Urban Simulation Platforms- A Review

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Abstract

Half of the global population lives in cities, and it is still increasing as people are moving to cities in search of better education, job opportunities, and so on. The existing infrastructures of the cities are being stretched beyond their capacity and requirements for well-organized urban environment and efficient urban management are rising. Urban simulation platforms create opportunities to review and analyze complex urban scenarios and help authorities in effective and efficient decision-making. The recent advancement in information and communication technologies (ICT) and data-driven environments have even aggravated the use of such platforms. To understand the current trend of the developed urban simulation platforms and to investigate the needs for future platforms, this study reviews academic research papers that focus on the subject area. From the findings of the study, it is observed that most of the developed simulation platforms focus on short-term analysis and cover specific sectors. Also, there exist merely few city-level deployment cases of such platforms. To this end, this study emphasizes the needs for multi-disciplinary, scalable, expendable, open and interactive simulation platforms for the development and management of future cities.

Keywords –

Urban simulation platforms, Urban complexity, Interdisciplinary simulation

1 Introduction

Cities are large settlements that accommodate large populations and support their diverse activities [1]. They are also systems of interacting people in densely built spaces serviced by infrastructure and managed by organizations [2]. In practice, they are commonly handled as vast land-use systems to be designed and managed based upon best practices from economics and engineering [3]. This approach often defines the operational issues as simple problems and mainly describes the short-term activities, but becomes insufficient when considering urban issues over long-term horizons and problems involved with human socioeconomic dynamics [4]. Since the nature of cities is complex, attempts to design and manage them with a few facets are risky. A more holistic understanding of cities becomes critical and is now an emerging trend of urban studies [5].

Theoretical and mathematical models have long been used to reduce complexity and produce concise understandings of urban structures [5]. Their values are to foster broad knowledge of underlying principles of urban development, but they are too simplified and abstract to support decision-making for agencies. To meet the operational needs in planning and governance decisions, computerized models were developed and used since the 1960s to simulate the dynamic processes and interactions of urban developments and components [6]. Nevertheless, these models mainly focus on one or a few disciplines and systems to provide insights for specific policies and investments in particular urban settings. They fall short to represent the relationships and complexity between different disciplines and systems within cities. With the rapidly developing ICT in recent years, researchers have started to develop urban simulation platforms which can accommodate various urban simulation models and data to provide more holistic pictures of urban dynamics [7]. However, an overall reflection on the past development of these urban simulation platforms and their needs and trends are lacking.

The objective of this study is to identify the needs and trends of developing urban simulation platforms for academia. Related academic literatures are collected and reviewed, and their developed platforms are analyzed by their related disciplines and technologies, target users, and study cases. Limitations and outlooks of current and future platforms are summarized based upon the review and analysis results. The outcome of this study provides readers the state-of-the-art knowledge of the development of urban simulation platforms and potential directions for future research.

2 Developed platforms

To understand the past development of urban simulation platforms by academia, relevant academic literature was collected using keywords including “urban/city”, “simulation” and “platform” for article titles via Scopus in mid-May 2021. 51 papers fitted the searching criteria and 14 of them were excluded because of their languages (non-English), types (book chapter), or focuses (not related to urban governance nor planning). The features of these platforms are presented as following subsections: their general profile (e.g., developed year, affiliation countries), related disciplines and technologies, target users and study cases.

2.1 General profile

To understand the research trend of urban simulation platforms, the collected literature is analyzed by their publication years, document types, and sources. The discussion on developing urban simulation platforms gained attention around 2005 and increased gradually throughout the years (as shown in Figure 1). Among the 37 collected pieces of literature, 26 of them are conference papers while the rest are journal articles. This indicates that many of the proposed platforms are still in their development process and are to be completed. As for the document sources of the collected literature, most of them are published by different sources and this might be because that the development of urban simulation platforms is related to a good variety of disciples (e.g., cyber-physical systems, transportation engineering, etc.).

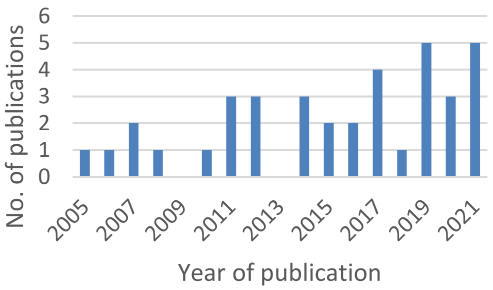

Figure 1. Year -wise number of publications

Among the collected literature, 37 urban simulation platforms are developed by 49 universities and research groups spreading across 20 countries in the world. Figure 2 shows the country-wise number of publications. China, Japan, Italy, USA, and Sweden are the top five countries in terms of the number of publications related to this field. Since Eastern Asia had experienced the most rapid urbanization, their needs for developing urban simulation platforms are higher than other regions.

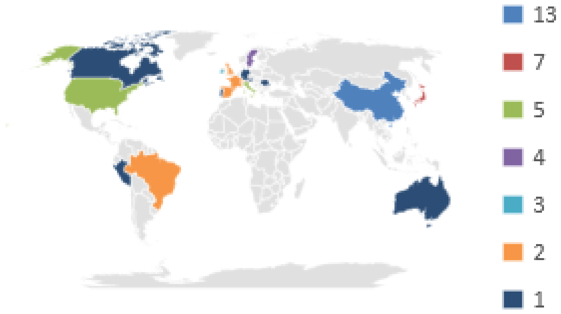

Figure 2. Country-wise number of publications

2.2 Related Disciplines

The developed platforms reviewed in this study are found to be of seven broad categories: traffic [8], energy and sustainability [9], disaster management and urban security [10], urban landscape [11], water supply [12], 3D visualization, and, inter-disciplinary [13]. From the distribution of the reviewed simulation platforms in Figure 3, it is observed that 78 percent of the platforms deal with single-discipline simulations and only 22 percent focus on simulations integrating multiple disciplines. Within the single-discipline applications, simulations of traffic-related aspects in the urban context are the most studied area followed by energy, sustainability, disaster management, and urban security aspects. Social and economic urban systems are overlooked by the existing platforms.

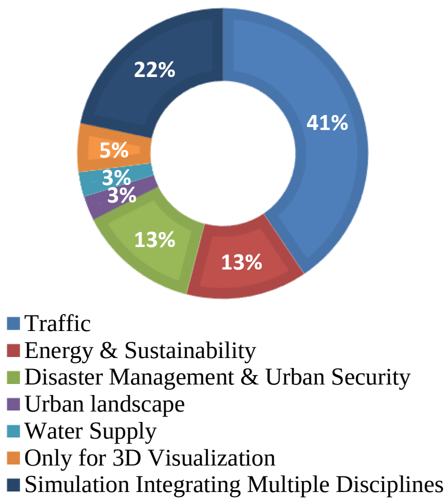

Figure 3. Related disciplines of the reviewed simulation platforms

Table1 shows the list of platforms that integrate more than one discipline in simulation scenarios for assessing inter-disciplinary impacts. The integration mostly focused on assessing the environmental impacts of urban mobility, holistic optimization of the city's energy system, and the impact on power supply from the incorporation of electric vehicles in the city. Recent applications such as Dong *et al.* (2021) [14] tried to simulate traffic, emission, and energy usage scenario together. Also, studies like De et al. (2019) [13] focused on integrating several disciplines within a scalable software system for large-scale simulation through an application programming interface (API). Among the reviewed platforms, although a few of them were open source [7], [14], this is the only one that was created with an open-design approach. In this platform the functionalities are delivered through API and users get the opportunity to customize the system to fit to their requirements. Because the urban environment works as a complex combination of multiple disciplines, simulation of a single discipline without considering the impact of other disciplines often leads to unrealistic outcomes.

Table 1. Simulation platforms that integrate multiple disciplines.

Name of the platform	**Integrated categories**	**Year**	**Ref.**
Opus (the open platform for urban simulation)	Land usage and Traffic	2006	[7]
A simulator integration platform for city simulations	Electric mobility and power supply	2011	[15]
A co-simulation platform for the analysis of the impact of electromobility	Electric mobility and power supply	2016	[16]
MobiWay (Smart City Mobility Simulation and Monitoring Platform)	Traffic, temperature, location, pollution	2017	[17]
InterSCity (A scalable smart city software platform with large-scale simulations)	Interdisciplinary scenarios (e.g., smart parking, smart grid)	2019	[13]
SureCity (Sustainable and Resource Efficient Cities platform)	Holistic optimization of the energy system including air quality, land usage, and water usage	2019	[18]
Diesel, petrol or electric vehicles: What choices to improve urban air quality	Air pollution and road traffic	2020	[19]
A smart city simulation platform with uncertainty	Traffic, emission, and energy usage	2021	[14]

2.3 Related Technologies

The advanced technology adoption in different urban simulation platforms was found for four main purposes: sensing, visualization, integrated large-scale simulation and computing. A list of technologies related to different purposes found in the reviewed literature is listed in Table 2. Sensing technologies are required for collecting data from the real-world environment. The collection of data from citizen's mobile devices through crowdsourcing is found to be effective in energy usage and carbon dioxide emission simulation [20], street lighting simulation [21], and traffic simulation [22]. The use of various wireless sensors was also found in many applications such as traffic simulation [17], urban flooding simulation [10], radiation [23] simulation, and so on. Some recent applications have also used vision-based sensing devices such as LiDAR [23], and image capturing devices [11] for simulating radiant heat and agricultural production respectively.

Visualization of simulation scenarios and outcomes through a map and/or three-dimensional representation provide end-users a better opportunity for well-informed decision making. OpenFlight was one of the early options for modeling 3D visualization systems [24], [25]. However recent simulation platforms have started using the latest 3D modeling technologies, such as building information modeling (BIM) [9] and CityGML [26], and represented them on the world map views using OpenStreetMap [27] and Geographic Information System (GIS) [11]. Software packages such as ArcGIS [11] and QGIS [26] are often used for the analysis of geospatial information. For more immersive user experiences, recent studies have represented the simulation scenarios through virtual reality models created using a 3D game engine named Unity [27]. Access to the simulation platforms through the web-based graphical user interface is also one of the recent trends [13][18].

The integrated simulations include multiple disciplinary simulations, and often those are simulated in real-time. As these tasks are computationally heavy, performing them in a centralized system will be time-consuming and inefficient. To overcome that, early researchers used de-centralized distributed simulation platforms [8][28][16] which follow High-Level Architecture (HLA) [29][30], a distributed simulation standard published by IEEE. Most recent studies have implemented cloud computing [13][21], and edge computing technologies for performing complex simulations in real-time. Some studies have also implemented Hardware-in-the-loop (HWIL) technology for simulation through complex real-time embedded systems [31]. Uninterrupted connectivity between systems and with sensing devices through 4G/5G wireless networks is essential for the effective implementation of integrated simulation platforms [32].

Although earlier simulation platforms have relied on various simulation models for analyzing the scenarios, recent ones are more inclined to data analytics through artificial intelligence techniques such as machine learning and deep learning. Agent-based models are widely adopted simulation models for simulating the actions and interactions of autonomous agents to understand the behavior of a system [16][33]. The use of various discipline-specific models was also observed during the review. For example, Simulation of Urban Mobility (SUMO) was used as a traffic simulation model [16][8][14], CupCarbon [21], and TinyOS [34] were used for wireless sensor network simulation, and so on. The latest AI techniques were adopted by Zhou and Dai (2021) [11] for agricultural production simulation and by Aviv *et al*. (2021) [23] for simulation outdoor radiant environment.

Table 2. List of technologies used for different purposes.

Purpose	Technology
Sensing	IoT, Vehicular sensor network, Wireless sensor network, Crowdsourcing mobile data, Images, LiDAR point clouds
Visualization	GIS (e.g., Open Street Map), 3D (e.g., OpenFlight), BIM (e.g., CityGML), 3D game engine, Virtual Reality
Simulation	Mathematic models, Artificial neural networks
Computing	Parallel Computing (e.g., De-centralized Distributed Platform & HLA), Hardware-in-loop, Cloud computing, Edge computing

2.4 Target users and study cases

Most of the developed urban simulation platforms are for city governments, infrastructure companies, and urban planners to monitor and operate existing infrastructure systems and to review and evaluate potential urban plans, which is regarded as the top-down approach [35]. However, in recent years, more developed platforms have also integrated the bottom-up approach, which emphasizes citizen engagement for urban governance and planning. The importance of model reuse and data sharing [9][13][36], crowdsourcing input [20][21][22], interactive interface [10][18], and immersive environments [25][27] is recognized by researchers to develop more public engaging urban simulation platforms, yet not addressed enough. How urban simulation platforms can interact with the public more should be investigated continually in the future.

Applying urban simulation platforms to real-life problems is valuable. Among the 37 developed platforms, less than half of them (17) was used to study real cases, while the rest were applied to virtual cases. More case studies should be fostered to validate the effectiveness and demonstrate the value of existing and future urban simulation platforms. Among the study cases mentioned in the collected literature, 6 of them are Asian cities (i.e., Tokyo, Kyoto, Beijing, Shanghai, Qingdao, Singapore), 6 are European (i.e., Dublin, Paris, Cologne, Stuttgart, Luxembourg, Judenburg), 3 are North American (i.e., Seattle, San Francisco, Philadelphia), and 2 are South American (i.e., Sao Paulo and Lima), whose sizes vary from 16,411 km^2 (Beijing) to 13.22 km^2 (Judenburg) and populations from 26 million (Shanghai) to 1 thousand people (Judenburg). How the developed urban simulation platforms can be used to study different cities with different sizes from different regions is rarely discussed in the collected literature and should be investigated in the future.

3 Limitations and outlooks of current and future platforms

The existing simulation platforms are still in early phase for city-scale urban simulation due to the following limitations and challenges. Firstly, only a few studies have tried to incorporate multiple disciplines and domains for co-simulations. Secondly, the existing platforms mainly focused on short-term analysis and covered specific sectors. The main drawback of such platforms is the inadequacy to support collaborative features and their limited or focused set of solutions. Thirdly, the open-source approach needs to be adopted for engaging more development communities in developing integrated platforms. Lastly, flexible platforms that support the easy integration of multiple disciplines need to be in the focus.

For existing integrated platforms, challenges lie in their scalability, interoperability, maintainability, and reuse in the context of different cities. Incorporating sufficient uncertainties in simulation is needed for making it more robust. These systems need to be tested for large-scale complex city scenarios. Production instances of such platforms need to be created with city-level applications. Real case studies highlighting the challenges and best practices are still limited in the present literature. Furthermore, the use of these urban simulation platforms still needs to deal with some open challenges such as the security and privacy issues of the cyber-physical systems, the requirement of highly skilled workforces for operating them, limited involvements of citizens and governments. All these challenges should be addressed for future urban simulation platforms.

The following characteristics are summarized as essential for future urban simulation platforms in response to future cities with more complex challenges and rapidly changing environments. Firstly, they should be interdisciplinary to reflect the essence of urban governance and planning. Secondly, they should be scalable, level and tempo-wise, to integrate different disciplinary simulations. Thirdly, they should be flexible and expandable to accommodate new simulation scenarios and models. Fourthly, they should be open data and source wise to enable future reuse and further development. Lastly, they should be web-based, interactive and immersive to engage more stakeholders for more inclusive urban planning and management.

4 Conclusion and future work

Urban simulations are needed to gain a deeper understanding of potential future developments and to support sustainable decision-making. In recent years, scientists have been working on various types of simulation platforms to perform such types of analysis. In this work, 37 of these urban simulation platforms were investigated and compared. This work shows that there is a clear rise in the number of platforms available over the last few years. With the increase of available real-world data and computational resources, more and more platforms make use of novel Machine Learning and Artificial Intelligent algorithms to predict future events. The analysis of the different platforms reveals that only a few are currently designed to integrate models from different disciplines. Furthermore, challenges in platform scalability, interoperability, maintainability, security, and privacy are identified. While the analyzed platforms build a solid foundation for urban simulations, further work is needed to enhance the simulations. An important aspect will be the capability to integrate approaches from multiple disciplines to better model real-world phenomena.

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