Review

Integrated design of transport infrastructure and public spaces considering human behavior: A review of state-of-the-art methods and tools

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Abstract In order to achieve holistic urban plans incorporating transport infrastructure, public space and the behavior of people in these spaces, integration of urban design and computer modeling is a promising way to provide both qualitative and quantitative support to decision-makers. This paper describes a systematic literature review following a four-part framework. Firstly, to understand the relationship of elements of transport, spaces, and humans, we review policy and urban design strategies for promoting positive interactions. Secondly, we present an overview of the integration methods and strategies used in urban design and policy discourses. Afterward, metrics and approaches for evaluating the effectiveness of integrated plan alternatives are reviewed. Finally, this paper gives a review of state-of-the-art tools with a focus on seven computer simulation paradigms. This article explores mechanisms underlying the complex system of transport, spaces, and humans from a multidisciplinary perspective to provide an integrated toolkit for designers, planners, modelers and decision-makers with the current methods and their challenges.

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Contents

1. Introduction

1.1. Background

Given the forecast that by 2050, two-thirds of the world's population will be living in urban areas (United Nations, 2014), issues of sustainable and resilient urban development have gained increasing attention in order to yield the "co-benefits" of public health and well-being. A city's transportation infrastructure plays a key role in ensuring such benefits as once it is built, it is difficult to change. In addition, the use of motorized transport, especially private cars, dramatically contributes to air, noise, and heat pollution, which in turn discourages individuals from participating in outdoor activities and impose negative impacts on health (De Nazelle et al., 2011). Urban public space network, however, can both support physical activity and stimulate social interactions in the population, which could ultimately lead to healthy lifestyles (World Health Organization, 2003). Consequently, creating sustainable transport (including active travel and public transport) infrastructures and attractive public spaces is vital for the development of livable and sustainable cities (European Union Regional Policy, 2011).

Of importance is that the amorphous and uncontrolled nature of transport construction often results in negative impacts on urban spaces, such as the large tracts of Space Leftover After Plan in the vicinity of linear infrastructure, e.g., a highway (Carmona, 2003). This issue is known as "community severance" at a neighborhood scale that could result in a disconnect in active travel networks, and inaccessible, impermeable and uninhabitable tracts of public space (Anciaes et al., 2016; Carmona, 2003; Trancik, 1986), leading to a decrease in users' physical activity (De Nazelle et al., 2011; Ewing and Cervero, 2010). Moreover, a separated design of transport infrastructure and public spaces have adverse effects on an individual's perception of the environment, for the leftover public spaces associated with transportation infrastructure (e.g., deserted parking areas) can raise the public's fear (Jacobs, 2016; Kim et al., 2013; Norris et al., 2002). This has led to growing interest in the integrated design of transport infrastructure and public spaces, with prioritizing the importance of serving the needs of people and creating better places over the enhancement of mobility (Cervero, 2009; Cervero et al., 2017; Ravazzoli and Torricelli, 2017; United Nations, 2013).

Consideration of human behavior in either transport engineering or public space design practices has a considerable history (Harris, 1966; Hellpach, 1935; Lynch, 1960). Chadwick (2013) emphasized that urban planning is related basically to human beings and their behavior. Along these lines, planning strategies of Woonerf (Constant, 1981) and Home Zones (Institute of Highway Incorporated Engineers, 2002) have been developed successfully to reconcile transport and public space systems and human behavior on neighborhood streets. Shared Space initiatives (Hamilton-Baillie, 2008) extended these applications beyond the neighborhood scale to build a whole public realm on urban streets that fosters a sense of safety and vitality for all road users.

In theoretical research, complex systems theory has been widely recognized as a powerful approach for understanding and managing the interplay between transport, spaces, and humans. A system consists of a group of subsystems organized in a hierarchical and decomposable structure (including a few levels) (Brady and Davies, 2014). Complex systems are systems constituted by many interacting heterogeneous components (also known as agents). The behavior of complex systems is not merely a sum of individual agents' behavior but is embodied as an "emergent behavior". Simon (1962) highlighted that complex
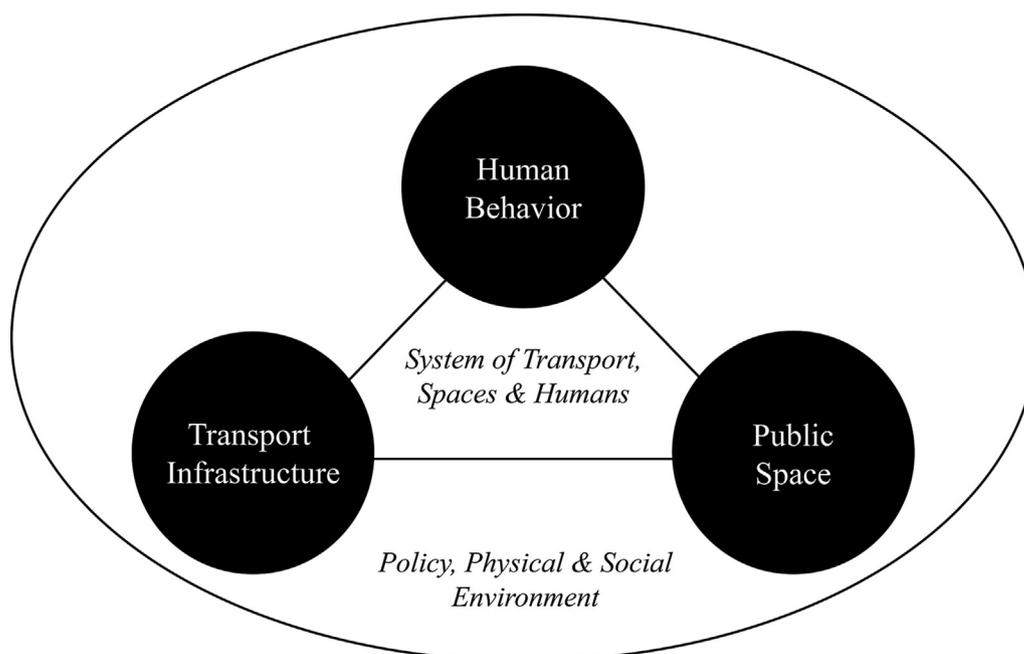

**Fig. 1** A description of the system of transport, spaces and humans.
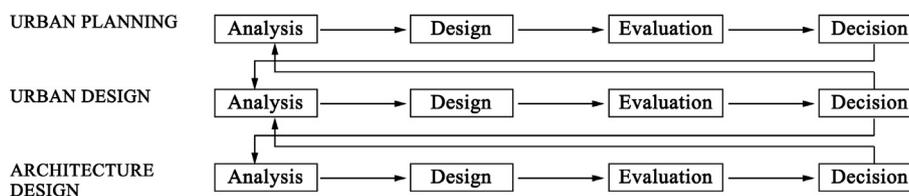
Fig. 2   An illustration of urban design, planning, and architecture design processes. Adapted from Moughtin (2003, p. 19).

systems have distinct features of non-static, non-linearity, and feedback loops. Besides, the system is open that exchanges mass, energy, and information with its surrounding environment. Urban systems are often classified as complex systems (Forrester, 1969). The two sub/urban systems, transport infrastructure system, and public space system, are also complex systems that both interact closely with human behavior. The components of transport, spaces, and humans, interacting with and transforming each other, could then be considered as an extensive system which has interplay with its surrounding policy, physical and social environment (as indicated in Fig. 1).

From the system view perspective, the design of transport infrastructures and public spaces should set a goal of system integration – forming a coherent transport, spaces, and humans system by coordinating interactions between the components (Whyte, 2016). In an attempt to reach system integration, Saidi et al. (2018) argued that it is critical first to analyze the correlation between system components and then to find strategies for creating short to long term coordination. In the urban design process, a systems approach (Mcloughlin, 1969) combining cyclical procedures with immediate loops is proved essential (Moughtin, 2003). Fig. 2 shows a model of the urban design process, which consists of analysis, design, evaluation, and decision-making procedures. Urban planners, designers, and architects go through such a co-dependent process to choose the optimal plans at different scales. In this process, decisions of the final plan are made depending on the results of the evaluation of multiple design alternatives, i.e., the different strategies for solving the problems extracted from the analysis of the target urban systems. Therefore, it is necessary to examine the mechanism and conflicts of the complex transport, spaces, and humans system, to choose suitable strategies to design, and to critically assess the alternative plans for the sake of making sensible decisions.

Traditionally, urban designers and planners applied subjective assessment methods to evaluate alternative transportation and public space plans. The advent of computer simulations capabilities supplements urban design with fresh insights into the analysis of the multi-agent urban systems, and with quantitative assessments of physical plans (Buchanan, 1963; Christaller, 1954; DeLanda, 2016; United Nations, 2013; Gan, 2014; Roscia et al., 2013; United States Federal Highway Administration, 1968). In addition, neither urban designers nor human behavior theorists are sufficient on their own to address the issues; instead, a combination of multidisciplinary research, policy-making, and urban design practice is identified to be a co-benefit approach that contributes to achieving overall sustainability (Braun et al., 2016; Lowe et al., 2014; Yigitcanlar and Kamruzzaman, 2014). For instance, the issue of community severance has been approached by Anciaes et al. (2016) through building a multidisciplinary toolkit that identified and mapped the methods employed in various research fields.

1.2. Gap and aim

Despite the growing research interest in the spatial integration of transport infrastructure and public spaces, there remains a need for human behavior considerations in the design process. Though a body of design practices have been applied to reconcile transport, spaces, and humans, they are mainly limited to urban streets – a certain type of transport infrastructure. Moreover, the complex interactions between the system components should be clarified, and the outcome of integrated plans needs to be examined quantitatively for choosing the optimal scenarios, e.g., the more walking- and cycling friendly scenarios. On the other hand, novel technological tools (e.g., agent-based simulation) which play a growing role in the analysis, design, and evaluation of such a complex system fall short of critical reviews. In summary, there is still a lack of multidisciplinary decision support toolkits that provide state-of-the-art methods and tools for the analysis-design-evaluation process in designing an integrated transport and spaces system with consideration of users' behavior.

To bridge this gap, the novelty of this paper lies in proposing elements of such a toolkit, which could provide benefits for the following stakeholders:

- Urban designers and planners with the state-of-the-art regarding knowledge in this field to assist them in the choice of suitable approaches to plan and assess alternative scenarios;
- Decision-makers and policy-makers with a toolkit that gives multidisciplinary research support to set goals for projects, to take effective management and to make efficient policies;
- Computer scientists with insights into relevant urban issues (e.g., the impact of a motorized transport infrastructure plan on human behavior) and technical tools, in order to develop realistic simulation models.

To this end, we first ask the following complementary research questions:

- What is the correlation between transport infrastructure, public space, and their users, and how to promote positive interactions?

- What kinds of policies, operational strategies, and urban design methods are used to integrate these three components?
- How to evaluate the effectiveness of an integrated system?
- What tools are employed to address this relationship?

This paper, for the first time, carries out a systematic literature review from a multidisciplinary perspective to answer these questions. To elucidate the theme of this review, three key terms are firstly defined in the following subsection.

1.3. Definitions

Urban transportation infrastructure, in this paper, is with reference to roads and rail-based transport lines (including streets, highways, railways, etc.). Urban transportation in particular faces challenges to the operation of existing infrastructure, the proposal of new infrastructure and the rethinking of redundant infrastructure by taking account of the "real needs" of people (London Assembly, 2015; Stimmel, 2015). This review mainly aims at addressing the first two of these challenges. With the large variety of public spaces, a possible classification introduces two dimensions of societalness and accessibility (Lévy, 2017). Based upon this, public space in this paper is defined as societal space with free access to the public, i.e., public realms such as streets, squares, and parks. Intertwined with transport infrastructure and public space is human behavior, which in the context of this paper refers to physical activity, social interactions, and travel mode choice behavior. Here, physical activity indicates both recreational activity and active travel (also known as non-motorized transport) such as walking, cycling, and scooters.

2. Methodology

2.1. A framework

To structure this literature review and propose a toolkit in the end, we developed a framework. The framework aims to support communicating reviewed methods and tools used in mechanism analysis, policy-making and urban design, and plan evaluation, and at the same time to allow for mapping them in different levels of the transport, spaces, and humans system. The key elements and structure of this framework are based on the system description shown in Fig. 1. To answer the four research questions, the review was performed in four parts, which are also positioned in the framework as presented in Fig. 3.

- Part I: review scientific studies of the relationship between human behavior and the transport and spaces environment (in Section 3).
- Part II: review design and policy strategies used for incorporating humans in an integrated transport and spaces system design (in Section 4).
- Part III: review metrics and methods applied for assessing integrated plan alternatives (in Section 5).
- Part IV: an in-depth review of state-of-the-art tools used by researchers in different fields to deal with the issue of reconciling transport, spaces, and humans (in Section 6).

After completing the review, this framework is populated with relevant tools and methods identified, leading to a proposed decision-making toolkit (shown in Section 7). The first three parts of this literature review were executed using a combined database search strategy; whereas, for the final part of this review, we relied on publications resulting from the first three parts (partly referred to the methodology used in (Bild et al., 2016)).
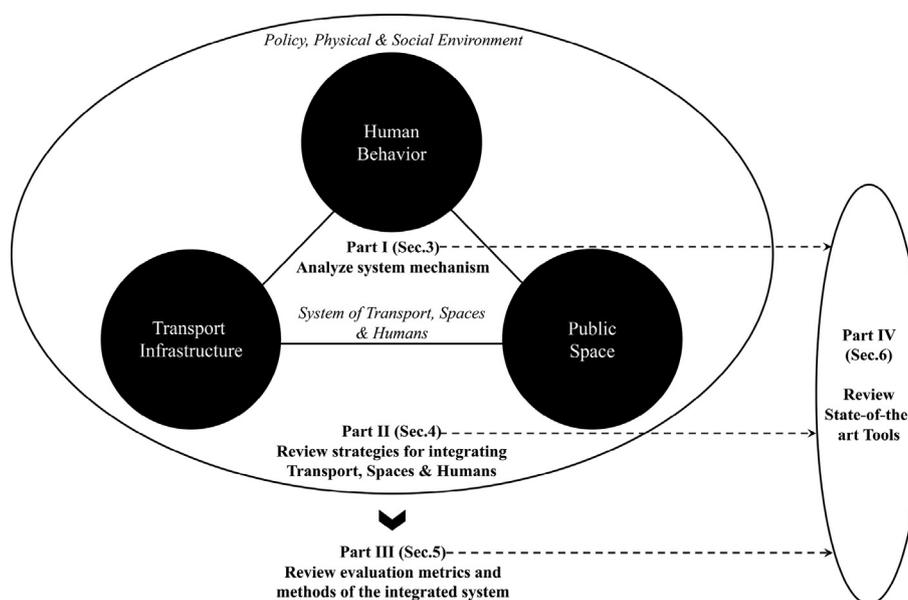

Fig. 3 The framework of the systematic review (black circles are the components for integration, in **Bold** are four parts of the review process).

2.2. Part I–III: a search for scientific knowledge and multidisciplinary methods

We began with a database search using Web of Science, and then an online search using Google Scholar. Based on the publications from the first two steps, finally, we reviewed the references they cited and the references in which they were cited, to reach literature not captured from the keywords searches but are influential in the topics of interest.

Initially, we searched on the Web of Science, which is one of the most recognized scientific databases for peer-reviewed high-quality journal content. The following combination of keywords was used: TOPIC= ((transport infrastructure) or (transportation infrastructure) or (high-speed transport) or mobility or traffic) AND TOPIC= ((public space) or (urban space) or (land use) AND TOPIC= (integrated or integrating or integration) AND TOPIC= ((urban plan) or (urban design) or planning or (architectural design) or (urban modeling)) AND TOPIC= ((human behavior) or (human activity) or (physical activity) or (public life) or (everyday life)). The justification of the topics is outlined as follows. The first two topics restricted the research to the area of transport infrastructure and public space systems. In order to provide an overview of the related transportation research, we expanded the keyword search to "high-speed transport, mobility, and traffic". To have a multi-scale review (from neighborhood to city) and to involve alternative terms for public space, "land use and urban space" were contained in the second topic. The third and the fourth topics defined the methodology of interest: only articles using integrated approaches—urban plan, urban design, architectural design, or modeling. The final topic reflected the interest of this paper, which relates to human behavior or public life that is influenced by the change of the built environment. Fig. 4 shows the records appeared after the year 2000 (only four results before 2000) on the Web of Science as categorized by research areas, indicating a multidisciplinary research background for our topics of interest.

However, the Web of Science covers only a fraction of the journal articles in the disciplines of urban design, planning, and architecture, a large part of which were excluded from the scientific domains. Consequently, we performed a search on Google Scholar encompassing the
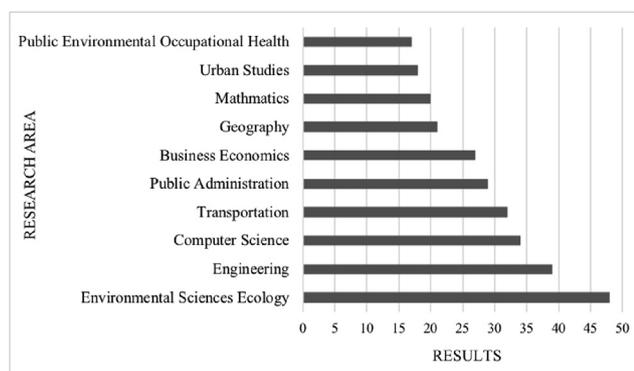
Fig. 4   Web of Science results categorized by research areas. Period: Jan. 2000—Mar. 2018.
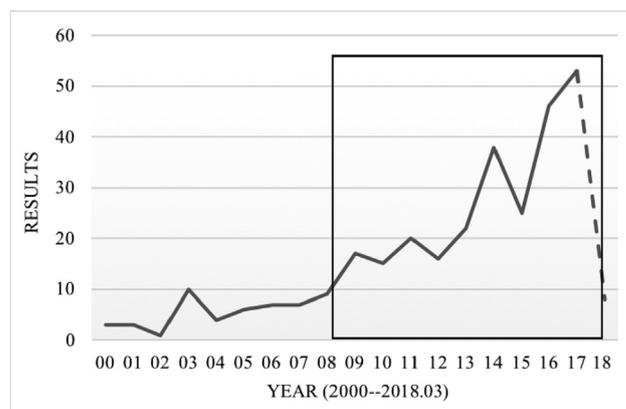
Fig. 5   Historical trends from the Web of Science and Google Scholar search. Period: Jan. 2000 to Mar. 2018.

same period, which publishes not only journal papers, but also books, dissertations, and other materials in a wide range of disciplines. Five keywords were used for the search: "transport infrastructure" (or "transportation infrastructure"), "public space", "human behavior", "integrated", "urban design". The interest in the topic is witnessed through the historical trend line in Fig. 5 (note: a dashed line is used in 2018 because data was collected by the end of March 2018 rather than the full calendar year). Noteworthy, research on the area of interest showed a rapid increase over the past decade, over 85% of all relevant articles have been published. Therefore, this study chose those published between 2008 and March 2018 on which to conduct a qualitative review.

Abstracts of all the 200 articles were initially reviewed to determine the relevance of the paper prior to any further detailed review. A total of 110 articles were published on the topics of interest from Web of Science, of which 64 were beyond the scope of the paper as stated in Section 1.2 (e.g., studies of contagious disease spread, the underground transportation development, the design of transport hubs and those quite focus on a specific case study). The search on Google Scholar resulted in 155 references, 78 of which were chosen for review. The criteria used to select these articles or books related to whether the paper aims to use the urban design or modeling methods to integrate at least two elements in the topics of transport infrastructure, public space, and human behavior. Finally, the 124 publications were reviewed qualitatively. All relevant literature that was the result of the structured search was briefly summarized, including the primary outcomes and insights provided.

2.3. Part IV: a review of state-of-the-art tools

Based on the previous parts of the review, we identified computer simulation as an increasingly used tool and described the leading paradigms for building simulation models referred to in the publications reviewed. In order to give an overview of the types of simulation paradigms, the authors' personal archive consisting of seminal literature from the original schools of thoughts were incorporated at

the same time. Based on these publications, especially three influential books: *Simulation modeling & analysis* (Law and Kelton, 1991), *Simulation for the social scientist* (Gilbert and Troitzsch, 2005), and *Agent-based models of geographical systems* (Heppenstall et al., 2011), a brief overview of the usage of simulation in urban systems, accompanied with a description of traditional modeling paradigms was offered. After critically compared the advantages and disadvantages of the leading and traditional paradigms, we addressed the opportunities and challenges of simulation tools. Considering our focus on providing a theoretical and empirical toolkit for modelers and designers, we also reviewed publications detailing the applications of the use of the selected simulation paradigms for integrating transport infrastructure, public space, and human behavior.

3. Scientific knowledge of the correlation between transport, spaces, and humans

This section covers those papers that deal with the analysis of the association between transport infrastructure and public spaces planning and human behavior.

3.1. Conceptual frameworks linking transport and public space design with human behavior

In the understanding of the correlation between users of spaces and their surrounding transport infrastructure and public space environment (a physical-social environment), it is generally accepted that humans interact with the environment through perception and behavior (Bild et al., 2016; Sallis et al., 2006; Schlüter et al., 2017). From an individual's perspective, perception is a process of gathering information from the outside while human behavior is a process of impact on the environment. The progress in-between these two processes is as follows. An individual perceives its environment (both the physical-social and policy environment), assesses the information, and forms a perceived environment in mind based on his interpersonal characters (e.g., demographics and family situations) and intrapersonal characters (e.g., past experience, values, and knowledge). This subjectively perceived environment and the individual's objective needs (or goals) co-stimulate the selection and executive of behavior.

A well-documented positive interaction between transport, spaces, and humans is the impact of some transport and public space design interventions on promoting behavioral changes for a healthier lifestyle, such as active travel increase and car use reduction. The following have been shown to improve active travel amongst the general population significantly: an increase in mixed-use and compact urban development, accessible and well-connected street configuration equipped with dedicated active mobility infrastructure, and high environmental quality public spaces with considering the use by children and elderly (Shirehjini, 2016; Townsend, 2016).

Certain scholars have concluded that active travel plans, i.e., prioritizing pedestrian, cycling, and scooting/skating, were advantageous to both public health and child development (Townsend, 2016). However, others cast doubt on the causal link between active travel plan and public health. Even though walkable neighborhoods can increase human energy expenditure by stimulating physical activity, pedestrians and cyclists may face greater exposure to air pollution and a higher risk of traffic injury (De Nazelle et al., 2011). Moreover, though street connectivity has a positive effect on walking for transport purposes, it may have a negative effect on walking for recreation (Koohsari et al., 2013). De Nazelle et al. (2009) and Kollert (2017) made efforts to build conceptual frameworks by taking account of the reciprocal relationship between policy, built environment design, human behavior, environmental quality, exposure, and health. Fig. 6 is a holistic framework containing the causal loops among these elements.

Given the side-effects, a combined methodology including an increase in active mobility, a decrease in motorized transport emissions and the provision of Green Infrastructure[1] seems to be more effective for both providing opportunities for physical activity and mitigating human environmental exposures (Mueller et al., 2017; Woodcock et al., 2009). For instance, a design of well-connected bicycle lanes and green spaces can stimulate cycling behavior and improve access to urban green spaces, which can alleviate individuals' exposure to local air pollution (Niță et al., 2018). To this end, a body of research examined the association of green spaces design, human behavior, and health. Xue and Gou, 2018 demonstrated that the "healing power" of green spaces could relieve mental health problems especially in a high-density urban context; this is also consistent with the Biophilia Hypothesis (i.e., humans love to connect with living structures in the environment) (Kellert et al., 2011). However, by using the Space Syntax (Balsas, 2017) methodology, Koohsari et al. (2013) proved that the proximity and attractiveness of green spaces were unrelated to the level of physical activity, which should be analyzed from two aspects separately: the initiation and the maintenance of physical activity. Therefore, more studies are needed by combining the measures of proximity and attractiveness with the count and size of green spaces to clarify the aforementioned association, and further gaps in this domain can be found in (Koohsari et al., 2013).

3.2. Quantitative analysis of the relationship between transport, spaces, and humans

Traditionally, a systematic review and statistical analysis have been utilized in analyzing the reciprocal relationship between the elements of transport-spaces-humans. Recent decades have seen the increasing introduction of simulation approaches, which enable scientists to represent an individual's decision-making process and explore the impacts of the built environment changes on humans. For instance, Aschwanden (2014) assessed the influence of walkability on walking behavior by comparing the ground-level aerosol concentration and air pollution exposure due to alternative urban plans. In order to estimate aerosol concentration, a machine learning algorithm using a Self Organizing Map was adopted; to evaluate individuals' exposure to pollutants, a combined model of procedural urban modeling together agent-based modeling was chosen. After conducting a study
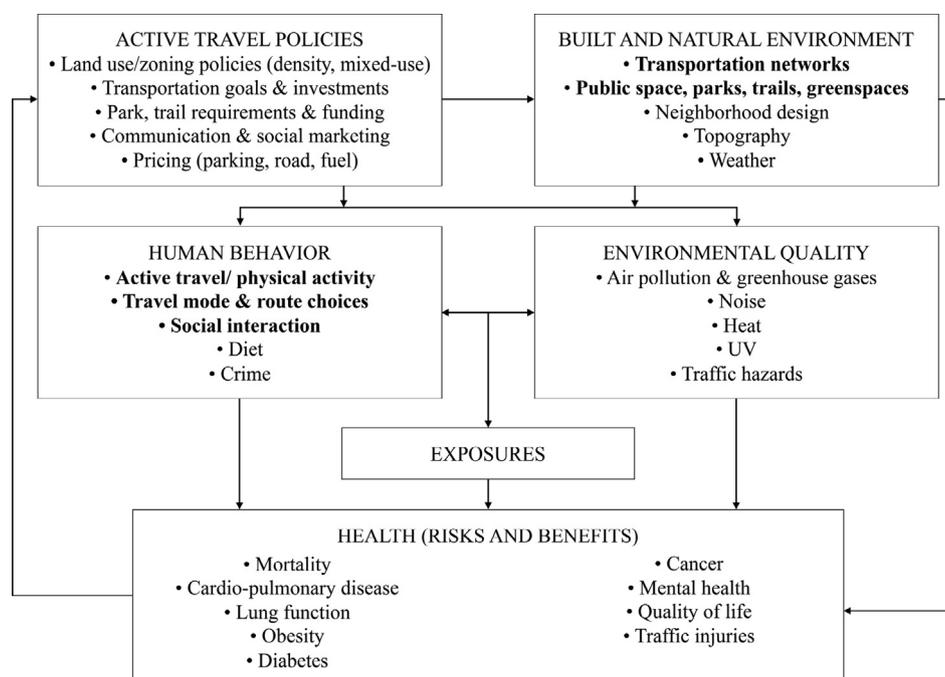
Fig. 6   A conceptual model linking policy, transportation and public space design, human behavior, and health (in **Bold** are components in the transport, spaces, and humans system). Adapted from De Nazelle et al. (2011, p. 768).

in Switzerland, Aschwanden concluded that the street layout and integration measures in residential areas are associated with the hazard of mortality. Among others, the Built Environment Stochastic Spatial Temporal Exposure (BESSTE) model estimated the impacts of an active travel plan on individual's daily energy expenditure and exposure to air pollution by using a Monte Carlo Simulation (De Nazelle, 2007). Chokhachian et al. (2017) used a coupled TRNSYS and ENVI-met model to simulate the microclimate in dense urban environments and people's outdoor comfort. To explore the limits of building density, they measured the heat tolerance of people in extreme outdoor conditions.

4. Strategies for integrating transport, spaces, and humans

All resulting papers that relate to policy initiatives, project management strategies, and design practices, incorporating the elements of transport, urban space, and behavior of people in this context are summarized here.

4.1. Policy and governance

4.1.1. Transport policies
To implement scientific knowledge into active travel policies, Kollert (2017) noted that the provision of walking and cycling infrastructure alone is insufficient to trigger high levels of active mobility. Effective policy and design interventions should be combined and coordinated, and based on behavior analysis. Townsend (2016) argued that social interventions, such as community communication

and cultural context analysis are supplementary. Consequently, Townsend recommended a practical combined socio-physical approach where policies promote cycling through planning cycling infrastructure, performing bike-sharing programs, and restricting automobile usage at the community scale. Groups of scientists use mode choice models to look into the impacts of urban design features on sustainable travel and private cars (Boulange et al., 2017). Interestingly, Braun et al. (2016) found that the provision of public transport stops and public transport-oriented travel demand encouragement may cause modal competition between public transport and cycling. Therefore, integrated cycling and public transport interventions would be useful to stimulate cycling in a short or medium term. Other research focuses on stimulating active mobility among the elderly. Srichuae et al. (2016) illustrated the need of distributing small public spaces and leisure activities within compact, walkable communities, while Aguiar and Macário (2017) highlighted that public transport could be the best option for the elderly.

4.1.2. Governance and financing
To achieve system integration, the closed governance characterized by central control is inefficient. For instance, in certain developing countries, where an individual policy-maker leads decision-making, the success of Transit-Oriented Development (TOD) is usually obstructed by institutional barriers (Mirmoghtadaee, 2016). Therefore, open governance based on coordinated action and co-production, encompassing common interests and synergetic effects, appears to be an efficient approach. The Public-Private Partnership (PPP), combining infrastructure and real estate development, tied with the sale of up-zoning rights to developers, seems to be a "win-win"

solution for involving market parties to finance the costs of the infrastructure development. For instance, in the case of rail-transit development in Hong Kong, the government owns the majority of shares in MTR Corporation; by selling 23% to private investors, broad public interest in transport-land use decision-making is ensured (Cervero, 2009). However, there are counterexamples to the PPP. In the city of Rio de Janeiro, the PPP has been applied to finance smart city initiatives in terms of infrastructure and ICT development, but De Oliveira and Pinhanez (2017) criticized that it results in bribery scandals and does not comply with the moral economy principles of smart cities.

4.2. Urban design and planning

4.2.1. Integrated transport-spaces framework
In the Habitat III[2], the role of public space was promoted as a transformative component of city-building, for comparing to other infrastructures it holds opportunities for citizens to improve their health, and social interactions. In responding to this, Farrell and Haas (2018) proposed a public space roadmap, in which a holistic urban plan integrating human-scale public spaces and other infrastructures was recommended. Sherman et al. (2014) presented an integrated framework for an urban mobility infrastructure plan—the Urban Parangolé. This formed a platform for merging innovative mobility strategies with ecological, social, and economic viability. Designers were designated to mediate between formal and informal urban areas, as well as between top-down planning and bottom-up initiatives. In order to enable self-organization through new forms of local spaces, only the structure of the built environment needs to be designed (Romice et al., 2017). Firstly, a set of multi-modal mobility networks and multi-scalar networked hubs was created to produce a seamless loop of connectivity. The hubs and underutilized urban spaces were reorganized as porous volumes of public spaces, preparing for additional programs and social infrastructure, including housing, educational centers, medical facilities, shops, and sports areas. Simultaneously, green infrastructure and pre-fabricated building components, energy-independent buildings, water recycling systems worked together to create a low-tech sustainable intervention in the fragmented community. More sustainable urban design interventions were demonstrated in (Connery, 2009; Shirehjini, 2016), which highlighted the concerns of biodiversity and the use of porous and permeable pavements, green roofs, and rain gardens.

In order to build a city as a whole, the design of an integrated urban transport and spaces system should incorporate both physical and virtual public spaces (e.g., Twitter, Facebook) (Lévy, 2017). In order to manage the distance between socially and physically segregated individuals for building a holistic society, three methods are mainly used: co-presence, mobility, and telecommunication. Lévy (2017) indicated that the three modes are in both cooperation and competition. However, many smart city models created massive amounts of virtual spaces that take the place of our needs to meet people in physical public spaces, and probably ease the spatial and temporal bounds linked human activities together — resulting in a decrease of getting health benefits from sensory interactions with the natural environment (Colding and Barthel, 2017). Therefore, there is a need to take the transport-public space system as a bio-socio-technological urban system.

4.2.2. Streets as public spaces
After cars had started encroaching in the streets, people (pedestrians and cyclists) and public spaces were turned aside. As a result, researchers have been aware of the necessity of reclaiming places back from vehicles for the use of people and for creating social life and then they call for "getting streets back to places", and "humanize the street environment" (Ahmed, 2017; Project for Public Spaces, 2008). In this regard, there is a trend of building a complete road for reconciling cars, people, and public transit, and proposals such as Home Zones have gained increasing attention. By restricting the vehicle speed to 20 km/h and prioritizing sustainable travel mode in neighborhoods, home zones proved beneficial for social inclusion and public life, in terms of enhancing the personal feeling of the environmental quality and traffic safety, and public participation in decision-making (Sauter and Huettenmoser, 2008). It was also highlighted that new home zone designs should create parking-free areas to preserve areas for play.

However, not every street should be traffic-calmed, and busy streets can be advanced to better entertain public life by expressing the identity, needs, and aspirations of a particular community in holistic environment design. Some design principles were displayed in *Streets as Places* (Project for Public Spaces, 2008) including the provision of aesthetic wide sidewalks, different types of squares, markets, vendors, the floor of public space (i.e., a walking surface integrated with street furniture, see (Tofiluk, 2015)), plants, public art (e.g. (Cushing and Pennings, 2017)), and events for gathering.

4.2.3. Design for promoting active travel
To enrich the knowledge of active travel design, Bahrami and Rigal (2017) explored the concept of physical effort, which is related to active mobility and urban experience and contributes to health. Individual's experiences of effort in active transport can be categorized as minimizing effort (making the least effort for mobility), the distraction from the effort (tolerating the walking experience by providing distractions), motivating and forming effort (training and practicing skills). Since traditional transport planning either tries to minimize effort or to distract people, Bahrami and Rigal argued that designers could take effort as a positive thing by such as creating training and exercise places along paths. A three-fold approach for stimulating non-motorized travel was then proposed, which includes a reduction of required effort through permeable street networks planning, a distraction of effort by building attractive and active spaces, and entertaining efforts. They further indicated that often fragmented existing public spaces, especially the linear spaces, need to form a meshwork, interlacing active mobility lines that provide city-wide accessibility, and diverse activities.

4.2.4. Transit-Oriented Development

The approach of TOD, which was originally demonstrated as a fundamental principle in the *Charter of the New Urbanism* (Congress for the new urbanism, 2000), has been widely utilized in planning livable cities. TOD aims to change citizen's travel behavior to use public transport in preference to private cars, and supplement public transit with walking and cycling for shorter distances within a healthy environment. Loo and Du Verle (2017) proposed a new approach for the TOD plan by unifying the theories of transit-oriented, people-oriented, and place-based design. A two-level full-scale sustainable transport solution and a multi-metric assessment framework for TODs (assessed by both public transit patronage and urban design features) were suggested. Moreover, Sainz Caccia (2017) highlighted that open public spaces can be the core of TOD planning, and to create a vivid and connected pedestrian environment in these spaces, an increase in density and place-making[3] proved useful (Cervero, 2009). A good practice here is Hang Hau Mass Transit Railway station in Hong Kong, which unified the ground floor shopping mall and the station with a second-level footbridge and landscape, bringing place-making premiums to the surrounding communities. To ensure a successful transfer of successful TOD practices, a comprehensive understanding of both the local cultural and institutional contexts is of importance (Masoumi and Mirmoghtadaee, 2016). An analytical framework for assessing local contexts can be found in (Mu and De Jong, 2012), which presented both important and critical planning conditions (including urban design aspects, governance aspects, and a transport service) for TOD proposals.

4.2.5. Accessibility as a planning method

The concept of accessibility has been utilized as a framework for the interactive planning and as a way of achieving social equity in an interconnected transport and land use system (Grengs et al., 2013). "Sustainable accessibility", with a goal of fulfilling the economic, social and environmental aims, was introduced by Bertolini et al. (2005, p. 209) as "the amount and diversity of places of activity that can be reached within a given travel time and/or cost". They incorporated the metrics of the amount and diversity of activity places that people can access in a specific period of travel time and/or cost, along with the percent of environmentally friendly transportation usage (i.e., the use of active transport, public transport, and cleaner cars).

However, others argued that "accessibility" itself could not make a thriving, livable city. The objective measurement of transport infrastructure and public space plans ought to be supplemented with subjective measurements. Having measured the accessibility and implemented satisfaction surveys in a research area, Lotfi and Koohsari (2009) highlighted that higher accessibility alone does not mean a higher satisfaction.

5. Evaluation of integrated transport, spaces, and humans plans

Papers from the literature, which relate to the prediction and evaluation of integrated plans, are summarized here.

5.1. Degrees of integration in projects

Heeres et al. (2016) put forward a conceptual framework for distinguishing different degrees of integration in transportation projects (see Fig. 7). A "solution space" method was applied to classify the integration as functional isolation (i.e., infrastructural issues are treated as isolated problems, dealt without cooperating with other land use sectors), sector-internal integration and external integration. They considered that sector-internal integration forms a multi-modal transport system with nodes and connections linking local and regional levels. External integration is more cost-effective because it expands the focus of directly improving the accessibility of transport systems to other interrelated interests, such as housing location, recreation activities, and the natural environment. Moreover, after distinguishing different inducements underlying integrated plans, they argued that a viable integration involves attention to both the strategic and operational goals. Having compared two case studies in the Netherlands, they highlighted that strategic plans should be followed up at the operational level, and local designs ought to be explored further to embed the project within a wider region.

5.2. Travel demand prediction

Responding to policy interventions, designers and computer scientists made efforts to predict the public transport and active travel demands under different urban transport-public space layouts, in order to select those that attract

Fig. 7   Matrix of the integration degree of transport projects. The horizontal axis indicates three perceived solution spaces, while the vertical axis illustrates the efforts made to achieve integrated coalitions. Adapted from Heeres et al. (2016, p. 426).

more people to use sustainable travel modes. Based upon a mobility pattern analysis of the use of taxi and bus, Y. Liu et al. (2017) proposed a mode choice model, which enables the prediction of bus travel demand for different bus routing. Dhanani et al. (2017) estimated pedestrian demand by combining the methods of space syntax measures of accessibility and using volume area ratios to calculate land use intensity.

5.3. User experience evaluation

To understand how the design of the spatial settings impacts on human behavior, and how people perceive the physical qualities of the urban public spaces, the Post-Occupancy-Evaluation (POE) has been used by groups of researchers, most of whom are in the field of environment-behavior studies. Shurbaji and Furlan (2017) explored the association between the spatial features of parks and social interaction; Rodrigues et al. (2013) probed the park user's experience through evaluating their preferences, needs and satisfaction levels using methods of observation, behavior mapping, surveys, and interviews. Kaiserman (2017) estimated three types of public spaces—streetscape, pocket park, and community garden—in terms of their mental health benefits by introducing a sensory framework based on how the place is experienced through five senses. Among others, L. Liu et al. (2017) applied a machine-learning model in measuring the continuity of street walls, after which the model results were compared with the public's on-site rating scores. In parallel, Xiang et al. (2017) developed a people-centric mobile Crowdsensing platform to understand the travel modes of different demographic groups and how individuals utilize public spaces. Here, qualitative data were collected from the survey, participatory workshops, Sensing data, CDR data, and Geo-tagged social network messages.

5.4. Public health assessment

The impact of the environment on health, which is captured in the notion of environmental health, has been assessed by using the approaches of Environmental Impact Assessment (EIA) and HIA. However, Verbeek (2017) criticized that EIA does not consider public health, are not legally bound, and too generic without considering local contexts. Nieuwenhuijsen et al. (2017) commented on the HIA that there is a need of introducing a holistic view, and a participatory process; thus, an integrated HIA was recommended (De Nazelle et al., 2011). Currently, a few integrated HIA models and tools such as the Health Economic Assessment Tool (HEAT) and the Urban and TranspOrt Planning Health Impact Assessment tool (UTOPHIA) have been used in certain case studies (more tools see (Nieuwenhuijsen et al., 2017)).

5.5. Resilient outcomes evaluation

Building resilient cities, featuring a high quality of life and a low ecological footprint, has taken a significant role in pursuing sustainability in many countries. Endeavors have been made to reorganize and manage the transport-land use system to improve the adaptive capability of the built environment; among others, urban models for representing the human-environment system, and evaluating resilient city outcomes under alternative policies have been proposed. The Wellington Integrated Land Use-Transport-Environment Model (WILUTE) is an integrated model, which adopts estimation metrics of transport-related energy consumption and pollutants, public health benefits, the adaptive capacity to sea-level rise and first-round socioeconomic outcomes (Zhao et al., 2013).

Compared with conventional system models, the agent-based WILUTE model is showed to be more capable of estimating human behavior changes. Simultaneously, by combining environmental effects and economic development within a wide spatial scale, it was applied in evaluating the impact of public transport policies, households income, parking fees, and land use on active mobility (Mackenbach et al., 2016). Among others, Xu and Xue (2017) focused on the evaluation of resilience on a relatively small scale, such as in complex public spaces, which are three-dimensional urban spaces and serve massive crowds. Ten indicators were then elicited containing the metrics of security and emergency planning, multi-layer structures with diverse functions, multi-stakeholder, financial support, and statistics of natural disasters.

Having evaluated the economic resilience of transport-public space projects, several researchers floated an idea that overall investment in transportation upgrade, superior civic places, and pedestrian facilities is an integral element of achieving economic sustainability. More than anyone else, Cervero (2009) elevated the roles of place-making, urban amenities enhancements, along with advanced sustainable transport modes as economic development approaches to balance the competitiveness between livability and mobility. He applied hedonic price modeling to estimate the influence of the proximity to a new linear park (updated from original freeways) on residential property values in the case studies of San Francisco, Seoul, and Boston. In addition, the model was utilized in assessing land value returns of the TOD designs in Hong Kong, which pursue a sense of place in the station-area development. Cervero proved that a well-designed and integrated transport-public space environment coupled with enhanced sustainable travel yields net profits in the residential sales price and attracts knowledge workers.

Table 1 summarizes some of the main research issues, and extant methods and tools for integrating transport, spaces, and humans in the literature covered in previous sections.

6. State-of-the-art tools

Having reviewed scientific knowledge, integration strategies, and evaluation approaches, we distinguish advanced computer simulation and machine learning tools from other scientific tools. As machine learning techniques are already well recorded (e.g. (Witten et al., 2016)), this paper focuses on the state-of-the-art in computer simulations. In the reviewed publications, three leading

Table 1 Research issues, methods, tools and key literature from 2008 to 2018.

Parts of Review	Research Issues	Methods	Tools Used in Literature	Key Literature
Part I: Analysis — Correlation between Transport, Spaces, and Human Behavior	Linking the Transport-Public Space Design with Human Behavior	• Systematic review • Statistical analysis • Conceptual model • Mathematic model • Computational model	o Gravity model o Space Syntax	De Nazelle et al. (2009); Koohsari et al. (2013); Mueller et al. (2017); Townsend (2016)
	Simulations for Objectively Analyzing the System Mechanism	• Machine learning • Computer simulation model	o A Self Organizing Map tool o Agent-Based Model o Monte Carlo Simulation o Coupled TRNSYS-ENVI-met tool	Aschwanden (2014); Chokhachian et al. (2017); De Nazelle (2007)
Part II: Strategies — Policy and Governance	Transport Policies	• A combined social-physical approach • Integrated cycling-public transport strategy	o A hybrid initiative for motorized transport reduction and sustainable transport promotion	Braun et al. (2016); Townsend (2016)
	Governance and Financing	• Open governance • PPP		Cervero (2009); Masoumi and Mirmoghtadaee (2016)
Part II: Strategies — Urban Design and Planning	Integrated Transport-Spaces Framework	• An integrated network of multi-modal mobility & multi-scalar hub • GI and Low-tech sustainable interventions • Integrating physical public spaces with virtual spaces and other infrastructures	o Pre-fabricated and energy-efficient buildings design o Porous and permeable pavements o Green roofs o Water recycling systems	Colding and Barthel (2017); Connery (2009); Lévy (2017); Sherman et al. (2014); Shirehjini (2016)
	Streets as Public Spaces	• Home Zones • Holistic street environment design	o Public art o Plants o Design floors of the public space	Sauter and Huettenmoser (2008); Project for Public Spaces (2008)
	Design for Promoting Active Travel	• Entertaining physical Effort	o Design training and exercise places along paths	Bahrami and Rigal (2017)
	Transit-Oriented Development	• Combined transit-people-oriented approach • Place-making in open spaces • Multi-metric assessment	o Assess TODs by public transit patronage and urban design features	Loo and Du Verle (2017); Mu and De Jong (2012); Sainz Caccia (2017)
	Accessibility as a Planning Method	• A combined approach of Sustainable Accessibility and satisfaction survey		Bertolini et al. (2005)
Part III: Evaluation — Integrated Transport, and Spaces Plan	Degrees of Integration	• Solution Space method for building a conceptual model		Heeres et al. (2016)
	Travel Demand Prediction	• Mathematic model • Computational model	o Mode choice model o Space Syntax	Dhanani et al. (2017); Y. Liu et al. (2017)
	User Experience and Public Health Evaluation	• POE • Self-recorded questionnaire • Machine learning	o Asus Multitouch PC T91MT™ o HEAT o UTOPHIA	L. Liu et al. (2017); Nieuwenhuijsen et al. (2017); Rodrigues et al. (2013); Shurbaji and Furlan (2017)

Table 1 (*continued*)

Parts of Review	Research Issues	Methods	Tools Used in Literature	Key Literature
	Evaluating Resilient Outcomes	• People-centric mobile crowdsensing platform • EIA and HIA • Integrated computational model for evaluating transport-related energy consumption, pollutants, public health benefits, and socio-economic outcomes • A set of resilience indicators of complex public spaces	o WILTE simulation o Hedonic price model	Cervero (2009); Xu and Xue (2017); Zhao et al. (2013)

simulation paradigms are used: Agent-Based Modeling, Microsimulation, and Monte Carlo Simulation. This section will go a step further to first position the simulation tool in urban design and transportation planning in Section 6.1. Then focus on seven selected simulation paradigms in order to provide their architecture in Section 6.2 and applications in Section 6.3. Finally, critique the different paradigms in Section 6.4 and highlight relevant challenges to the use of state-of-the-art tools in the following section.

6.1. Combined design-simulation tools

Information and Communication Technologies (ICT) is a central issue in the building of future smart cities, and a promising way of designing a city not only by aesthetic and qualitative means but also by quantitative methods. In this respect, Batty et al. (2012) proposed a structure of a *Futur*ICTs smart city in which the use of computer simulation modeling within urban planning was well recognized. Simulation models provide urban planners and decision-makers with a systematic and rational way of selecting design alternatives by objectively analyzing urban contexts, monitoring real-time urban changes, and by predicting environmental and economic outcomes. Moreover, combined design-simulation methods proved efficient for supporting an integrated urban design. Gan (2014) combined the physical technique of a "simulation desk" with simulation tools including ArcGIS, Matlab, ENVI-met, Morphologic, CASAnova, Karalit, and Modelur for Sketch-up. The integrated approach follows a process of parametric urban parcels, real-time simulation, and plan evaluation, referring to an urban indicator index, which includes people, accessibility, environment, energy, and morphology.

On the one hand, computer simulation can be used to represent an existing transport-spaces-humans system, which is constructed as a baseline scenario in computer programs (which could be compared with alternative scenarios). Poidomani (2013) critically reviewed five cutting-edge Microsimulation models and concluded that an Integrated Land Use, Transportation, Environment (ILUTE) model or a combined MATSim-UrbanSim model is an ideal representation of such a system at a neighborhood scale (for further details of the models see Section 6.3). Computer models aided by individuals' transport data have been used to examine the interrelationship between transport network planning and route choice behaviors. Traditional aggregate simulation models are built on a simplified representation of traffic flow, while disaggregate agent-based models are suitable for describing detailed human behavior. Given that agent-based modeling has drawbacks in requiring considerable computational capacity and time cost, Manley et al. (2014) presented a framework that combines a micro-level agent-based driver behavior model with a macro-level roadway traffic dynamics model. Note, however, some transport datasets are geometrically misaligned with existing transport network data that hamper human behavior analysis. Kang et al. (2015) developed a Split-Match-Aggregate algorithm to integrate sidewalk data with the GIS transport network.

On the other hand, individual-based modeling can be used to improve human-centered designs by integrating human behavior into the public space design process which shed light on the needs of the inhabitants. Esposito and Camarda (2016) developed a conceptual model representing the objectives and the internal state of human behavior and an urban environment. In conjunction with these, integrated physical-digital approaches have gained widespread attention. Finally, simulations have been widely used in integrated urban land use-transport planning (e.g. (Fatmi and Habib, 2017)), decision-making support and participation process (e.g. (Tannier et al., 2016)).

6.2. Computer simulation paradigms

Simulation tools are built following a number of paradigms and those widely used in social and geographical systems

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L. Yang et al.

Table 2 Simulation paradigms that could be applied to model urban geographical and social systems.

Paradigm / Property	System Dynamics	Discrete-Event Simulation	Continuous Simulation	Monte Carlo Simulation	Micro-simulation	Cellular Automata	Agent-Based Modeling
Input	Stock attributes of the level, rate, and targets; Inflows and outflows.	Entity attributes; Simulation clock; Event list with start and end.	State variables at a point in time.	Probability distribution and a number of samples.	Selected properties of a representative sample of the target population.	State (attitudes, characteristics or actions) of each cell and transition rules.	Agents' characteristics (state, objective, constraints) and behavior.
Output	System state; Graphical descriptions.	Estimations and reports of the desired measures of performance.	Values of the variables in a time period; Tendency graphs.	Expected values of a physical quantity or a phenomenon.	Results of actions from the simulated units.	Patterns of interactions among cells.	Complex emergent behaviors in system level.
Method	Closed loops (information feedback and circular causality): positive or negative.	The next-event time-advance approach with routines of timing, initializing, event, and library.	A set of differential equations; Numerical-analysis techniques.	Repeated sampling techniques and algorithms; Average equations.	Dynamic or static transition probabilities.	A regular grid; Fixed rules of cell's state from the previous state and its neighbors'.	"If-then" rules within agent itself.
Feature of the system	An endogenous first-order differential equation system.	Focus on process or event; Inactive periods are skipped over.	Good at predicting the trend of a system.	Problems are multiple-integral, in unanalyzable statistics.	Widely applied to the simulation of the effects of scenarios on units.	Best used to model the emergence of properties from local interactions; Strong spatial focus.	Capture emergent phenomena; Simulate real environment; Interaction structures are flexible.
Limitation	Exogenous disturbances are usually not seen as causes of the system.	Target systems are represented by aggregate entities; Entities are passive;	Mutations of variables' continuous state and the relationship are excluded.	No real-time simulation; Results obtained are subject to the laws of chance.	One-direction interactions between units which can't learn; Simplified description of units' behaviors.	Attributes of cells are limited and locations are fixed; The rules are the same.	Highly-required computation capacity and time cost; Difficult to calibrate and validate.
Key references (for the above)	Forrester (2007, 1994); Richardson (2001); Radzicki and Taylor (1997)	Zeigler et al. (2000); Robinson (2005); Nance (1996)	Cellier and Kofman (2006); Zeigler et al. (2000)	Rubinstein and Kroese (2016); Feldman and Valdez-Flores (2010)	Harding (1991); Gilbert and Troitzsch (2005)	Benenson and Torrens (2004); White and Engelen (1997)	Macal (2016); Van Dam, Nikolic, and Lukszo (2013); Heppenstall et al. (2011)

are described in (Gilbert and Troitzsch, 2005; Heppenstall et al., 2011; Law and Kelton, 1991). Early simulation approaches were rooted in differential equations, stochastic process, and game theory, after which a group of simulation paradigms blossomed in the mid-1950s, such as System Dynamics (SD) and Discrete-Event Simulations (DES). SD is used for framing, understanding, and discussing dynamic problems arising from complex systems. From an endogenous point of view, i.e., the significant dynamic features of a system are generated from the inner working of the system itself, it plots the trajectories of independent levels (integrations or stocks) in the system and their flows over time, by using causal loop diagrams (Radzicki and Taylor, 1997; Richardson, 2001). DES concerns the modeling of a physical system as it evolves by either a mathematical or a logical representation, in which the state entities change at precise points in time (Nance, 1996). On the contrary, Continuous Simulations (CS) model a system in which the state variables change continuously over a period by using differential equations; the precise time and state relationships that cause discontinuities are not portrayed in this paradigm (Nance, 1996). Since the progress of a majority of systems is seldom absolutely discrete or continuous, the combined Discrete-Continuous Simulation has been applied in modeling these systems. In such a combined simulation, either a discrete event changes the value or relationship of a continuous state variable, or a continuous state variable meets a threshold causing a discrete event to occur (Zeigler et al., 2000). To address some stochastic or deterministic problems where random sampling is needed, Monte Carlo Simulation (MCS) is exploited. In this simulation, a random variable-a numerical quantity drawn from a probability distribution-is evaluated through computation, and the output is observed from a large number of such samplings (Feldman and Valdez-Flores, 2010; Kahn, 1956). The traditional models outlined above have been broadly employed to simulate dynamic urban systems and to estimate the social-environmental effects of built environment changes (Albeverio et al., 2007).

In contrast to modeling systems as a representation of aggregate entities (e.g., homogeneous humans, households, cities), individual-based paradigms focusing on disaggregated and heterogeneous agents have flourished. The newly developed disaggregate models consider small units of analysis and effectively mimic real situations resulting from the detailed data on which they are based. Microsimulation (MSM) is a pioneer individualized-model and was applied to urban modeling after the 1980s. Starting from a target population from which a sample is chosen, MSM works on small area microdata, by detailing a group of properties of heterogeneous individual units at a point in time. After several simulation steps, the microdata is updated following transition probabilities, a predicted sample generated, and the results aggregated and scaled up if required (Gilbert and Troitzsch, 2005). Cellular Automata (CA) emerged later as a means of depicting the complex urban system by dividing it into a regular two-dimensional or three-dimension grid of cells which have values in the interval of [0,1]. The state and behavior of each cell can change following a set of rules, and take into account the cell's current state as well as those of its neighbors

(different settings could define the neighborhood) (Benenson and Torrens, 2004). State-of-the-art individualized simulation paradigm is Agent-Based Modeling (ABM), which is composed of heterogeneous agents (such as companies, citizens, and institutes) that have autonomous, reactive and proactive behaviors formalized using behavioral rules. The crucial difference between ABM and the other two paradigms is that the "agents" are capable of learning and making decisions (Van Dam et al., 2013). System-level behavior then emerges from the output of the individual action.

Likewise, all of these modeling approaches are based on systems theory, describing the system's outer behavior as the relationship between input and output, respectively viewing the system's inner structure as state and state transition mechanisms (Zeigler et al., 2000). The difference between the simulation models is their mathematical or computational method of transforming the current state into a goal state as well as the elements that they consider and their level of detail. In Table 2, we describe the critical properties of the four traditional simulation paradigms (SD, DES, CS, MCS) and three relatively new paradigms (MSM, CA, ABM).

6.3. Applications of the simulation paradigms

6.3.1. System Dynamics (SD)
SD has been successfully used to analyze the reciprocal relation between transport planning and travel behavior, e.g., a model for explaining the failures of utilizing road-building programs to mitigate traffic congestion. Policy-makers build new roads to relieve traffic congestion and an SD model presented by Sterman (2000) showed that new road construction, which contains both new roads and the capacity improvements of existing roads, increases the attractiveness of cars and decreases the attractiveness of public transport. This consequently results in greater motorized travel than before construction, i.e., in the well-known phenomenon of "road generated traffic". His causal loop diagram was calibrated by the paradigm cases of congestion in cities such as Los Angeles, Boston, London. Furthermore, Sterman concluded that innovations (e.g., High-Occupancy Vehicle lanes), technical solutions (e.g., intelligent vehicle-highway systems), and policies aimed at relieving the symptom of traffic congestion, usually fail because they cause compensating feedbacks.

Moreover, SD was also applied in Land Use Transport Interaction (LUTI) models, aimed at predicting the interrelationship between transport demand and economic development and vice versa. Compared to other equilibrium-based and individual-based LUTI models (Iacono et al., 2008), the Metropolitan Activity Relocation Simulator (MARS) is an SD model, which is capable of forecasting changes in the future and pays attention to aggregate effects. Pfaffenbichler et al. (2010) proposed MARS to assess the impact of exogenously given transport-land use policies, socio-demographic dynamics and economic scenarios. The model has subsequently been calibrated in the cities of Vienna (Austria) and Leeds (United Kingdom) using census data.

6.3.2. Discrete-event simulation (DES) & continuous simulation (CS)

DES is a traditional approach in the healthcare systems optimization, while recent research has made breakthroughs in supporting interactions between simulation modelers and a team of stakeholders. Kotiadis et al. (2014) presented a framework for participative and facilitative conceptual modeling, which could be introduced to other simulation processes. Their framework consists of three key stages and three sub-stages, involving two workshops in which a group of stakeholders participated. In the domain of transportation network simulation, a group of models was based on the combined Discrete-Continuous Simulation paradigm. One of the applications in railway simulation is OpenTrack (Nash and Huerlimann, 2004), a microscopic platform for assessing the impacts of new infrastructure installation, operating schedules, alternative signaling systems. It integrates the discrete progress of delay distributions and signal box states with continuous train motion equations, and users can define accidents and take transport infrastructure out of services in order to assess alternative scenarios.

6.3.3. Monte Carlo Simulation (MCS)

MCS was widely adopted for traffic-related air pollution simulation and human health risk assessment. Setton et al. (2011) used MCS to produce an exposure dataset for the Metro Vancouver urban area in British Columbia to examine the effects of mobility on pollutant exposure. The model simulated representative work-related activity schedules and provided annual averages of pollutant exposures per person. MCS was also used in environmental risk assessment (Whyte and Burton, 1980), in which the uncertainty and variability of exposure variables (e.g., contaminant concentration, contact rate, exposure frequency) play significant roles. Others adopted MCS to address the uncertainties and variability of human behavior, in terms of the travel mode choice, activity engagement, destination choice and temporal variability (De Nazelle et al., 2009). Furthermore, this efficient sampling method was introduced to pedestrian modeling for tracking multiple individuals in crowded environments (Mihaylova et al., 2014). For instance, a data-driven Markov chain Monte Carlo approach presented in Zhao et al. (2008) used bottom-up image observations (e.g., human appearance and shape) to explore the sophisticated solution space and accelerate the sampling process.

6.3.4. Microsimulation (MSM)

MSM is suited for simulating individual daily activity patterns for traffic demand forecasting, namely, trip generation, trip distribution, and mode choice (Kitamura et al., 2000). Compared to the conventional four-step demand forecasting (Mcnally, 2007), MSM takes advantages of computational savings in calculation and storage, as well as advantages of describing various decision-making. One of the first implementations of activity-based MSM models is the Florida Activity Mobility Simulator, consisting of a population synthesizer and an individual activity-travel simulator (Pendyala, 2004). The model system has been assessed and validated using the 2000 Southeast Florida Household Travel Survey dataset. Among others, Vovsha et al. (2002) developed a demand-modeling system for

the New York-New Jersey-Connecticut metropolitan area. To complement discrete-choice models and activity-based models, Arentze and Timmermans (2005) used MSM to develop a cognitive map model for representing an individual's decision-making under spatial search and spatial cognitive learning. The model is based on Bayesian principles of belief and focused on the human's cognition of locations. More specifically, Yang et al. (2006) elaborated on modeling a human's road crossing behavior (i.e., law-obeying and opportunistic) in transport systems, by comparing with questionnaires and videotape data collected from certain intersections in the city of Xi'an, China.

One of the most popular software tools developed for traffic simulation is VISSIM, developed by PTV Planung Transport Verkehr AG (Fellendorf and Vortisch, 2010). VISSIM is a discrete traffic simulation tool modeling multimodal transport and traffic operations. Common applications include signal control, alignment of public transport lanes with refinements to design solutions, the inspection of traffic calming strategies, coupled with extensions of emission calculation. The model has been applied in case studies of Istanbul freeways, and Sanand toll plaza in India.

The line between MSM and ABM can be opaque. Generally, most MSM only simulates one-direction interactions in contrast to ABM. For instance, in the process of policy-making modeling, MSM only models the impacts of policy implementation on humans, without any consideration of how an individuals' behavior influences policy and the interaction among individuals (Heppenstall et al., 2011).

6.3.5. Cellular Automata (CA)

CA has become one of the most widely used spatially sophisticated approaches for exploring a variety of urban phenomena, from transport simulation and regional-scale urbanization to Land-Use or Cover Change (LUCC) (Verburg et al., 2004). However, the simplicity of CA models has been taken as the most significant weakness for their representation of real-world. Thus, numerous efforts have been made to modify and expand their transition rules to contain such notions as self-modification, stochasticity, and utility maximization. Torrens and O'sullivan (2001) demonstrated that CA should be infused with urban theory, new solutions for validation, scenarios testing, and simulation related to urban planning practices. Yang and Lo (2003) applied a self-modifying CA urban growth model in the Atlanta metropolitan area; an early version of the model was built by Clarke and Gaydos (1998) and tested to San Francisco and Washington/Baltimore area for long-term urban growth estimation. The input data of urban extent (e.g., residential use), transportation gravity, slope resistance, and land transition possibility, in parallel with a variety of urban growth and self-modification, are included. The model validated the dynamic urban growth from past to present, followed by tests of possible future urban growth scenarios, according to the different development and environmental conditions. Verburg et al. (2004) employed CA to implement neighborhood interactions in LUCC models over a specific time. White and Engelen (1997) introduced an integrated approach consisting of CA, GIS, and regional economic and demographic model to

anticipate the possible socio-economic consequences of environmental change.

Moreover, CA microsimulation has been applied to vehicular flows and traffic networks. Blue and Adler (2001) applied CA for modeling bi-directional pedestrian walkways. By implementing a small rule set, their model captured three modes of bi-directional pedestrian flow. Huang et al. (2017) proposed a behavior-based CA model that involved environmental features and neighbors' behaviors into pedestrian evacuation modeling. This paradigm has been widely used in traffic demand modeling. One of the most advanced approaches is TRansportation ANalysis SIMulation (TRANSIMS) developed by Los Alamos National Laboratory, which integrates a series of sub-models including a population synthesizer, an activity generator, a route planner and a micro-simulator (Nagel and Barrett, 1997). In this day-to-day route-based simulation tool, feedback from the micro-simulator is used as an input to the route planner and iterates to the Nash equilibrium. CA successfully models the ecological and geophysical aspects of LUCC; however, it faces challenges when attempting to model human decision-making.

6.3.6. Agent-based modeling (ABM)

ABM has been increasingly adopted by social scientists, especially those involved in urban studies and transport planning. "Social science" is a discipline in the understanding of how humans behave and of their interactions result in emergent group behaviors and ABM provides for rigorous testing and refinement of existing theories, as well as to a more in-depth exploration of the underlying mechanisms in social systems. Chen (2012) conducted a systematic review of ABM approaches to urban and architectural research. A variety of state-of-the-art applications are detailed in the proceedings of two annual conferences: Social Simulation Conference, and the International Conference on Autonomous Agents and Multi-Agent Systems. ABM was used to examine complex Coupled Human And Natural Systems (CHANS). Various decision models adopted in the agent-based modeling of CHANS were reviewed in by (An, 2012). ABM is specifically beneficial for simulating dynamic human activities,

especially for explaining and testing needs-driven behavior. Based on the functions between needs and the utilities of activities, Märki et al. (2011) extended the standard models with two calibration systems: 1) agents are told when they can, cannot or must satisfy their needs, 2) a system enabling diverse need growth rates according to the evolution of time. Their model proved capable of representing real behavior when compared with a six-week travel diary in Switzerland, from which ten needs were extracted, their decrease and increase functions calibrated and activity-location pairs generated.

Traffic and transportation is a significant area where ABM has witnessed widespread utilization (Bernhardt, 2007). The most prevailing practices are the simulations of behavior involving route choice, lane-changing, and car following, as well as macroscopic demand modeling. Wise et al. (2017) reviewed various novel applications of ABM to transportation. One of the recent large-scale agent-based simulators is Multi-Agent Transport Simulation (MATSim), which started from Swiss Federal Institute of Technology in Zurich (ETH Zurich) and evolved in the Technical University of Berlin (TU Berlin). MATSim aims to simulate traffic and congestion patterns according to individual travelers' daily or weekly activity schedules (Horni et al., 2016). It was successfully adapted to represent transport flows across the whole of Switzerland (Waraich et al., 2009). In comparison with TRANSIMS, MATSim is quicker because of its simplified traffic flow simulation. In the field of integrated land use-transport planning, ABM gives supports for addressing the challenges of implementing integrated operational models in the political and planning process. UrbanSim (Waddell, 2011) is one of the most efficient urban simulation systems and is designed by the University of California, Berkeley. Due to its flexibility (more accessible to unskillful modelers), computational performance (reduced run times of the model system), transparency and behavioral validity, UrbanSim has been widely applied in numerous case studies, e.g., Detroit, Honolulu, and San Francisco. Further research is required to achieve the goal of integrating models into the participatory decision-making process.

Table 3 A comparison of the simulation paradigms. √ means typically; (√) means can be in some cases.

| Paradigm / Dimension		System Dynamics	Discrete-event Simulation	Continuous Simulation	Monte Carlo Simulation	Micro-simulation	Cellular Automata	Agent-based Modeling
Simulation way	Bottom-up				√	√	√	√
	Top-down	√	√	√				
States of the system	Stochastic				√	√	(√)	√
	Deterministic	√	√	√			√	(√)
	Dynamic	√	√	√		√	√	√
	Static		√		√	√		√
Spatial scale	Micro scale		√	√		√	√	√
	Macro scale	√	√	√	√		√	√
Variables	Independent				√	√		√
	Dependent	√	√	√				
	Disaggregate				√	√	√	√
	Aggregate	√	√	√				
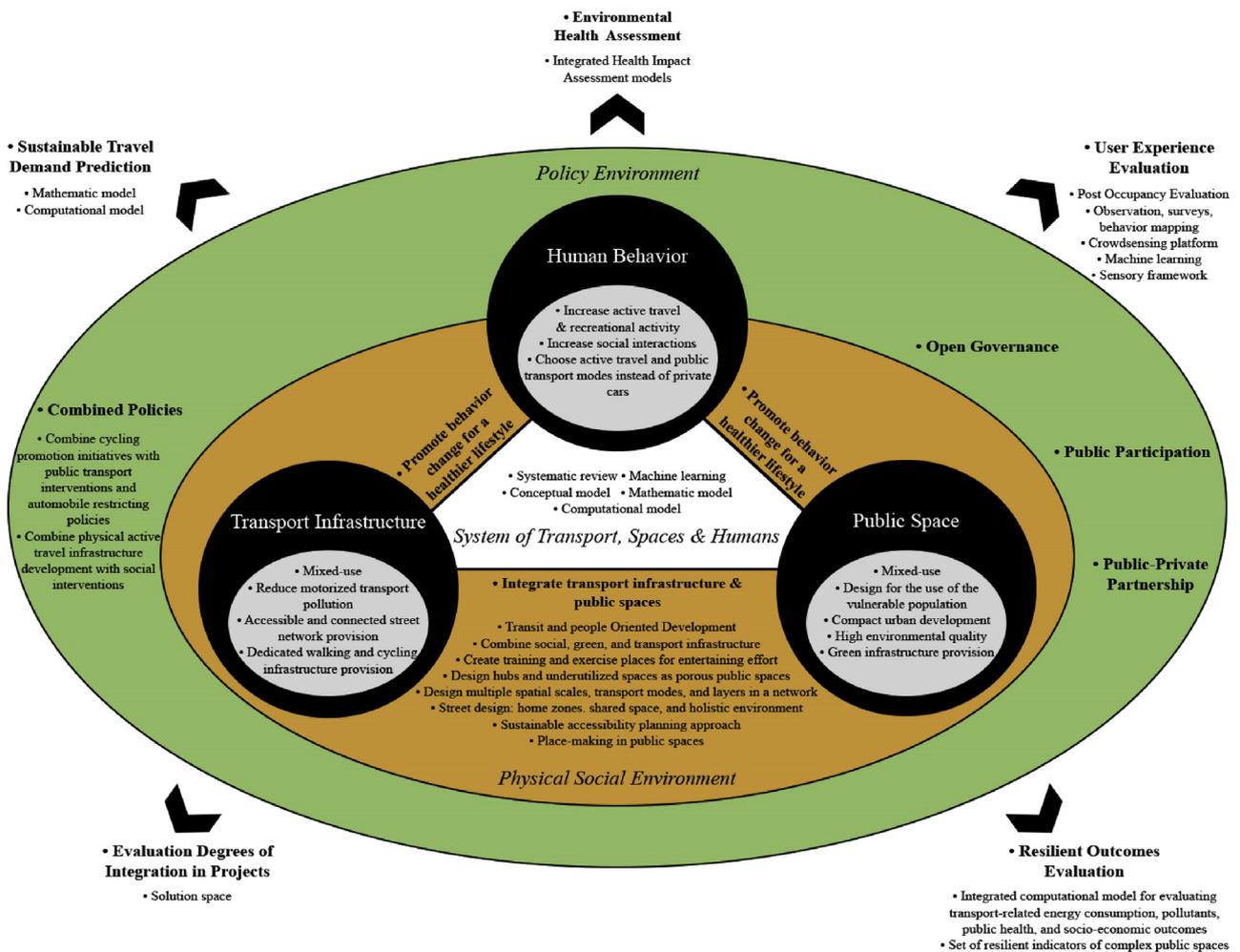
Fig. 8 Proposed components of a toolkit for designing integrated transportation infrastructure and public spaces system with considering human behavior. Items starting with ● are methods recognized as effective for relationship analysis, components integration, or plan evaluation. Methods in **Boldface** are high-level methods, in regular are sub-methods.

6.4. Paradigm comparisons

To critically compare the simulation techniques, we introduce a set of criteria, grouped into four dimensions, and verify how many of those are presented in the different studied paradigms. The choice of criteria follows the classification of simulation modeling defined by Law and Kelton (1991): "stochastic or deterministic (contains no random variables and the output is determined)", "dynamic or static (a system at a specific time or time plays no role in the system)" and "continuous or discrete (the state of a system may change at separate and countable points in time)". We further combined this with the structure introduced by Batty (2010): "the spatial scale is micro or macro", "simulate in the way of top-down or bottom-up", "the variables are dependent on others or independent in the system (i.e., originate endogenously or exogenously to the system)" and "aggregated" or "disaggregated". In Table 3, we compare the seven simulation paradigms according to their means of simulation and the systems on which they have been mainly adopted.

7. Toolkit design and research challenges identified

7.1. A multidisciplinary toolkit

This article aimed to answer our research questions through a systematic literature review, which is structured by the review framework (presented in Fig. 2). Fig. 8 is inspired by previous frameworks of the environment and human behavior interactions (Bild et al., 2016; Sallis et al., 2006).

7.1.1. Key strategies of policy-making and urban design
In Fig. 8, the interdependency between transport infrastructure, public space, and human behavior is indicated by a triangle. Because traditional urban planning has prioritized mobility and its supporting infrastructure typically have a mega form, transport infrastructure plays a dominant role in shaping public spaces in general, though urban public spaces do have an impact on transport in return. For instance, the design of roadside public places may occupy and reshape commuting areas on streets. To coordinate

interactions between the two components, a holistic design of integrated transport and spaces system is needed. Both transport and spaces interact with humans through the individual's perception and behavior. To stimulate positive synergy, transport infrastructure and public space designs should promote behavior change for a healthier lifestyle. In this figure, the health behavior changes and corresponding planning and design strategies are listed within the black circles of transport infrastructure, public space, and human behavior to indicate that these are component-specific methods. Moreover, the policy environment is also capable of promoting health behavior change. Significant strategies in policy formation include active travel infrastructure development coupled with social interventions and active travel policies combined with initiatives of public transport promotion and private cars restriction.

In the purpose of building integrated transport and spaces systems, urban planning approaches could be categorized into three groups according to the spatial scales of projects. 1) Transport Networks. To plan a holistic network that integrates multi-layered, multi-modal transport networks with public space networks. Here, sustainable accessibility is a powerful method. 2) Streets. To design places to entertain effort and creating an inclusive environment. Home Zones is a profitable strategy for neighborhood streets design. 3) Transport Hubs and Open Spaces. To plan people-oriented and context-based TODs around transport nodes by applying the place-making approach in the enhancement of open spaces. To redesign underutilized spaces around transport infrastructure as porous public spaces to form the social infrastructure in cities. In all scales, integration of green, social, and transport infrastructure is of great importance. Simultaneously, open governance, citizen participation, and PPP are essential indicators for supporting these strategies.

Finally, to assess the effectiveness of an integrated system, solution space is an applicable approach for determination of the degree of integration of a project. Functional isolation, sector-internal integration, external integration could be used as a grading system. KPIs for evaluation include resilient outcomes, sustainable travel demand, user experience, and environmental health, which focus on assessing the whole system, transport infrastructures, public spaces, and humans, respectively.

7.1.2. Analysis methods

Within the triangle centered in Fig. 8, the primary methods for analyzing the mechanism of the transport, spaces, and humans system are listed. Besides, these analysis methods can be used to evaluate the effectiveness of using the different urban design and policy approaches reviewed beforehand when applied to a particular situation.

Systematic reviews are "literature reviews that adhere closely to a set of scientific methods that explicitly aim to limit systematic error (bias), mainly by attempting to identify, appraise, and synthesize all relevant studies in order to answer a particular question (or set of questions)" (Petticrew and Roberts, 2008, p. 9). It has been usually used in medicine, public health and economy. A systematic review is limited in answering questions that are too broad or too vague while it is capable of addressing the focused questions about system effectiveness or causation. In

contrast, data analytics approaches such as machine learning are disadvantageous for determining the causal relationships. Machine learning is a valuable technique to visualize and validate the correlation between system components and the outcomes of changes in complex urban systems.

Apart from the literature and data analytic approaches, the various conceptual, mathematical and computational urban models are capable of explaining and describing urban processes (Parker et al., 2003) and supporting the physical planning process. When facing simple relationships in a system, analytical solutions are sufficient; however, to deal with complex relationships, simulated solutions are often needed. In the 1990s, urban researchers noted that computer simulation could serve as an accessible surrogate for a city's complex systems (Decker, 1993). The simulation tool can model complex adaptive urban systems over time by following logical or mathematical rules (Batty, 2013), and undertake quantitative analyses via large-scale computing (Law and Kelton, 1991). Moreover, computer simulations are less abstract than pure conceptual or mathematical models. Gilbert and Troitzsch (2005, p. 10) indicated that "the only generally effective way of exploring non-linear behavior is to simulate it by building a model." Edmonds (2017) highlighted that simulation models could be built for prediction, explanation, theoretical exposition, description, and illustration.

7.2. Research gaps identified

Building on this review, we also identify potential research gaps in scientific knowledge, strategies development, and plan evaluation.

7.2.1. Gaps in scientific knowledge of the relationship between transport, spaces, and humans

Based on the reviewed research on the relationship between transport, spaces, and humans, this paper identifies three gaps. Firstly, the quantitative relations between active travel plan and public health should be clarified better. The causal loop between green infrastructure and physical activity should be explored by taking account of multiple green infrastructure metrics and by specifying their impacts on the initiation and maintenance of behavioral change. Though a few researchers proposed frameworks to link active mobility policies and design features with human behavior and public health, a holistic, systematic framework, considering the indicators of active travel, green infrastructure, and motorized travel policies is still lacking. Here, combined methods of computer simulation, machine learning, and space syntax could be applied to analyze the impact of an integrated "active transport-green infrastructure -low motorized transport design" not only on human exposure to air pollution and heat, but also on exposure to noise, UV, and traffic hazards locally, as well as to greenhouse gases emissions globally.

7.2.2. Gaps in integration strategies

In policy and management domains, more endeavors are required to implement and evaluate effective short to medium term integrated cycling-public transport

interventions, and to carry out open governance and community participation in the transport infrastructure projects (especially in developing countries). Successful case studies which accomplished the goal of external integration, and those applied PPP to fund smart transport-spaces projects, should be reviewed.

In the urban planning strategies for creating an integrated transport-spaces framework, the Urban Parangolé concept, created for the city of São Paulo, could be translated and employed to other cities, by holistically design physical-virtual public spaces. In an attempt to bring streets back to the public realm, more efforts are needed to reconciling people and traffic on busy streets. Though shared space has been declared as a promising strategy to these streets, POE should be conducted on implemented projects, similar to the evaluation of home zone implementations. The sustainable accessibility approach can be utilized to meet the needs of an overall population; for example, the elderly demands distributed small public spaces and leisure activities within compact, walkable communities. In searching for an integrated design of transport infrastructure, public spaces, and human behavior, there is a lack of integrated methodology. Computer simulation and space syntax could be combined to supplement the design process.

7.2.3. Gaps in evaluating integrated transport, spaces, and humans plans

Despite the increasing research on predicting the sustainable travel demands of urban plans, only one travel mode is estimated in the paper reviewed, so predicting the demand for pedestrian, cycling, public transport, and motor vehicle in parallel, and taking account of multi-modal nature of many trips are needed. To examine user experience and health benefits, a combined methodology linking objective assessment, subjective self-reported questionnaire, and visualization should be formulated. Moreover, though the WILUTE is efficient to estimate resilient outcomes in a city-scale, it is unique to the city of Wellington, and how to transform the model to other cities is unclear. In a scale of public spaces, the literature focused on eliciting resilient indicators of complex public spaces, which are mainly transport hubs; hence, how to evaluate the resilience of other kinds of public spaces such as linear spaces along transport infrastructure should be investigated. Knowing that a price model is a potent way of assessing the economic outcomes of place-making and TOD plans, it is, therefore, promising to utilize it in appraising other integrated transport-spaces plans, such as a shared space plan.

7.3. Using the potential of new forms of simulation tools

The critical review of state-of-the-art simulation tools both indicates the limitations in the process of pure bottom-up and disaggregate simulation, and highlights the trend of multi-paradigm integration (Perez et al., 2017). In particular, even though individualized models such as ABM and MSM are advanced tools, they cannot always substitute traditional aggregate paradigms of simulation (Siebers et al., 2010). For instance, if we want to see the

interactions between transport and public space systems with other urban systems (e.g., energy systems), we may aggregate transport infrastructure and public spaces as a holistic system. In that way, the aggregated simulation models are suitable since they can be successfully constructed and validated in conjunction with domain experts. Moreover, they can complement one or more disaggregate models, for they are simplified, require less time and easier to explain to stakeholders.

Hence, a hybrid modeling approach is a sensible strategy (see "limitations" in Table 2). The ABM-MSM (Birkin and Wu, 2012; Boman and Holm, 2004), ABM-DES (Heath et al., 2011), CA-SD (Han et al., 2009) and CA-ABM (Parker et al., 2003) are appropriate forms of model integration as they offer additional perspectives on the urban system simulated. For instance, the typical LUTI model could be categorized as macro, meso, and micro (Chabrol et al., 2006); three branches of it are static models, spatial equilibrium models and agent-based microsimulation models (Keirstead and Shah, 2013). However, micro-scale simulation is data intensive, and the meso-level models lack details, giving rise to a demand for combining traffic models at different levels (Casas et al., 2011). To support the multidisciplinary decision-making process, these tools need to be made accessible to stakeholders from a variety of backgrounds so that the models can be applied in practice without requiring much background knowledge of computer science. In this manner, bespoke scenarios can be tested to identify interdependencies within the system, explore trade-offs, and provide feedback to designers, and the tools can thus support a co-design process.

In addition, other techniques could be introduced to complement such a hybrid computer-based methodology, such as: the machine learning Self Organizing Map, the "What-if" exploratory scenario planning approach (Klosterman, 1999), Participatory Planning Support Systems and Role Playing Games, since these have been successfully applied in infrastructure renewal projects (Dray et al., 2006). This will enable participatory decision-making, in which design methods and planning practices successfully demonstrated elsewhere can be tested with simulation models and discussed with key stakeholders and their ideas can be explored further with the help of these tools. In addition, the integration of computer simulation modeling with hybridization of related theories, scientific knowledge, policies, and design methods is capable of providing rational-comprehensive decision-making supports to real problems. By using such modeling techniques, theories and methods can be tested and further developed.

8. Conclusion

This paper began by recognizing the lack of any coherent analysis-design-evaluation decision-making toolkits (including state-of-the-art methods and tools) in the pursuit of integration of transport infrastructure, public space, and human behavior, despite growing recognition of the need. In order to address this gap, this paper proposed components of such a toolkit by conducting a systematic multidisciplinary review, which can provide benefits for a variety of stakeholders. This review ultimately led to a set

of guidelines that the authors believe can act as the basis for the development of an integration toolkit. This, in turn, will significantly assist practitioners and researchers in selecting relevant approaches for an integrated urban design process that takes into account the needs of its users, an urgent requirement in an urbanized world.

Notes

1. The European Commission defines Green Infrastructure as "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" (European Commission, 2016).
2. The Habitat III refers to the Third United Nations Conference on Housing and Sustainable (United Nations, 2016).
3. More than just promoting better urban design, place-making facilitates creative patterns of use, paying particular attention to the physical, cultural, and social identities that define a place and support its ongoing evolution (Project for Public Spaces, 2016).

Conflict of interest

The authors declare no conflicts of interests.

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