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System dynamics models for the simulation of sustainable urban development

A review and analysis and the stakeholder perspective

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Abstract

Purpose - System dynamics is a whole-system modelling and learning approach, useful for tackling non-linear problems, such as sustainable urban development. The purpose of this paper is to review system dynamics applications in the simulation of sustainable urban development over a period from 2005 to 2017.

Design/methodology/approach - The analysis reveals that the number of applications of system dynamics modelling in the area of urban sustainable development increased in the analysed period. Research has changed its focus from the modelling of environmental problems to more complex models, portraying the multidimensional socio-economic processes that have an impact on the sustainability of urban development. Analysed case studies most often use the behaviour reproduction test for model validation, but without a unified approach. In most cases, modelling has been done in China, Germany and the USA, while urban development in the Eastern European countries, Africa and Latin America has not often been investigated. This paper indicates the knowledge gaps and suggests future research directions.

Findings - Papers that report the use of system dynamics modelling reveal a wide range of applications in urban sustainability. The analysis shows significant emphasis on environmental problems, while the interest for modelling social problems has been increasing during the last several years. Most of the modelled problems examine the sustainability of resources (land, water) and waste management, which are used for insights into the reasons for the system behaviour, forecasting future behaviour and policy testing.

Originality/value - The presented models were developed in most cases for the purpose of understanding the phenomena examined, as well as the future use of the models in policy planning. This brings us back to the need for greater stakeholder involvement, not only in the initial phase, but also during the whole modelling process, which could increase understanding, use and ownership of the models in the future, and thus increase their practical application.

1. Introduction

Intensive use of space for transport, production, habitation and the use of natural resources has a strong impact on the urban environment. Since the effects of the deterioration of land, urban, transport facilities and water sources become apparent only in the long term, careful planning and scenario analysis are required to prevent them from becoming deteriorated. Previous research emphasizes that sustainable urban development has been neglected and is tackled only partially, since it requires the amalgamation of different issues, such as international and regional economics, transport, economic development and growth, ecology and environmental science (Holden, 2004; Parnell, 2016).

In these conditions, there is a great need for methods for the assessment and evaluation of sustainable urban development, both from strategic and tactical perspectives. A number of methods of operational research and statistical modelling have been widely used to investigate sustainable urban development. Examples include cellular automata (Santé et al., 2010), Monte Carlo simulations (Arhami et al., 2013), random utility (Cartenì et al., 2016), equilibrium methods in terms of the general, network and land use equilibrium (Ma and Lo, 2012), input-output analysis (Li et al., 2012), agent-based modelling (Robinson and Brown, 2009) and system dynamics (Schwarz et al., 2010). This review focuses on the application of system dynamics modelling for sustainable urban development.

System dynamics is a simulation modelling method based on the feedback control theory, which is suitable for studying complex systems. It has been used for analysis, decision-making and policy formation regarding a number of applications in almost any sort of system, e.g. industrial, health, environmental, demographic systems. Its origin goes back to the 1950s, and the field has been developed based on the work of J. W. Forrester at MIT Sloan School of Management (Radzicki, 2003). System dynamics applications often reveal the unexpected consequences of human actions that stem from bounded rationality phenomena (Gigerenzer and Selten, 2002; Simon, 1991) and limited predictability, indeterminate causality and evolutionary change (Hjorth and Bagheri, 2006).

System dynamics has no universal definition (Kennedy, 2011). Different authors understand system dynamics as an approach to understanding the nonlinear behaviour of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays (Abidin et al., 2014). Wolstenholme (1990) defined it as:

> a rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information, organisational boundaries and strategies, which facilitates quantitative simulation modelling and analysis for the design of system structure and control.

Although these definitions stress the quantitative aspect of system dynamics modelling, the demonstration of systemic insights has been the province of system dynamics from its early days in the beginning of the fifties years of 20 century (Forrester, 1990; Meadows, 1982).

System dynamics generic structures (e.g. system archetypes) have often been used to describe insights in terms of system structure and its associated behaviour over time. For example, generic "infrastructures" based on stocks and flows (Richmond 2002; Paich 1985), generic "system archetypes" based on causal loop maps (Senge, 1990; Wolstenholme and Coyle, 1983; Wolstenholme, 1990; Kim, 1992) and other classifications (Lane and Smart, 1996) have been proposed.

In 21st century, system dynamics is being used throughout the public and private sector for policy analysis and decision-making support. The system dynamics is studying real situations and so contributes to understanding the general system behaviour and structure as opposed to reductionist methodologies, which tend to seek understanding by examination of the individual components of a system (Kennedy, 2011). The system dynamics approach is especially suitable for studying complex problems, such as sustainable development (Schwarz et al., 2010), over longer periods.

System dynamics modelling in urban sustainable development has become widely known since the development of the Urban Dynamics Model, published in the book Urban Dynamics, which Jay W. Forrester wrote in 1969 (Forrester, 1969). The author analysed with using repeated computer simulations the changing ratios of critical urban development factors, which are population, housing, and industry. Forrester also exposed a problem how this changes in urban development factors would affect a city's growth.

The importance of this book is in identifying and describing the systemic structure responsible for the dynamics of urban development and decay (Sanders and Sanders, 2004). It represents a possibility of analysing urban problems while connecting the engineering and the social sciences (Forrester, 1969; Meadows et al., 2004). It uses system dynamics methodology for analysing socio-economics processes in order to simulate urban development.

One controversial conclusion in Urban Dynamics was that the most commonly accepted plans for improving an urban area (such as financial assistance) might actually hurt a city's long-term health. Financial aid, job training, other job programs and low-cost housing were each found to be ineffective and potentially harmful for the city system because they can lead to other problems such as overpopulation and greater tax demands on the underemployed. Forrester (1969; 1971) defined a "counterintuitive behaviour of social systems." According to Forrester, the counterintuitive discoveries in Urban Dynamics are indicative of the nature of all complex systems. Pushing on one facet of a system will eventually create repercussions in other, seemingly unrelated areas. Any city improvement program will change the balance of the system as a whole, regardless of the potential of the individual program. For example, every city has a natural rate of upward mobility through which the unemployed move into the labour pool. If a city becomes dependent on job training programs to spur such growth, other job-creating initiatives will be deemphasized. Because of this shift, you can never experience a positive program's full benefits. Sterman (2000) said that in the case of the counterintuitive behaviour or policy resistance is going for actions taken to alter the state of the system feedback into the system. Sterman (2000) concluded that unanticipated effects often arise in complex systems. Such a complex system present urban centres where cause and effect are distant in time and space. Therefore, in any complex system, the most obvious solutions are those most likely to fail. In the system dynamics literature, it could be founded a lot of cases that show people incapability of assessing the effects of their actions in a comp.

The book Urban Dynamics is a fundamental work in the field of the system dynamics methodology. However, Alfeld (1995) noted on its generated intense controversy. Alfeld justified the fundamental critism on the methodology of urban dynamics in three sets:

1) the boundary problem;
2) the problem of the limitless environment;
3) the use of data.

The boundary problem occurs when it is choosing the system boundary in a way that its environment does not substantially influence the system and vice versa. Different authors (Graham, 1974; Gray et al., 1972; Rochberg, 1972) formulated critical positions about the perceived exclusion of interactions between the city and its suburbs. Authors notified that the urban dynamics model does not include commuting across the boundary and that the model rules out the possible effects of actions taken to improve the situation in the city on the larger society, by choice of the closed boundary.

The critic of the Forrester model is that author encouraged local optimization rather than global optimization. Babcock (1972) and Gray et al. (1972) said that the majority of people in the US live in the cities. This is the reason why the environment be viewed as a collection of cities.

The urban dynamics model did not include empirical data. The model is specified a hypothetical city and Forrester drew general conclusions from his specific model. The use of the data from a real city invalided the results of the Forrester model (Gray et al., 1972). Jaeckel (1972) warns that alternative data should be presented to validate the policy recommendations. Sanders and Sanders (2004) exposed that the concept of the limitless environment omits the spatial dimension.

The critical urban development factors, which Forrester identified, are still present today (Haag, 2017; Haase and Schwarz, 2009; Sanders and Sanders, 2004). So far, a number of reviews have been conducted on applications of simulation modelling methods in the field of sustainable urban development. Alfeld (1995) presented an overview of five applications of urban dynamics, constituting an interesting historical appraisal of the development of system dynamics. Haase and Schwarz (2009) reviewed simulation models whose subjects are interactions between humans and nature in urban landscapes in terms of several methodologies: spatial economics, system dynamics, cellular automata and agent-based approaches. Mingers and White (2010) emphasize sustainable development as one of the main domains of the application of system thinking in operational research and management science.

Schwarz et al. (2010) examined the use of simulation models with respect to urban shrinkage. Most of the presented reviews tackle several simulations and modelling methods and focus on just one aspect of sustainable urban development. None of the reviews uses a comprehensive approach to sustainable urban development with an in-depth analysis of system dynamics modelling applications.

The goal of this study is to provide an overview of system dynamics applications that focus on sustainable urban development over a period from 2005 to 2017 to provide a systematic analysis of the specific problems examined by the system dynamics methodology; the use of software and other methodologies; model validation; and the use of models for policy analysis and public outreach.

When applying system dynamics for modelling urban sustainability development, decisions have to be made on a number of issues. First, the modeller has to set the model boundaries in an appropriate manner and to decide which aspects of urban development will be included in the model (in the form of model sectors), e.g. economic, environmental, and demographic. Second, the modeller should decide which system dynamics software to use, and to decide if other methodologies should be included and for which purposes. Third, a validation procedure should be chosen to support the credibility of the model. Fourth, a topic of research should be chosen that sheds light on issues and regions that have not been sufficiently investigated. Finally, it has to be decided if the public affected by the sustainable issues being modelled can be reached through communication channels other than scientific publication.

To provide an overview of system dynamics applications in sustainable urban development, and to provide specific guidance on the research challenges listed above, a review is made of scientific papers published in peer-reviewed journals. The analysis is guided by the system dynamics modelling process as defined by Morecroft (2007). This consists of six steps, providing answers to the following questions:

Q1. What are the main problems being modelled?

Q2. What approach to modelling in terms of sector selection was used?

Q3. By what means were the models developed in terms of software and other methodologies?

Q4. Can the models be trusted, taking into consideration validation procedures?

Q5. What are the purposes of the models? and

Q6. What is the public outreach of the models presented?

The paper is organized as follows. Section 2 presents the methodology for tracking system dynamics applications in peer-reviewed papers in the field of sustainable urban development and sets criteria for evaluating the applications found. Section 3 presents the results of the review in terms of answering the previously stated questions. Conclusions are drawn in Section 4.

2. Methodology

This review presents an insight into the system dynamics modelling applications in sustainable urban development from 2005 to 2017. The review exclusively analyses empirical studies published as peer-reviewed papers. The subsections that follow present the methodology deployed to gather literature and to conduct a review analysis.

2.1 Gathering literature

Gathering literature was conducted in the following steps. First, the Web of Science research platform was used for searching SCI-EXPANDED and SSCI databases to identify appropriate papers. The Boolean keyword combination was used for searching the relevant work (system dynamics AND urban*). The timeframe was set from 2005 to 2017. The results of the search were limited only to articles published in peer-reviewed journals, and conference proceedings were omitted from the analysis. In addition, the review was limited to scholarly literature written in English and was therefore not intended to offer a full-scale assessment of state of the art.

Searching the Web of Science resulted in 402 articles, which were narrowed to 304 articles published in peer-reviewed journals. A careful review of abstracts and full texts was performed and 212 irrelevant papers, i.e. those that do not present applications of system dynamics in sustainable urban development, were removed from the analysis, resulting in a final list of 92 articles published in 25 journals.

Table I presents the journals, which published papers dealing with the application of system dynamics modelling in sustainable urban development. Most of the papers were published in journals directly related to urbanism, building and land use (e.g. Landscape and Urban Planning, Building and Environment, Habitat International, Land Use Policy, Cities, and the Journal of Spatial Science). A significant number of papers were published in journals related to environmental modelling, management, and planning (e.g. Journal of Cleaner Production, Waste Management, Ecological Modelling, Journal of Environmental Management, Environment and Planning B: Planning and Design, and Environmental Modelling and Software). Other papers were distributed among journals which have a general focus (e.g. Sustainability) or which focus on specific issues (e.g. Science China – Earth Sciences).

Information from the subset of papers selected based on a reading of the abstract and full text was entered into a template that was used for the review analysis.

2.2 Review analysis

In accordance with the goal of the paper, specific information regarding each article was collected. The system dynamics modelling process that consists of six steps (Morecroft, 2007) was used as a review-analysis framework:

1) Define the problem;
2) Describe the system;
3) Develop the model;
4) Build confidence in the model;
5) Use the model for policy analysis; and
6) Use the model for public outreach.

Therefore, the following information was collected:

Research topics: To capture the specific problems in sustainable urban development that were examined by the system dynamics methodology, titles, keywords, abstracts and full texts of articles were analysed. Based on the collected information, the research topic of the paper was defined with a focus on the geographic regions examined (Table II).

System description: System dynamics models consist of levels, rates and auxiliary variables that are usually clustered in sectors that influence each other by means of feedback loops. Sectors of the model portray the specific processes in urban settings, e.g., economic, environmental and demographic, which affect specific aspects of urban sustainability development. Sectors covered in the investigated research papers were grouped into environment-related sectors and sectors related to the economy and society (Table III).

Model development: The goal of the analysis of model development was to provide an insight into current practice regarding the selection of system dynamics software and specific areas of sustainable urban development that were modelled with the support of additional methods (e.g., cellular automata).

Building confidence in the model: Model validation is important to help build confidence in the model. The presence of validity tests was analysed with a focus on the time span used for behaviour validity tests (Table IV and Table V).

Use of the model for policy analysis: The specific purposes of the model were investigated (Table VI). In addition, an Urban Development Sustainability Assessment Model (Xing et al., 2009) was used as a framework for exploring which environmental and social impacts on the urban development were modelled and which have so far not been sufficiently investigated (Table VII).

Use of the model for public outreach: The public outreach of system dynamics modelling plays an important role and, therefore, cooperation and communication with stakeholders is explored in terms of participation in the modelling, the use of management flight simulators and communication with public authorities and/or media (Table VIII).

3. Results

3.1 Research topics

Based on the in-depth analysis of the examined papers (title, abstract, keywords and full text), the research topic of each paper was defined (Table II). The following areas were those most investigated: land use, water, waste management. Transportation, housing, energy, and environmental issues were also investigated.

The most common research topics were related to land use: land use planning (Chang and Ko, 2014; Liu et al., 2007; Jin et al., 2016; Cox et al., 2017; Wang et al., 2017; Xu et al., 2015), land use change (Lee et al., 2008; Wu et al., 2012; Zheng et al., 2012; Wu et al., 2015) and land use allocation (Liu et al., 2013; Liu et al., 2017a; Liu et al., 2017b). In most cases, land use was investigated in relation to urban development (Han et al., 2009; Haase et al., 2012; Levine et al., 2008; Li and Wu, 2013; Shen et al., 2009; Wu et al., 2011; Yuan et al., 2008, Geng et al., 2017). In other cases, land use was discussed in combination with other topics, such as climate change (Huang et al., 2014), air quality and demand for water and energy (Güneralp and Seto, 2008; Fu et al., 2017), wetland mitigation (Bendor, 2009) or even trade-offs between ecosystem services and socio-economic development (Vidal-Legaz et al., 2013).

Water was also among the top-ranking issues, with research topics dealing primarily with problems related to urban water planning (Gober et al., 2011; Rozos et al., 2016; Sahin et al., 2017; Zhou et al., 2017; Zeng et al., 2016; Qiang et al., 2016; Yalçıntaş et al., 2015; Wei et al., 2016; Ghasemi et al., 2017), water supply and demand (Qin et al., 2012; Chhipi-Shrestha et al., 2017) and water environmental management (Qin et al., 2013; Zarghami and Akbariyeh, 2012; Bettini et al., 2015; Chang et al., 2015; Faust et al., 2017; Xi and Poh, 2015). This was also combined with other topics, such as the environment, livelihood, security, and culture (Fernald et al., 2012; Güneralp and Seto, 2008; Wang et al., 2017; Yin et al., 2017).

Popular topics also included: waste management (Dyson and Chang, 2005; Guan et al., 2011; Sufian and Bala, 2007; Sukholthaman and Sharp, 2016; Guo et al., 2016; Chen et al., 2016; Dasgupta et al., 2017), transportation (Bernardino and van der Hoofd, 2013; Friedman, 2006; Liu et al., 2015; Haghshenas et al., 2015; Cao and Menendez, 2015; Wen and Bai, 2017; Ercan et al., 2017; Guzman and Orjuela, 2017; Ercan et al., 2016; Macmillan and Woodcock, 2017; Macmillan et al., 2016; Cheng et al., 2015), housing (Eskinasi and Vennix, 2009; Lauf et al., 2012a; Lauf et al., 2012b; Mahamoud et al., 2013) and energy consumption (Feng et al., 2013).

A number of papers focussed on narrow environmental topics, such as national park management in relation to urban development (Antunes et al., 2006), global warming and climate change (Fong et al., 2009; Allington et al., 2017; Li et al., 2015; He et al., 2015; Moon et al., 2017), the ecological footprint (Jin et al., 2009), fossil-fuel emissions (Pataki et al., 2009; Hiasa et al., 2016; Procter et al., 2017), safety and terrorism (Thompson and Bank, 2010; Yu and Fang, 2017), ecosystem modelling (Jiang and Chen, 2011; Tsolakis and Anthopoulos, 2015; Xu and Kang, 2016), the self-sufficient and sustainable cities city (Park et al., 2013; Li et al., 2016; Wan et al., 2017; Fang et al., 2017), electricity demand forecasting (He et al., 2017) and chronic diseases in the urban environment (Brittin et al., 2015; Brittin et al., 2015).

The most of the papers presented the implementation of the model in China (43 papers), the USA (13 papers), Germany (4 papers), Korea (3 papers), and Taiwan (3 papers). Other countries for which issues of sustainable urban development were modelled are Canada, Australia, New Zealand, Iran, Singapore, Turkey, Japan, UK, Greece, Mongolia, India, Bangladesh, Canada, Hong Kong, Malaysia, Colombia, The Netherlands and Spain. Therefore, most of the papers reported modelling cities and regions in China, Germany and the USA. Other countries being modelled are in most cases from Asia. This regional coverage raises concerns, especially since such applications of system dynamics have not been found for Africa, Australia and post-communist Eastern European countries. The research in these areas is needed since the accomplishment of sustainable urban development will be difficult in developing countries, especially in Africa (Cohen, 2006).

3.2 System descriptions

To portray the simulation models that the authors developed, sectors of the models were analysed (Table III). The sectors are divided into three groups: environment-related sectors, sectors related to the economy and society and management. Depending on the topic of their paper, the authors focus on different environment-related sectors (e.g. land use, waste management, the environment and ecosystem, the ecological footprint, the air system sector, and water demand) and sectors related to the economy and society (e.g. income, housing and labour, supply and demand for social housing, population, and GDP). The management sectors represent the mechanism of decision-making that could influence urban sustainability. A full list of the model sectors of the research papers is provided in Table AI. The sectors most often included in the papers are population (71 per cent of the papers), economy (63 per cent), land use (41 per cent), natural resources (39 per cent), and transport (21 per cent). None of the papers provides an in-depth discussion of the process of setting the model boundaries and sector selection.

Most of the papers combine sectors related to the environment with those related to the economy and society, but with a different level of detail and scope of the model. Based on the complexity and focus, three groups of papers can be roughly defined. The first group consists of research papers that develop general models, consisting of land use, population and some form of economic activity (Huang et al., 2014; Lauf et al., 2012a; Lauf et al., 2012b; Li and Wu, 2013, Liu et al., 2013; Zheng et al., 2012; He et al., 2015; Wu et al., 2015; Xu and Kang, 2016; Fu et al., 2017; Geng et al., 2017). The second group consists of papers that develop more complex environment-related sectors, often with specific sectors reflecting the topic under study (Levine et al., 2008; Pataki et al. 2009; Tsolakis and Anthopoulos, 2015; Yu and Fang, 2017; Zhou et al., 2017) but with a simpler structure than that of the sectors related to the economy and society (Yuan et al., 2008; Chhipi-Shrestha et al., 2017; Guzman and Orjuela, 2017). The third group of papers present models that consist only of sectors related to the economy and society or environment-related sectors. Several articles do not have sectors related to the economy and society (Bendor, 2009; Lee et al., 2008; Sufian and Bala, 2007; Thompson and Bank, 2010; Li et al., 2015; Li et al., 2016), while only a few articles lack environment-related sectors and focus mainly on the economic aspects of urban development (Mahamoud et al., 2013; Park et al., 2013; He et al., 2017), or the spreading of chronic disease (Brittin et al., 2015).

Only a few papers take into account management-related sectors. Antunes et al. (2006) investigate whether decision-making mitigates the impact of urbanization on national park sustainability. Bendor (2009) questions the impact of mitigation management on wetland mitigation processes, and Eskinasi and Vennix (2009) consider the impact of the policy response to housing construction. Sterman (2007, p.13) states that “Narrow model boundaries are all too common, from the mental models of the person on the street to the formal models published in the most highly respected scientific journals.” Our analysis indicates authors rarely take into account the impact of public and private decision-makers on the sustainability of urban development (Ghasemi et al., 2017; Guo et al., 2016). In other words, model boundaries are set narrowly to exclude the role of different actors (e.g. local and national governments, corporations, NGOs) in society.

3.3 Model development

Model development has been investigated through different software solutions and other methodologies.

3.3.1 Software use.

The development of system dynamics models is conducted almost exclusively by means of system dynamics specific software developed solely for this purpose. In most cases, the system dynamics specific software used for modelling is mentioned in the paper. In the total number of 41 articles, 30 papers mention well-known software packages for system dynamics, with Vensim being the most often used (36 papers) and Stella (11 papers), while other papers mention Powersim, Simile and iThink. In addition, purpose-specific system dynamic models, such as the Sustainability Engine (Levine et al., 2008), WaterSim (Gober et al., 2011) and SyDWEM (Qin et al., 2013) were used. For other methodologies, the following software packages were used: e.g. Metronamica for the modelling of cellular automata (Lauf et al., 2012a) and ArcGIS (Xu and Coors, 2012).

The analysis indicates that the most frequent means to select software is to choose commercially widely used software, such as Vensim and Stella for system dynamics and Metronamica for cellular automata. In some cases, another programming language was employed for the development of a specific solution. An example of such a solution is WaterSim (Gober et al., 2011) which was later successfully adopted for public administration education (Hu et al., 2012).

3.3.2 Use of other methodologies.

Among the selected papers, 17 combine system dynamics with one or more other methodologies.

GIS methodologies were used most often in combination with system dynamics modelling for land use planning (Lee et al., 2008; Liu et al., 2007; Wu et al., 2011; Wu et al., 2015) or to model urban growth (Han et al., 2009; Xu and Coors, 2012; Xu et al., 2017). Guan et al. (2011) combined system dynamics modelling with GIS methodologies for the modelling of air pollution and solid waste management.

Cellular automata were paired with system dynamics to uncover land use dynamics driven by human decision-making (Lauf et al., 2012a; Liu et al., 2017b), as well as to model land use and climate change (Huang et al., 2014; He et al., 2015), and water planning (Rozos et al., 2016). Two papers combined system dynamics, cellular automata and GIS (Han et al., 2009; Liu et al., 2017a). Cellular automata were also combined with system dynamics and agent-based modelling for the purpose of modelling urban shrinkage (Haase et al., 2012).

System dynamics modelling was also used in unison with Conversion of Land Use and its Effects (CLUE) models (Li and Wu, 2013; Zheng et al., 2012) to simulate land use and urbanization models. The papers combining system dynamics with GIS and cellular automata were oriented towards the modelling of a specific geographic area with the goal of supporting on-going decision-making in land use planning. For example, Liu et al. (2007) allow the forecasting of land use management of lake areas in the urban fringe of Wuhan City, central China, which is under significant urbanization pressure. The same applies to the combination of system dynamics and CLUE, which simulates the spatio-temporal dynamics of land use change in Changqing, Jinan, China.

Other methods used are the ecological footprint (Jin et al., 2009), mediated modelling (Antunes et al., 2006), hybrid particle swarm optimization (Liu et al., 2013) and multiple-objective programming (Chang and Ko, 2014; Yuan et al., 2008). This group of papers aims at the development of a new methodological approach and tests it on a specific case study. For example, Antunes et al. (2006) use mediated modelling in a participatory decision-making context, and test the approach using a case study developed in a protected coastal wetland (Ria Formosa, Portugal). The same approach was used by Macmillan and Woodcock (2017).

3.4 Building confidence in the model

The simulation process is conducted with the goal to forecast future scenarios or to explain past behaviour, usually in a certain future period. However, if we want to believe that a system dynamics simulation model can be used for forecasting future behaviour or for explaining past behaviour with some degree of certainty, the model has to be verified, most often by the replication of the behaviour of the real system in the past (Barlas, 1996; Saysel and Barlas, 2006). The most frequently used test for the validation of system dynamics models is a behaviour reproduction test, which compares the real behaviour of the system with the simulated behaviour of the system, during a certain period in the past (Groesser and Schwaninger, 2012).

Most of the papers (67 out of 92; 73 per cent) present behaviour reproduction test. Among the papers that report the results of behaviour reproduction tests, there are significant differences. Several questions emerge regarding the length of the simulation and verification periods. For how long did the authors simulate future behaviour? What length of the behaviour in the past of the real systems was reproduced in order to gain confidence in the model? What is the ratio of the simulation and the verification length? Tables III and IV present some answers to these questions.

Table IV presents in detail the simulation and the verification period for each of the articles investigated. It can be noticed that, for most of the articles, the verification period is usually shorter than the simulation period, and only in a few cases is it about the same length or longer. The ratio of the verification period is calculated as a percentage of the simulation period.

Table V presents the average verification and simulation lengths in years, as well as their average ratios for each of the examined papers. The results indicate that most models were used to simulate medium- to long-term behaviour. The verification lengths indicate that most simulations rely on shorter verification periods. The significance of this result becomes more apparent when the verification as a percentage of the simulation is taken into account. As many as 23 out of the 92 authors did not provide any verification for their models, and the verification ratios for 17 more papers are under 20 per cent. Moreover, a simulation period of 300 years into the future has a validation period of only two years in the research conducted by Friedman (2006). This indicates a potential problem with the verification of such models, which could result in a lack of confidence in the models or even in their lower overall quality.

The average simulation length is 31.06 years with a standard deviation of 36.71 years. Five studies reported a simulation period shorter than 10 years. Nine papers do not report any simulation at all. The majority of papers report a simulation period longer than 30 years. However, due to a simulation length of 300 years in Friedman (2006) and simulation length of 101 years in Geng et al. (2017), the average simulation length calculated in this table is somewhat skewed. If we eliminate that model from the calculation as an outlier, the average simulation length is reduced to 26.93 years, and its standard deviation is reduced to 20.59 years.

The average verification length is much shorter, and it is 9.78 years with a standard deviation of 7.38 years. Most of the studies report a verification length ranging from 1 to 10 years, while only three papers report a verification length longer than 20 years. A total of 23 papers do not report any verification at all.

The average length of the verification period reported by the articles is 42.92 per cent of the length of the simulation period. Most of the papers reported shorter verification as a percentage of simulation (up to 20 per cent).

Based on the presented analysis, it can be concluded that there is no unified approach to the use of the behaviour reproduction test, but the following common patterns emerge. First, the length of the simulation of the system behaviour in the future is at least 10 years, with most of the studies simulating a period that is longer than 25 years. On the other hand, the verification length in most cases is shorter than 15 years.

A number of papers (23 out of 92; 25 per cent) do not use a behaviour reproduction test at all, and these papers are distributed evenly throughout the time range of the analysis. Some of these research papers also did not report on simulating the future model behaviour (Antunes et al., 2006; Bernardino and van der Hoofd, 2013; Fernald et al., 2012; Levine et al., 2008; Thompson and Bank, 2010; Jin et al., 2016). However, the lack of a behaviour reproduction test in these papers cannot be attributed to low-quality modelling, since one group of these models is oriented towards very specific topics (e.g. urban parking policies in Bernardino and van der Hoofd, 2013), and another group is oriented towards the modelling of optimal future development (e.g. transforming villages in sustainable towns in Levine et al., 2008). However, another group of papers that does not report the use of a behaviour reproduction test, at the same time reports on simulating future model behaviour (Brittin et al., 2015; Güneralp and Seto, 2008; Park et al., 2013; Sufian and Bala, 2007; Vidal-Legaz et al., 2013; Li et al., 2015; Tsolakis and Anthopoulos, 2015; Yalçıntaş et al., 2015; Guo et al., 2016; Hiasa et al., 2016; Jin et al., 2016; Rozos et al., 2016; Chhipi-Shrestha et al.,2017; Ghasemi et al., 2017; Guzman and Orjuela, 2017; Procter et al., 2017; Sahin et al., 2017). These papers do not report any validation procedure, and still simulate the behaviour of the model, even for 50 years, as in the case of Park et al. (2013).

3.5 Use of a model for policy analysis

Table VI presents the use of a model for policy analysis and public outreach.

The examined models indicate three groups of purposeful use:

to model the drivers that influence urban sustainable development (Guan et al., 2011; Güneralp and Seto, 2008; Jiang and Chen, 2011; Shen et al., 2009; Tsolakis and Anthopoulos, 2015; Yalçıntaş et al., 2015);

to support policymaking (Jin et al., 2009; Zarghami and Akbariyeh, 2012; Haghshenas et al., 2015; Macmillan et al., 2016; Allington et al., 2017); and

to simulate future behaviour (Dyson and Chang, 2005; Fong et al., 2009; Pataki et al., 2009; Sufian and Bala, 2007; Wei et al., 2016; Fu et al., 2017, Geng et al., 2017).

The Urban Development Sustainability Assessment Model (UD-SAM), developed by Xing et al. (2009), was used to assess the models for policy analysis in a systematic manner. The sustainability indicators of the UD-SAM framework are divided into four major categories: environmental impacts, social impacts, economic impacts, and whole-life value. Table VII presents environmental impacts and social impacts. Economic impacts and whole-life value are omitted from the table but are discussed later on.

Table VII indicates the prevalence of environmental impacts over social impacts in the frequency with which they appear as subjects in system dynamics models. This is confirmed by the following data: models presented in 87 out of the 92 papers examined include at least one of the environmental impacts, while a smaller number of studies (48 papers) simulate at least one of the social impacts.

It is also visible that the authors preferred to focus on a larger number of aspects of sustainable urban development since 61 out of the 92 papers modelled more than three of these impacts. This result indicates that system dynamics is applied more often in the form of larger, more comprehensive models.

3.5.1 Environmental impacts.

Environmental impacts were divided into ten indicators and the following codes were assigned to them: fuel (En1), materials (En2), land (En3), water (En4), biodiversity (En5), particulate emissions (En6), fluid emissions (En7), gaseous emissions (En8), wave emissions (En9) and waste (En10). The first five indicators address the problem of natural resources depletion, while the next four represent different types of emissions.

Table VII shows that the environmental impacts that were modelled most frequently include: land impacts (En3 – 55 papers), water-related impacts (En4 – 46 papers), gaseous emissions (En8 – 38 papers), waste-related impacts (En10 – 34 papers), fuel (En1 – 22 papers), particulate emissions (En6-19 papers), and materials (En2 – 15 papers). The table also suggests that there is continued interest throughout the observed period in using system dynamics to model some environmental issues, such as the use of land and water (En3 and En4), as well as energy and gaseous emissions (En8), while a lower level of interest in modelling biodiversity (En5), and wave emissions (En9) is a constant throughout the observed period.

3.5.2 Social impacts.

Social impacts were divided into seven indicators and assigned the following codes: education (So1), health (So2), housing provision (So3), crime and security (So4), physical interconnectivity (So5), wellbeing (So6), social capital (So7). Education and housing provision represent direct impacts, crime and security, physical interconnectivity, wellbeing, and social capital are considered to have indirect impacts, while health has both a direct and an indirect social impact. Table VI shows that, out of the 7 social impacts included in the UD-SAM framework, the ones most commonly modelled were: housing provision (So3 – 15 papers), social capital (So7 – 18 papers), physical interconnectivity (So5 – 23 papers), and wellbeing (So6 – 25 papers).

It is also important to highlight that most of the examined models have a demographic component. Although population size, growth, and flows are not included in the UD-SAM framework, most of the papers found it necessary to include them in some way.

3.5.3 Economic and whole life value impacts.

Although economic and whole life value impacts were omitted from this analysis due to the low number of indicators defined within the UD-SAM framework, as well as the lack of papers dealing with whole life value impacts in the context of sustainable urban development, it is important to note that most of the examined papers include some economic variables or even sub-models. In fact, 58 out of the 92 papers implemented economic variables in a more or less supportive manner in relation to the main environmental or social impacts that were modelled. In most cases, those variables were GDP, employment, and income, but some also included the prices of land, real estate, goods and services, different costs and other economic aspects.

Figure 1 presents the average number of environmental and social impacts examined for policy planning. The average number of environmental impacts is substantially higher than the average number of social impacts, until 2012, when these two groups of impacts became equally represented as the focus of policy planning. This indicates that during the earlier period, more focus was placed on environment-related topics, possibly as a result of the lack of understanding of the interrelation between the environment and society, as indicated by Hjorth and Bagheri (2006).

3.6 Usage of the model for public outreach

System dynamics is a methodology used not only for modelling, but also for policy analysis in a group process with the stakeholders of the model (Stave, 2002). The participation of stakeholders in the modelling process increases understanding of the model. The additional benefit is that stakeholders become “owners” of the model that becomes “embedded” as a part of their own mental model. Thus, the probability that the model will be used increases. Since urban development is an important issue for a great number of people, it could be expected that stakeholders are incorporated into the modelling process as often as possible. However, only 11 papers report the participation of stakeholders in the modelling process.

Table VIII provides an overview of stakeholder participation and public outreach in the examined publications. First, it can be noted that the number of studies reporting on stakeholder participation increases after 2008. The authors describe stakeholders in most of the papers in great detail, reflecting the specific area of application (e.g. water supply, highways, healthcare). In most of the papers, stakeholders participated in the modelling process. Most of the authors report that interviews were conducted for the purpose of initial model building and parametrization. For example, Brittin et al. (2015, p. 3) state that the researchers used “local stakeholder input gained via community and health-care organization engagement.” Other authors report more intensive cooperation with stakeholders. For example, Antunes et al. (2006) and Pataki et al. (2009) report on the use of mediated modelling in order to include stakeholders. Eskinasi and Vennix (2009) report that a group of stakeholders (managers and stakeholders) participated in model development and simulator workshops using the system dynamics model of urban transformation in Haagelanden, the Netherlands, which increased their understanding of the system. Pataki et al. (2009) included stakeholders (decision-makers, political advisors, and gatekeepers for various politically and economically influential social groups) in the modelling of fossil fuel emissions in the Salt Lake Valley, UT. Some authors report “exercises helped participants think systemically about the local airshed and enabled them to identify key issues, concerns, and interrelationships between variables affecting pollutant emissions” (Pataki et al., 2009, p.3). Similar examples occur in later periods (Guo et al., 2016; Allington et al., 2017; Cox et al., 2017; Moon et al., 2017).

Research gaps are present in the use of management flight simulators and channels for public outreach. Only two studies report on the development and use of management flight simulators (the Sustainability EngineTM and WaterSim), and three studies report on planned communication with the public, with very specific planned actions (Fong et al., 2009). Levine et al. (2008, p. 311) report on the development of the sustainable city simulation game (the Sustainability EngineTM) which is “intended to be a tool to manage and bring to light the many tangled and sometimes overlooked interconnected relationships.” The authors do not report on how the game was actually used in terms of stakeholder participation.

4. Summary of research

This paper reviews the applications of system dynamics modelling in the area of sustainable urban development. The papers were investigated using the typical phases of the system dynamics modelling process (Morecroft, 2007). A brief review of the answers collected for each question will be presented. Based on the results, knowledge gaps and prospects for future research directions are elaborated.

4.1 What are the main problems being modelled?

Papers that report the use of system dynamics modelling reveal a wide range of applications in urban sustainability. The analysis shows significant emphasis on environmental problems, while the interest in modelling social problems has been increasing during the last several years. Most of the modelled problems examine the sustainability of resources (land, water) and waste management, which are used for insights into the reasons for the system behaviour, forecasting future behaviour, and policy testing.

4.2 What approach was used for modelling in terms of sector selection?

Authors report a different degree of detail regarding the main variables/sectors that are the subject of modelling. However, certain similarities were found. The common sectors for a great number of models are population and economy, although they mostly play a supportive role to the main problems and are mainly present in models that deal with environmental issues and urban growth. Specific sectors modelled in these papers mostly relate to land, water and housing, while other sectors cover a broad spectrum of different environmental and social aspects.

4.3 By what means have the analysed models been developed in terms of software and other methodologies?

The highest degree of similarity was found in the use of simulation software, and authors reported the use of well-known software in that field. The models examined were in most cases developed by STELLA, iThink, Vensim, Powersim and Simile. When the system dynamics methodology was combined with other methodologies, a high level of diversity was found. Models are increasingly combined with other methodologies for various purposes. The methods that are combined with system dynamics modelling the most often are cellular automata (for the purpose of modelling urban growth) and GIS (for the purpose of modelling land use planning).

4.4 Can the models be trusted, taking into consideration validation procedures?

The validation approach is heterogeneous. Most of the papers report the use of behaviour reproduction tests, although about one-fifth of the papers does not report a validation procedure. For the papers that report behaviour reproduction tests, we raise some concerns regarding the periods of replicated behaviour that are in some cases too short, especially in comparison to the length of the simulation. The most important issue is the great heterogeneity with regard to validation and simulation lengths that were, in most cases, subjectively chosen and data-driven. In other words, it seems that in some cases the authors chose simulation lengths without a solid theoretical base and that the validation length depended on the data available to the authors.

4.5 What are the purposes of the analysed models?

The purpose of the research papers that is most often reported is to model the drivers and feedback that influence sustainable urban development. Models are also used to support policymaking and to simulate future behaviour, thus enabling the development of better plans and strategies. Most of the applications have been developed for a few countries and regions, and it is possible that they were chosen as the subject of study due to the availability of data, and not because of an urgent need for sustainable urban development. The specificity of the research topics and the modelled variables required the application of a more general urban sustainability indicator framework, such as UD-SAM, which allowed for easier categorization and provided a basis for comparison. This specificity, however, also indicates that such frameworks are rarely if at all, used as tools during the model planning and development stages.

4.6 What is the public outreach of the analysed models?

Although the system dynamics methodology is well known for its active approach regarding stakeholder engagement with the goal of increasing model understanding, ownership, and use, such practices are still not reported very often, especially related to the use of management flight simulators and channels for public outreach.

4.7 Knowledge gaps and research opportunities

The research has revealed the following knowledge gaps related to the modelling process and the purpose of the analysed models. First, the examined papers do not provide a clear view of the selection of the model boundaries, and selection of the model sectors, although the presented analysis provides an insight into which sectors are used the most often (e.g. population, economy, land use). Second, there is no unified approach to the validation of the system dynamics models using a behaviour reproduction test, although some patterns emerge, e.g. the validation period is mostly shorter than 15 years, while the simulating period is mostly longer than 25 years. There is no evidence that an objective approach was used for the selection of the validation and simulation period. Instead, authors have validated mostly the period based on the data available, and have simulated the period in the future based on criteria that are not elaborated with sufficient argumentation. Third, knowledge gaps are present in the areas of the environmental and social impacts of urban development, e.g. biodiversity, particulate emissions, fluid emissions, education, health, and crime. Fourth, there is insufficient research in the area of the use of management flight simulators and communication channels with the public regarding the modelling results.

Therefore, the following research opportunities emerge in using system dynamics modelling in urban sustainability development:

Setting model boundaries and a model structure. A procedure for the selection of and reporting on the boundaries of the model in terms of the selection of model sectors may be proposed. A case study reporting the modelling of an urban sustainability problem with different sectors included could be developed to assess the impact of the different model boundaries on the model behaviour. More research is also needed to take into account the role of different actors (e.g., local and national government, corporations, NGOs) in the sustainability of urban development.

Validation. The procedure for the selection of and reporting on validity tests specific to the use of system dynamics modelling in urban sustainability development might be proposed. Other tests, besides a behaviour reproduction test, should be described from the perspective of urban sustainability development. A case study reporting validation using a different length of the validation and simulation period could be developed in order to test its impact on the perceived validity of the system.

Environmental and social impact of urban development. Possible research avenues include: the impact on biodiversity that results mainly from land use (McDonald et al., 2008; Wu et al., 2015); the impact on particulate emissions since this has become an urgent issue related to air quality in cities (Burtscher, 2005; Thompson and Bank, 2010, Xu and Coors, 2012; Cheng et al., 2015; Macmillan et al., 2016; Xu and Kang, 2016; Guzman and Orjuela, 2017; Wen and Bai, 2017); fluid emissions (Dupré et al., 2014; Sukholthaman and Sharp, 2016; Chhipi-Shrestha et al., 2017; Dasgupta et al., 2017); and the impact of urban development on the sustainability of education, health and crime and security. For example, Eskinasi and Vennix (2009) developed a model with the following sectors: housing, supply, and demand for social housing, and policy response. However, due to the possible impact of social housing on crime and security, and indirectly on education, these additional sectors should be taken into account in future modelling efforts.

Public outreach and stakeholder engagement of the system dynamics models. More case studies using management flight simulators in the field of urban sustainability could be developed to test its impact on the participants' understanding of the environmental and social problems related to urban sustainability. One such example is the use of the WaterSim model for the purpose of increased understanding of dynamic behaviour as part of public administration education (Hu et al., 2012). The discussion is also needed on the use of public media and social media for the purpose of public outreach of the modelling results.

5. Conclusion

The main goal of this review paper was to determine the main characteristics of system dynamics modelling for studying sustainable urban development. To attain this goal, a systematic search of articles published in peer-reviewed papers was conducted. Papers published from 2005 to 2017 were analysed, knowledge gaps identified and research opportunities for future research proposed.

In general, this review reveals that during the last decade the application of system dynamics modelling in sustainable urban development has substantially increased, both in terms of the number of papers and the variety of topics modelled. The research focus has moved from solely environmental issues to a broad understanding of the interrelation between environmental, societal and economic issues. This will open a window of opportunity for even more applications in future, taking into account holistic understanding of the feedback loop between people and their environment.

Most of the analysed papers present modelling of urban phenomena in China, the USA and some Asian countries. Latin America and Africa as the regions that face the most challenging period regarding urban sustainability are a promising area of research since specific challenges are present there due to their exponential population growth and underdevelopment.

Validation of system dynamics modelling is a challenge for future research since the investigated papers demonstrate various approaches to validation. Future standards in this area would be welcome, especially those providing recommendations in relation to the acceptable length of the forecasting vs. the verification period.

The presented models were developed in most cases for the purpose of understanding the phenomena examined, as well as the future use of the models in policy planning. This brings us back to the need for greater stakeholder involvement, not only in the initial phase, but also during the modelling process, which could increase understanding, use, and ownership of the models in the future, and thus increase their practical application. Case studies presenting recommendations for future best practice of cooperation with stakeholders would be welcome in order to increase public outreach of the future models (Francis, 2001; Yin, 2013). Authors should take into account both negative and positive experiences in terms of stakeholder cooperation and public outreach.

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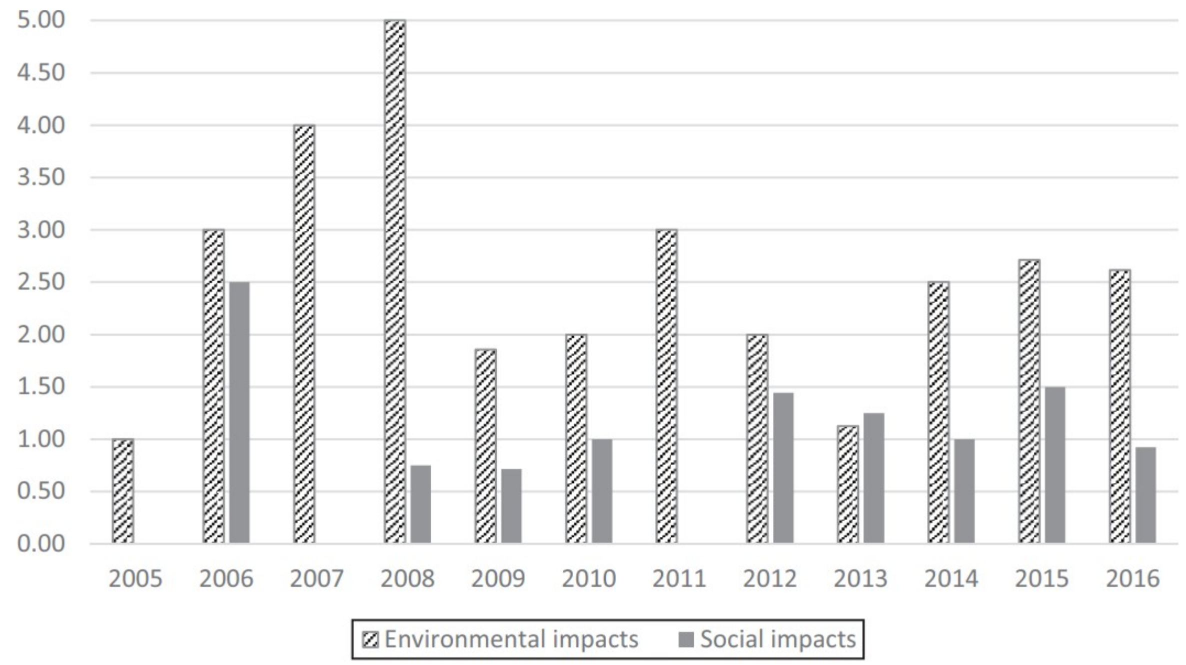

Source: Authors' research

Figure 1. The average number of environmental and social impacts examined for policy planningSource: Authors' research

Table 1

Journals that published papers dealing with the application of system dynamics modelling in urban sustainable development

Journal	No. of papers
Journal of Cleaner Production	7
Landscape and Urban Planning	7
Ecological Modelling	4
Habitat International	4
Journal of Environmental Management	4
Waste Management	4
Building and Environment	3
Cities	3
Sustainability	3
Water Science and Technology: Water Supply	3
Energy Policy	2
Environment and Planning B: Planning and Design	2
Environmental Modelling and Software	2
Journal of Water Resources Planning and Management	2
Land Use Policy	2
System Dynamics Review	2
Sustainable Cities and Society	2
Accident Analysis and Prevention	1
Applied Energy	1
Carbon Management	1
Chinese Geographical Science	1
Clean Technologies and Environmental Policy	1
Communications in Nonlinear Science and Numerical Simulation	1
Current Opinion in Environmental Sustainability	1
Ecological Complexity	1
Ecological Economics	1
Ecological Indicators	1
Ecology and Society	1
Energies	1
Energy	1
Environment, Development and Sustainability	1
Environmental Earth Sciences	1
Environmental Management	1
Environmental Modelling and Assessment	1
Environmental Science and Policy	1
European Journal of Transport and Infrastructure Research	1
Frontiers of Environmental Science and Engineering	1
Global Environmental Change	1
Journal of Environmental Sciences	1
Journal of Simulation	1
Journal of Spatial Science	1
Journal of Transport and Health	1
Journal of Urban Planning and Development	1
Resources, Conservation and Recycling	1
Science China – Earth Sciences	1
Social Science and Medicine	1
Sustainability	1
Water Policy	1
Science of the Total Environment	1
Transport Dynamics	1
Transportation Research Part B: Methodological	1
Water Resources Management	1
Water Science and Technology	1
Total	92

Source: Authors' research

Table II.
Papers reviewed, research topic and geographical focus

Authors, year of publication	Research topic	Geographical focus
Dyson and Chang, 2005	Solid waste management	San Antonio, Texas (USA)
Antunes *et al.*, 2006	National park management	Ria Formosa, Portugal
Friedman, 2006	Highway pavement maintenance	United States
Liu *et al.*, 2007	Land use planning of lake areas in the urban fringe	Wuhan City, China
Sufian and Bala, 2007	Solid waste management	Dhaka, Bangladesh
Güneralp and Seto, 2008	Land use, air quality, and demand for water and energy	Shenzhen, South China
Lee *et al.*, 2008	Land use change	Keelung City, Taiwan
Levine *et al.*, 2008	Urban growth (transition of villages into sustainable towns)	South-Western Yunnan, China
Yuan *et al.*, 2008	Urban growth (taking into account multiple objectives)	Beijing, China
Bendor, 2009	Wetland mitigation processes	Chicago region, USA
Eskinasi and Vennix, 2009	Housing construction	Haaglanden, Netherlands
Fong *et al.*, 2009	Global warming	Iskandar, Malaysia
Han *et al.*, 2009	Urban growth (taking into account environmental impacts)	Shanghai, China
Jin *et al.*, 2009	Ecological footprint	Wanzhou, China
Pataki *et al.*, 2009	Fossil-fuel emission	Salt Lake Valley, Utah (USA)
Shen *et al.*, 2009	Land use and urban development	Hong Kong
Thompson and Bank, 2010	Building design in the event of bioterrorism	N/A
Gober *et al.*, 2011	Urban water planning	Phoenix, Arizona, USA
Guan *et al.*, 2011	Air pollution, solid waste management	Chongqing, China
Jiang and Chen, 2011	Ecosystem modelling	Beijing, China
Wu *et al.*, 2011	Urbanization and land use	Jinyun County, China
Fernald *et al.*, 2012	Water, environment, livelihood and culture	Northern New Mexico, USA
Haase *et al.*, 2012	Urban shrinkage	Leipzig, Germany
Lauf *et al.*, 2012a	Residential development	Berlin, Germany
Lauf *et al.*, 2012b	Demography and housing demand	Leipzig, Germany
Qin *et al.*, 2012	Water supply and demand	North China Plain, China
Wu *et al.*, 2012	Land use change	Suichang County, China
Xu and Coors, 2012	Residential development	Stuttgart, Germany
Zarghami and Akbariyeh, 2012	Wastewater management	Tabriz, Iran
Zheng *et al.*, 2012	Land use change	Changqing, Jinan, China
Bernardino and van der Hoofd, 2013	Parking policy and urban mobility	Lisbon, Portugal
Feng *et al.*, 2013	Urban energy consumption and CO_2 emissions	Beijing, China
Li and Wu, 2013	Urbanization, natural ecosystem service values	Daqing, China
Liu *et al.*, 2013	Land use allocation	Panyu, Guangdong, China
Mahamoud *et al.*, 2013	Urban health and social interventions	Toronto, Canada
Park *et al.*, 2013	Self-sufficient city	Korea
Qin *et al.*, 2013	Integrated water environmental management	Shenzhen River, China
Vidal-Legaz *et al.*, 2013	Land use, trade-offs, ecosystem services and socio-economic development	Abla and Abrucena, Spain
Chang and Ko, 2014	Land use planning	Cijin District of Kaohsiung, Taiwan
Huang *et al.*, 2014	Land use and climate change	Northern China, China

Bettini *et al*, 2015	Water management, adaptive capacity	Adelaide and Perth, Australia
Brittin *et al*, 2015	Sustainable interventions in chronic disease outcomes, related to urban development	Chicago, Illinois, USA
Cao and Menendez, 2015	Urban traffic, parking	N/A
, Chang *et al*, 2015	Water resource security	Urumqi, China
Cheng *et al*, 2015	Urban transportation management, carbon ermss1ons	Kaohsiung City, Taiwan
Haghshenas *et al*, 2015	Urban transportation	Isfahan, Iran
He et aL, 2015	Urban landscape, climate change	Beijing-Tianjin-Tangshan megalopolis, China
Li *et al.*, 2015	Urbanization and CO2 emissions	Liaoning Province, China
Liu *et al*, 2015	Urban passenger transport, energy conservation, emission reduction	Beijing, China
Tsolaki and Anthopoulos, 2015	Eco-cities, urban planning	Hsinchu Science Park, Taiwan Tianjin Eco-City, China
Wu et al, 2015	Land use change	Baoshan District - Shanghai, China
Xi and Poh, 2015	Sustainable water resource management	Singapore
Xu et aL , 2015	Industrial development, landscape ecology	Harbin-Daqing-Qiqihar industrial corridor, China
Yak;mta§ *et al*, 2015	Urban water management	Istanbul, Turkey
Chen *et al*, 2016	Household sector and CO_2 emissions	China
Ercan *et al* , 2016	Public transportation, reduction of carbon emissions	USA
Guo et al, 2016	Household waste, waste management	Baltimore, USA
Hiasa *et al*, 2016	Environmental impacts of highways, CO_2 em1ss1ons	Shin-Meishin expressway, Japan
Jin *et al*, 2016	Land use, consolidation	Fulin, China
Li *et al.*, 2016	Sustainable development of green space	Beijing, China
Macmillan *et al*, 2016	Cycling	London, UK
Qiang *et al.*, 2016	Urban water resources	Jiamusi, China
Rozos et aL, 2016	Water-infrasb-ucture planning	Attica, Greece
Sukholthaman and Sharp, 2016	Solid waste management	Bangkok, Thailand
Wei et al , 2016	Urban water management	Macau, China
Xu and Kang, 2016	Ecological risk in urban development	Harbin, China
Zeng *et al*, 2016	Water carrying capacity	Tongzhou district, Beijing, China
Allington *et al*, 2017	Urbanization, environment policy effects	Suhkbaatar Aimag and Xilingol Leauge, Mongolia
Chhipi-Shrestha *et al*, 2017	Urban water systems, energy use, carbon emis ion	City of Penticton, Canada
Cox *et al*, 2017	Land use planning, urban development (transportation)	Durham and Orange county, North Carolina, USA
Dasgupta *et al*, 2017	E-waste management system	India
Ercan *et al*, 2017	Urban development, public transportation	USA
Fang *et al.*, 2017	Sustainability of urban ecological-economic systems	Beijing, China

Faust *et al.*, 2017	Human and water systems interdependencies in shrinking cities	USA
Fu *et al.*, 2017	Land use change, carbon emissions	Shanghai, China
Geng *et al.*, 2017	Sustainable land use	Beijing, China
Ghasemi *et al.*, 2017	Urban water management	Tehran, Iran
Guzman and Orjuela, 2017	Transport and emissions modelling	Bogota, Colombia
He *et al.*, 2017	Electricity demand forecast	Tianjin, China
Liu *et al.*, 2017a	Land use and land cover change	China
Liu *et al.*, 2017b	Land use change	Beijing, China
Macmillan and Woodcock, 2017	Bicycling in cities	Auckland (New Zealand), London (UK), Netherlands
Moon *et al.*, 2017	Climate change policy, risk management, urban and rural areas	Korea
Procter *et al.*, 2017	Light rail transit and CO_2 emissions	North Carolina, USA
Sahin *et al.*, 2017	Water management	Gold coast region, Australia
Wan *et al.*, 2017	Urban sustainable development	Hadaqi industrial corridor, China
Wang *et al.*, 2017	Wetland water resources management	Beijing, China
Wang *et al.*, 2017	Urban growth management	Yiwu city, Qingtian County, China
Wen and Bai, 2017	Urban traffic	Beijing, China
Yin *et al.*, 2017	Urban water security	Guizhou province, China
Yu and Fang, 2017	Public safety in cities	Shanghai, China
Zhou *et al.*, 2017	Water environment capacity	Changzhou, China

Source: Authors' research

Table III.

Model sectors in the research papers

	Environment-related sectors				Sectors related to the economy and society						
Authors, year of publication	Waste	Land use	Natural resources	Specific issues	Economy	Population	Specific issues	Housing	Urban structure	Transport	Management sectors
Dyson and Chang, 2005	✓				✓[a]	✓					
Antunes *et al.*, 2006		✓	✓		✓[b]	✓[b]					✓
Friedman, 2006				✓[c]			✓[d]				
Liu *et al.*, 2007		✓	✓		✓[b]	✓[b]					
Sufian and Bala, 2007											
Güneralp and Seto, 2008	✓[e]										
Lee *et al.*, 2008		✓	✓		✓	✓		✓			
Levine *et al.*, 2008		✓[f]	✓[g]						✓		
Yuan *et al.*, 2008	✓[h]	✓			✓[i]	✓					
Bendor, 2009				✓[j]							✓[k]
Eskinasi and Vennix, 2009							✓[l]	✓[m]			✓[n]
Fong *et al.*, 2009				✓[o]	✓[p]			✓[q]		✓	
Han *et al.*, 2009		✓[r]			✓[b]	✓[b]					
Jin *et al.*, 2009				✓[s]	✓	✓					
Pataki *et al.*, 2009		✓[r]		✓[t]	✓	✓				✓[u]	
Shen *et al.*, 2009		✓[r]			✓[v]	✓		✓		✓	
Thompson and Bank, 2010				✓[w]							
Gober *et al.*, 2011			✓[x]			✓					
Guan *et al.*, 2011			✓		✓[y]						
Jiang and Chen, 2011			✓						✓		
Wu *et al.*, 2011		✓	✓						✓		
Fernald *et al.*, 2012		✓	✓[z]		✓	✓					
Haase *et al.*, 2012		✓				✓		✓			
Lauf *et al.*, 2012a		✓			✓	✓		✓			
Lauf *et al.*, 2012b		✓				✓		✓[aa]			
Qin *et al.*, 2012	✓[ab]		✓[ac]								
Wu *et al.*, 2012		✓	✓		✓[b]	✓[b]			✓		
Xu and Coors, 2012			✓		✓[b]	✓[b]		✓			
Zarghami and Akbariyeh, 2012			✓[ad]			✓					
Zheng *et al.*, 2012		✓			✓	✓					

Bernardino and van der Hoofd, 2013			••						' '		
Feng et al. 2013					ag						
Li and Wu, 2013					ai					••	
Liu *et al*, 2013											
Mahamoud *et al*, 2013							aj				
Park *et al*., 2013							ak				
Qin *et al*., 2013			x		ai						
Vidal-Legaz *et al*, 2013			. '				al				
Chang and Ko, 2014											
Huang *et al*, 2014			'''		ai						
Bettini *et al*, 2015											''''
Brittin *et al*, 2015					•		an				
Cao and Menendez, 2015										au	
Chang *et al*., 2015			. '	• P							
Cheng *et al*, 2015				• P	•		• q				
Haghshenas *et al*, 2015				• P	''	a $				'''	
He *et al*, 2015			''		ai						
Li *et al*, 2015				○					au		
Liu *et al*, 2015				o			aq				
Tsolakis and Antanopoulos, 2015				• P	av		aq				
Wu *et al*., 2015			ac		ai				au		
Xi and Poh, 2015			''''								
Xu *et al*, 2015				• P	cg						
Yalc;mta9 *et al*, 2015			'								
Chen *et al*., 2016				ax			' 9				
Ercan *et al*, 2016				ay			a q			''	
Guo *et al*, 2016	00					bb					
Hiasa *et al*, 2016				''							
Jin *et al*., 2016					be	b<l	be				
Li *et al*, 2016				ap					bf		
Macmillan *et al*, 2016										bg	
Qiang *et al*, 2016		'	'		ai						
Rozos *et al*, 2016			bh			bi					
Sukholthaman and Sharp, 2016					bj						
Wei *et al*., 2016			bk	''Y							
Xu and Kang, 2016				' P	bl		bm				
Zeng *et al*, 2016			bn								
Allington *et al*, 2017							bo				
Chhipi-Shrestha *et al*, 2017	bp		'''	bq							
Cox *et al*, 2017			ac		'''		aq	bs			
Dasgupta *et al*, 2017	bl				bu						
Ercan *et al*, 2017				• P	bv					bw	
Fang *et al*, 2017				bx	by						
Faust et al, 2017			b2		''						
Fu *et al*, 2017					b	b					
Geng *et al*, 2017											
Ghasemi *et al*., 2017			''								
Guzman and Orjuela, 2017				ax							
He *et al*, 2017				'b	p						
Liu *et al*, 2017a											
Liu *et al*, 2017b			ac		ai						
Macmillan and Woodcock, 2017										bg	
Moon et al, *2017*				''			bo				
Procter *et al*., 2017							aq			'd	
Sahin et al, 2017			ac		'		d				
Wan *et al*, 2017				cg							
Wang et al, *2017*	•b		ac			b					
Wang et al, 2017									ch		
Wen and Bai, 2017				cb	ai					ci	
Yin *et al*, 2017	ab		ac		ai						
Yu and Fang, 2017					''		<j	ck	''''		
Zhou *et al*, 2017	cl		''								
Total (no. of paper)	15	38	36	27	58	65	19	14	15	19	6
(%)	16	41	39	29	6.3	71	21	15	16	21	7

Notes: '-income; b -socio-economic activities; '-pavement condition; d -highway accidents and repair spending; '-waste management and waste generation; ' . agriculture resources; •-natural system; hagricultural waste; '-income and expenditures; '-animals, energy, water, crops, wetland mitigation banking, wetland impacts; -mitigation management '-supply and demand for social housing; m -social housing construction; "-policy response; "-CO_2 emissions; P commercial and industrial; 9-residential; ' -urban land; ' -ecological footprint and biocapacity; '-fuel, CO_2, trees, electricity, natural gas, climate; "-traffic, roads, density; v_ employment w -air system and infection sectors; -water demand, water supply; ' -GDP technology, production, labour, capital; . hydrology and ecosystem; aa_ housing preferences, vacancies and demolition; b . water pollution; '''•water resources; •J.s applied ground and surface water and returned water; ''' •congestion; f parking, private and public transpoli, cost; '''•industry and residence; a h . consumption of sectors; '''-GDP; •i.social cohesion, healthcare, behavioural; al-service facilities and education welfare; •'-services sector; m . innovation and learning, deciding and acting capacity; n . migration, chronic disease; ''. traffic, parking; p environment; 9-energy; " -GDP per capita, revenue and expense; ''''-user cost; at•transportation supply and demand, transportation utilities; ' "-urban development, urbanization; " -business, industry, services; w .water resources, supl?JY, demand, management; ax-environment, emissions; •Y.climate; az-traffic congestion, public transportation; 00-waste disposal, waste collection; b b social norms; -capital input-output; bd-social impact; be-agricultural production; b . g een space; b cycling; b_ , water-saving technology; b i consumers; b i.costs; b water system water conservation- b'-GDP investment' bm industry enterprise; b" -water use water treatment, water supply, w ter reclamation ; 00-agriculture facilities d infrastructure; b , astewater; bq-energy: carbon; b ' -GRP (gross r gional product), GOS (gross operating surplus), employment, unemployment; b '.costs and value; b 1electronic appliances; 00-GDP, GDP per capita; bv revenue, taxes, government's spending; b w_public transportation; bx-emergy (environmental resources); ''' -industries services, agriculture, tourism, energy; bz . wastewater, stormwater; '''• revenue, costs; b_ e l tricity and energy consumption demand; '''-climate change, food; '''- light rail; " -p,ice of water; d -water demand;' <-environment, energy; h urban development; " -urban traffic,volume, density;" -urban crime and instability, urban disaster; k . urban housing and liveability; d_pollutant emissions

Table IV.

Simulation and verification periods, their length and verification as % of simulation

Authors, year of publication	Simulation period	Verification period	Simulation length	Verification length	Verification as % of simulation (%)
Dyson and Chang, 2005	2000-2010	1993-1999	10	7	70.0
Antunes *et al.*, 2006	N/A	N/A	N/A	N/A	N/A
Friedman, 2006	300 years	2000-2001	300	2	0.7
Liu *et al.*, 2007	2006-2020	2005	15	1	6.7
Sufian and Bala, 2007	1995-2025	1995-2005	30	10	33.3
Güneralp and Seto, 2008	1979-2030	N/A	51	N/A	N/A
Lee *et al.*, 2008	1971-2005	2005	35	1	2.9
Levine *et al.*, 2008	N/A	N/A	N/A	N/A	N/A
Yuan *et al.*, 2008	2003-2020	1996-2003	17	7	41.2
Bendor, 2009	1980-2100	1993-2004	120	11	9.2
Eskinasi and Vennix, 2009	2003-2015	1998-2003	12	5	41.7
Fong *et al.*, 2009	2005-2025	1994-2005	20	11	55.0
Han *et al.*, 2009	2000-2020	1979-2000	20	21	105.0
Jin *et al.*, 2009	1997-2020	1997-2005	23	8	34.8
Pataki *et al.*, 2009	2005-2030	1980-2005	25	25	100.0
Shen *et al.*, 2009	1990-2030	1992, 1994, 1996, 1998, 2000, 2002 and 2004	40	5	12.5
Thompson and Bank, 2010	N/A	Comparison with other models	N/A	N/A	N/A
Gober *et al.*, 2011	2010-2030	1970-2011	20	41	205.0
Guan *et al.*, 2011	1998-2050	2007	52	1	1.9
Jiang and Chen, 2011	1994-2044	2004	50	1	2.0
Wu *et al.*, 2011	2004-2020	1996, 2003, 2004	16	3	18.8
Fernald *et al.*, 2012	N/A	N/A	N/A	N/A	N/A
Haase *et al.*, 2012	2001-2025	1990-2001	25	11	44.0
Lauf *et al.*, 2012a	1992-2007	1992-2007	15	15	100.0
Lauf *et al.*, 2012b	2005-2030	1992-2005	25	13	52.0
Qin *et al.*, 2012	2000-2030	2000-2007	30	8	26.7
Wu *et al.*, 2012	2008-2020	1999-2007	13	9	69.2
Xu and Coors, 2012	1991-2020	2001, 2002, 2006, 2007, 2008	30	5	16.7
Zarghami and Akbariyeh, 2012	1996-2020	1996-2008	24	12	50.0
Zheng *et al.*, 2012	2006-2020	1996-2005	15	10	66.7
Bernardino and van der Hoofd, 2013	N/A	N/A	N/A	N/A	N/A
Feng et al. 2013	2005-2030	1995-2005	26	11	42.3
Li and Wu, 2013	2005-2015	2001-2005	10	5	50.0
Liu *et al.*, 2013	2008-2030	2008	22	1	4.5
Mahamoud *et al.*, 2013	2006-2046	2001,2006	40	2	5.0
Park *et al.*, 2013	50 years	N/A	50	N/A	N/A
Qin *et al.*, 2013	2011-2020	2010	10	1	10.0
Vidal-Legaz *et al.*, 2013	1990-2010	N/A	20	N/A	N/A
Chang and Ko, 2014	1996-2025	1996-2010	30	15	50.0
Huang *et al.*, 2014	1978-2030	1990-2005	52	15	28.8
Bettini *et al.*, 2015	N/A	2000-2010	N/A	N/A	N/A

Brittin *et al* ,2015	NIA	NIA	25	NIA	NIA
Cao and Menendez, 2015	NIA	NIA	NIA	NIA	NIA
Chang *et al*,2015	2011-2030	2007-2011	20	5	25
Cheng *et al* ,2015	1995-2025	1995-2013	31	19	61.29
Hagh hena *etal*, 2015	2012-2025	1990, 1995, 2001	14	3	21.43
He *etal.*, 2015	2009-2030	1990, 2000, 2009	22	3	13.63
Li *etal*, 2015	2013-2030	NIA	18	NIA	NIA
Liu *etal*, 2015	2011-2020	2002-2010	10	9	90
Tsolaki and Anthopoulos, 2015	2015-2065	NIA	50	NIA	NIA
Wu *et al*,2015	2011-2025	2004-2010	15	7	46.66
Xi and Poh, 2015	2000-2100	2000-2011	101	12	11.88
Xu *et al*, 2015	2015-2020	2005-2009	6	5	83.33
Yal<;mta *et al*,2015	2015-2018	NIA	4	NIA	NIA
Chen *et al*, 2016	2000-2020	2000-2014	21	15	71.43
Ercan *et al*, 2016	1990-2050	1990-2013	61	24	39.35
Guo *et al*,2016	2years	NIA	2	NIA	NIA
Hiasa *et al*, 2016	2000-2030	NIA	31	NIA	NIA
Jin *etal*, 2016	15 year	NIA	15	NIA	NIA
Li*etal*, 2016	2000-2025	2000-2015	26	16	61.54
Macmillan *etal.*,2016	NIA	1992-2012	NIA	10	NIA
Qiang *et al*, 2016	2000-2030	2000-2010	31	11	35.48
Rozas *et al*, 2016	2010-2020	NIA	11	NIA	NIA
Sukhol thaman and Sharp, 2016	2013-2023	2000-2013	10	14	140
Wei *etal.*,2016	2013-2022	2006-2012	10	7	70
Xu and Kang, 2016	2005-2015	2005-2009	11	5	45.45
Zeng *et al*, 2016	2003-2020	2003-2007	18	5	27.77
Allington *etal*, 2017	1991-2050	1991-2013	60	23	38.33
Chhipi-Shrestha *et al,2017*	2005-2014	NIA	10	NIA	NIA
Cox *et al.*, 2017	2000-2040	2000-2014	41	15	36.59
Dasgupta *etal*, 2017	2012-2025	2012-2015	13	3	23.08
Ercan *et al* , 2017	1990-2050	1990-2015	61	26	42.62
Fang *et al*, 2017	2015-2030	2011-2013	16	3	18.75
Faust *etal*, 2017	lOy ears	2008-2013	10	5	50
Fu *et al*, 2017	2000-2025	2000-2013	26	14	53.85
Geng *etal*, 2017	2000-2100	2000-2015	101	16	15.84
Ghasemi *et al* , 2017	2011-2041	NIA	30	NIA	NIA
Guzman and Orjuela, 2017	2010-2026	NIA	17	NIA	NIA
He *et al*, 2017	Multiple simu lation	2009-2014	NI	6	NIA
Liu *et al*, 2017a	2010-2050	2000-2010	41	11	26.83
Liu *et al* , 2017b	4 year	2010	4	1	25
Macmillan and Woodcock, 2017	2000-2026	2000-2012	27	13	48.15
Moon *etal*, 2017	2000-2050	2000-2014	51	15	29.41
Procter *etal.*, 2017	2000-2040	NIA	41	NIA	NIA
Sahin *et al.*, 2017	lO years	NIA	10	NIA	NIA
Wan *et al* , 2017	2020-2035	2010-2014	16	5	31.25
Wang *et al*,2017	2006-2030	2006-2013	25	8	32
Wang *et al*,2017	2013-2020	2012	8	1	12.5
Wen and Bai, 2017	2000-2020	2000-2014	21	15	71.42
Yin *et al.*, 2017	2005-2025	2005-2010	21	6	28.57
Yu and Fang, 2017	2010-2025	2000-2009	16	10	62.50
Zhou *etal.*,2017	1995-2050	1995-2010	56	16	28.57

Source: Author ' research

Table V.

Analysis of simulation lengths, validation lengths and verification ratios

Simulation length (years)	No. of studies	Verification length (years)	No. of studies	Verification as % of simulation	No. of studies
1-4	3	1-4	15	0-9	8
5-9	2	5-9	21	10-19	9
10-14	15	10-14	16	20-29	11
15-19	13	15-19	11	30-39	8
20-24	12	20-24	3	40-49	8
25-29	9	25-30	2	50-59	7
30 +	29	30+	1	60+	16
N/A	9	N/A	23	N/A	25
Average no. of years	31.06	Average no. of years	9.78	Average percentage	42.92%
SD	36.71	SD	7.38	SD	34.59%
Total no. of papers	92	Total no. of papers	92	Total no. of papers	92

Source: Authors' research

Table VI.

Use of a model for policy analysis and public outreach

Authors, year of publication	Use of a model for policy analysis / public outreach
Dyson and Chang, 2005	Prediction of solid waste generation
Antunes *et al.*, 2006	Addressing sustainability issues of a natural park
Friedman, 2006	Optimum pavement management
Liu *et al.*, 2007	Developing land use management strategies
Sufian and Bala, 2007	Predicting solid waste generation, collection capacity and electricity generation from solid waste
Güneralp and Seto, 2008	Model of the drivers and environmental impacts of urban growth
Lee *et al.*, 2008	Simulating land use and land cover change
Levine *et al.*, 2008	Modelling how villages can evolve into sustainable towns
Yuan *et al.*, 2008	Investigating urban dynamics and achieving multiple-objective programming
Bendor, 2009	Analysing wetland loss and compensation as dynamic processes
Eskinasi and Vennix, 2009	Simulating urban transformation
Fong *et al.*, 2009	Projections of future CO_2 emission trends, under various options of urban policies
Han *et al.*, 2009	Understanding environmental impacts and supporting urban planning toward sustainable development
Jin *et al.*, 2009	Supporting policymaking for urban sustainable improvement
Pataki *et al.*, 2009	Improving fossil fuel emissions scenarios with urban ecosystem studies
Shen *et al.*, 2009	Comparing different dynamic consequences brought by various policies and decisions for the purpose of land use and urban development planning
Thompson and Bank, 2010	Analysis of a building subjected to a bioterrorist attack
Gober *et al.*, 2011	Assessing water sustainability and planning for climate change challenges
Guan *et al.*, 2011	Modelling and evaluating urban development in a city suffering from depletion of resource and degradation of the environment
Jiang and Chen, 2011	Detecting factors that will influence the sustainability of cities
Wu *et al.*, 2011	Assessing the impacts of urbanization policy on land use change
Fernald *et al.*, 2012	Identifying the types and amounts of change in the communities and ecosystems
Haase *et al.*, 2012	Evaluating the impacts of different actors and factors on urban shrinkage
Lauf *et al.*, 2012a	Analysing household dynamics and housing decisions as driving forces of residential development
Lauf *et al.*, 2012b	Simulating demography and housing demand in an urban region, using growth and shrinkage scenarios
Qin *et al.*, 2012	Evaluating water use scenarios
Wu *et al.*, 2012	Assessment of the land use change led by the development of priority zoning.
Xu and Coors, 2012	Sustainability assessment of urban residential development
Zarghami and Akbariyeh, 2012	Simulating the conditions of the urban water system
Zheng *et al.*, 2012	Simulating spatio-temporal dynamics of land use change
Bernardino and van der Hoofd, 2013	Assessing the effectiveness of urban parking policies
Feng et al. 2013	Providing a quantitative base for effective energy and emissions planning
Li and Wu, 2013	Simulating the impact of urbanization on ecosystem service values
Liu *et al.*, 2013	Generating alternative land use patterns
Mahamoud *et al.*, 2013	Simulating the impact of social determinants on urban health
Park *et al.*, 2013	Analysing the dynamics of urban development projects, with a particular focus on a self-sufficient city development policy
Qin *et al.*, 2013	Evaluating socio-economic and/or water engineering policies
Vidal-Legaz *et al.*, 2013	Facilitating and testing land use policies with the goal to assess trade-offs between ecosystem services and socioeconomic development
Chang and Ko, 2014	Supporting better land use planning

Huang *et al*, 2014	Simulating the effects of climate change on water resources
Bettini *et al*, 2015	Identifying and exploring the institutional dimensions of water resource governance systems
Brittin *et al.*, 2015	Informed decision-making about urban design and public health programme planning
Cao and Menendez, 2015	Design and evaluate different parking policies, strategies or scenarios for traffic operations and control, transportation or land use planning and parking management
Chang *et al*, 2015	Reference for water resource allocation and urban planning in arid areas
Cheng *et al*, 2015	Examines the appropriate urban transportation policies that mitigate a global warming effect mainly from CO_2 emissions
Haghs henas *et al*, 2015	Identifying the best policy regarding sustainability in urban transportation for a specific level of investment and financial resource
He et al, 2015	Providing a scenario-based solution for assessing the potential impact of various driving forces on urban landscape dynamics
Li *et al.*, 2015	Analysing the effect of the urbanization process on the regional energy structure and CO_2 emissions
Liu *et al*, 2015	Identifying solutions to problems associated with urban passenger transport energy conservation and emission reduction during urbanization in the developing countries
Tsolakis and Anthopoulos, 2015	Adopting effective policies for monitoring and assessing the sustainable perfom1ance of eco-citie
Wu et al, 2015	Providing insight into better understanding of the possible impacts of land use change on ecosystem service value
Xi and Poh, 2015	Making critical decisions with significant long-term implications in water systems and beyond
Xu *et al*, 2015	Analysing factors that could possibly affect both industrial development and the landscape ecology
Yak;mta§ et al, 2015	Assessing the effectiveness of water conversation and supply policies in order to achieve sustainable urban water rnanagement
Chen *et al*, 2016	Dynamically simulating household energy consumption and CO_2 emissions under different conditions
Ercan *et al*, 2016	Forecasting the potential of public transportation to mitigate b·ansportation-related CO_2 emissions
Guo *et al*, 2016	Identifying the most promising intervention option and analysing effects of individual interventions, positive interactions and other potential interventions on household waste management
Hiasa et al, 2016	Analysing effects of new highway consb·uction on CO_2 absorption and emissions in construction area
Jin *et al*, 2016	Evaluating the socio-economic impacts of land consolidation
Li et al., 2016	Providing support for decision-making designed to improve the overall condition of urban green space
Macmillan *et al*, 2016	Understanding role of media in shaping cycling trends and identifying effective policy levers to achieve sustained growth in cycling
Qiang *et al*, 2016	Simulating the supply-demand structure to provide guidance regarding the scientific and reasonable utilization of water resources
Rozos *et al* , 2016	Producing scenarios of urban expansion and analysing the adoption rate of the water -aware technologies

Sukholthaman and Sharp, 2016	Providing a decision support tool to comprehend cause-and-e ffect interactions of different variables in solid waste management system
Wei *et al.*, 2016	Simulating dynamic interactions between urban water demand and influencing factors to evaluate the improved water use efficiency for the urban water system
Xu and Kang, 2016	Identification of layout model m t uitable for urban ecological development
Zeng *et al*, 2016	Providing dynamic simulations of water metabolism process for different scenarios
Allington *et al* , 2017	Evaluating the potential impacts of changes in policy, internal migration and climate on trajectory of grassland biomass production and livestock population
Chhipi-Shrestha *et al*,*2017*	Making informed decisions for reducing water consumption, energy use and carbon emis ions
Cox *et al.*, 2017	Providing complement to b.aditional land use and transportation models in the regional planning process
Dasgupta *et al*,2017	Delineation of guideline for policy orientation concerning e-waste towards protection of human health and environment
Ercan *et al*, 2017	Projecting the impacts of U.S. transportation system
Fang *et al*, 2017	Analy ing the u tainable development capacity under different scenario
Faust et al, 2017	Enabling the assessment of interdependencies between human and water ctor infra b·uctw·e y tern with parameter tailored to a city' unique characteristics
Fu *et al*, 2017	Simulating and predicting spatiotemporal city-level net carbon emissions
Geng *et al*, 2017	Enabling an analysis of variations in land use intensity under different scenarios
Ghasemi *et al* , 2017	Stimulating management strategies dealing with Tehran metropolitan water re w·c y tern
Guzman and Orjuela, 2017	Evaluating the impacts of possible policy interventions on u·ansport sector and tran port related emi ion and to a i t the deci ion-making proce
He *et al*, 2017	Analysing new influencing factors and establishing the quantitative relation hip based on econometrics for predicting the elecb·icity demand of Tianjin
Liu *et al*, 2017a	imulating land use development sb·ategies by con idering various socio-economic and natural climatic factors for policy recommendation
Liu *et al*, 2017b	Simulating, foreca ting and di playing geographical di tribution and land use change
Macmillan and Woodcock, 2017	Policy recommendation for different citie on cycling trajectory
Moon *et al*, 2017	Projecting changes in climate change-induced risks and providing policy alternatives to mitigate the risks of climate change effects in urban and rural areas
Procter *et al.*, 2017	Enabling policy makers to make sb·ategic choices about regional growth with utilization of light rail transit
Sahin *et al*, 2017	Allowing water planner to explore policy alternativ and optimize best-practice decisions considering water conservation and management
Wan *et al*, 2017	Achieving coordinated development of social development and ecological environment
Wang et al, 2017	Policy optimization for urban wetland water resources management
Wang *et al*, 2017	Identification of different driving modes for urban growth management in different regions according to the functional positioning of their DPZ
Wen and Bai, 2017	Driving restrictions on vehicle registration number or via a lottery system, developing of public b·an portation infrasb1.1ctures
Yin et al ,2017	Providing suggestions for the management of freshwater for the cities of Guizhou province in China
Yu and Fang, 2017	Simulating potential public safety dynamics of Shanghai
Zhou *et al*, 2017	Providing a ba i for reasonable indu try and population pattern according to water environment capacity

Source: Author 'research

Table VII.

Simulated environmental and social impacts

Auftthors, year of publication	Environmental impacts										Social impacts						
	En1	En2	En3	En4	En5	En6	En7	En8	En9	En 10	So1	So2	So3	So4	So5	So6	So7
Dyson and Chang, 2005	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Antunes *et al.*, 2006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Friedman, 2006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Liu *et al.*, 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sufian and Bala, 2007	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Güneralp and Seto, 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lee *et al.*, 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Levine *et al.*, 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Yuan *et al.*, 2008	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bendor, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Eskinasi and Vennix, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fong *et al.*, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Han *et al.*, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jin *et al.*, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pataki *et al.*, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shen *et al.*, 2009	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Thompson and Bank, 2010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Gober *et al.*, 2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Guan *et al.*, 2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Jiang and Chen, 2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Wu *et al.*, 2011	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fernald *et al.*, 2012	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Haase *et al.*, 2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lauf *et al.*, 2012a	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lauf *et al.*, 2012b	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Qin *et al.*, 2012	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Wu *et al.*, 2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Xu and Coors, 2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Zarghami and Akbariyeh, 2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Zheng *et al.*, 2012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bernardino and van der Hoofd, 2013	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	
Feng et al. 2013	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Li and Wu, 2013	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Liu *et al.*, 2013	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Mahamoud *et al.*, 2013	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Park *et al.*, 2013	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Qin *et al.*, 2013	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Vidal-Legaz *et al.*, 2013	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Chang and Ko, 2014	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Huang *et al.*, 2014	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	
Bettini *et al.*, 2015				✓													
Brittin *et al.*, 2015	✓	✓	✓		✓	✓	✓		✓		✓	✓	✓	✓		✓	✓
Cao and Menendez, 2015	✓		✓					✓							✓		
Chang *et al.*, 2015			✓	✓						✓							
Cheng *et al.*, 2015	✓					✓		✓				✓			✓	✓	
Haghshenas *et al.*, 2015	✓		✓			✓		✓	✓	✓					✓		
He *et al.*, 2015			✓	✓												✓	
Li *et al.*, 2015			✓					✓				✓	✓			✓	
Liu *et al.*, 2015	✓							✓				✓			✓	✓	
Tsolakis and Anthopoulos, 2015				✓				✓		✓	✓		✓			✓	✓
Wu *et al.*, 2015			✓	✓	✓					✓							
Xi and Poh, 2015				✓						✓							
Xu *et al.*, 2015		✓	✓	✓			✓	✓		✓							
Yalçıntaş *et al.*, 2015				✓								✓				✓	
Chen *et al.*, 2016							✓	✓									
Ercan *et al.*, 2016	✓					✓		✓				✓			✓	✓	
Guo *et al.*, 2016			✓							✓							
Hiasa *et al.*, 2016			✓					✓				✓			✓		
Jin *et al.*, 2016			✓														
Li *et al.*, 2016			✓		✓	✓		✓				✓				✓	
Macmillan *et al.*, 2016			✓			✓		✓				✓			✓	✓	
Qiang *et al.*, 2016			✓	✓													
Rozos *et al.*, 2016				✓												✓	
Sukholthaman and Sharp, 2016	✓		✓			✓	✓	✓		✓							
Wei *et al.*, 2016			✓	✓												✓	
Xu and Kang, 2016			✓			✓		✓		✓							

Zeng *et al.*, 2016				✓				✓									
Allington *et al.*, 2017			✓		✓												
Chhipi-Shrestha *et al.*, 2017				✓			✓	✓		✓		✓				✓	
Cox *et al.*, 2017	✓		✓	✓		✓		✓		✓					✓		✓
Dasgupta *et al.*, 2017		✓	✓				✓			✓							
Ercan *et al.*, 2017	✓					✓	✓	✓					✓		✓		✓
Fang *et al.*, 2017	✓			✓	✓			✓		✓							
Faust *et al.*, 2017				✓						✓			✓			✓	✓
Fu *et al.*, 2017			✓	✓	✓			✓									
Geng *et al.*, 2017			✓														
Ghasemi *et al.*, 2017				✓						✓						✓	
Guzman and Orjuela, 2017	✓		✓			✓		✓				✓			✓		
He *et al.*, 2017								✓								✓	
Liu *et al.*, 2017a			✓	✓	✓												
Liu *et al.*, 2017b			✓	✓													
Macmillan and Woodcock, 2017						✓		✓				✓			✓	✓	✓
Moon *et al.*, 2017			✓	✓									✓	✓			✓
Procter *et al.*, 2017	✓		✓			✓		✓				✓			✓	✓	
Sahin *et al.*, 2017				✓													
Wan *et al.*, 2017		✓				✓	✓	✓		✓					✓		✓
Wang *et al.*, 2017			✓	✓						✓							
Wang *et al.*, 2017			✓								✓				✓	✓	✓
Wen and Bai, 2017	✓		✓			✓	✓	✓		✓					✓		✓
Yin *et al.*, 2017				✓			✓			✓							
Yu and Fang, 2017		✓		✓		✓	✓	✓		✓				✓		✓	
Zhou *et al.*, 2017			✓	✓		✓		✓									

Source: Authors' research

Table VIII.

Summary of stakeholder participation and public outreach

Authors, year of publication	Description of stakeholders	Participation in the modelling process	Use of management flight simulator	Channel of public outreach
Antunes *et al.*, 2006	Representatives of nature conservation, regional authorities, local authorities, NGOs, Industry, Universities and research institutes	Yes, 4 workshops	Not described	Not described
Güneralp and Seto, 2008	Experts on Shenzhen and China	Yes, during model building and validation	Not described	Not described
Levine *et al.*, 2008	No description	Not described	Yes; sustainability Engine™	It is planned to contact stakeholders of villages transforming into urban areas
Eskinasi and Vennix, 2009	Managers and stakeholders	Yes, 2 workshop	Yes, management flight simulator	Workshops with stakeholders using management flight simulator
Fong *et al.*, 2009	State planning committee.	Not described	Not described	Presenting simulation experiments in the form of a technical report for evaluations by the public and a decision by the state planning committee
Pataki *et al.*, 2009	Decision-makers, political advisors, and gatekeepers for various politically and economically influential social group	Yes, 6 workshops	Yes	Not described
Gober *et al.*, 2011	Water stakeholders, the private sector, community leaders, and the public	Yes, in the initial phase	Yes, WaterSim	Not described
Fernald *et al.*, 2012	Stakeholders from acequia communities	Yes, in the initial phase	Not described	Not described
Mahamoud *et al.*, 2013	Local community and academic researchers; NGOs; policymakers and decision-makers at the municipal and provincial levels	Yes, in the initial phase	Not described	Not described
Vidal-Legaz *et al.*, 2013	Local water suppliers, town councillors	Yes, in the initial phase	Not described	Not described
Bettini *et al.*, 2015	Government management and executives; environment, health, and planning departments; consultancies	Yes, in the initial phase	Not described	Not described
Brittin *et al.*, 2015	Community and healthcare organizations	Yes, in the initial	Not described	Not described

Guo *et al*, 2016	Governments, sociologists, policy makers, households	Yes, during model building	Notdescribed	Not described
Guzman and Orjuela, 2017	Local government at thecity level	Not described	Yes, Metropolitan Activity Relocation Simula tor (MARS)	Not described
Jin *et al.*, 2016	Experts, project stakeholders	Yes, series of workshops	Notdescribed	Not described
Sukholthaman and Sharp, 2016	Policy makers, strategic planners, solid waste management, government	Yes, duringmodel building, 77 **interviews**	Notdescribed	Interviewswith related stakeholders, including householders, waste collection and transportation staff, BMA officers, MSWM experts, and two contracted company officers
Allington *et al*, 2017	Herdowners, researchers	Yes, workshop	Notdescribed	Workshop with stakeholders
Cox *el al.*, 2017	Local and regional planning organizations, localgovernment, planners	Yes, during model building	Notdescribed	Not described
Fausteta/., 2017	Local communit ies, decision-makers, engineers, researchers, planners	Not described	Notdescribed	It is planned tocontact stakeholders by deployingsurveystothelocalcommunities
Macmilla n and Woodcock, 2017	Policy makers, community (including existing and "would-be"cyclists) and research sta keholders	Yes, during model building	Notdescribed	Interviewsand workshops
Moon *et al.*, 2017	Government, researchers, specialist,	Yes, during model building	Notdescribed	Interviewswith specialist and practitioners
Procter *et al.*, 2017	Representativesfromtheregionaltransit authority, local sus tainability and health departments, cityand regional land use and transportationplanning departments	Yes, during model building	Notdescribed	Not described
Sahin *et al.*, 2017	Gold coast households, COGC experts, stakeholders	Yes, during model building	Notdescribed	Workshops, consultationsand surveys

Source: Authors' research