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Urban models: Progress and perspective

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ABSTRACT

Urban modelling is an important branch of land use science. It integrates geography, surveying and mapping, information science, system science, economics, sociology and other disciplines to establish urban models, which have been used to provide support for urban policymaking or analyses. Urban models are used to understand, analyse, evaluate and reproduce the process of urban development, and predict the consequence of urban planning scenarios. In this paper, we provide a systematic review of urban models, including the evaluation, classification, application of urban models, and the timeline of urban models' development. According to their modelling styles and applications, urban models can be classified into three categories: aggregate static models of economic and spatial interaction, urban dynamics models, and behavioural models of individual agents which linked to spatial location. According to the different modelling methods, urban models can be classified into two categories: top-down and bottom-up. Nowadays, emerging technologies, especially Information and Communication Technologies (ICT), are gradually but significantly changing the organization form of urban economic activities. It enables regions to break the location limitation and join in the national even global industry division, and that triggers a new bottom-up rural urbanization process, which formed a significant challenge for urban models. Based on above discussion, we proposed two perspectives for improvements of urban models, inculding the integration of ICT with tradtional urban models and integaration of top-down and bottom-up models.

1. Introduction

Land use science is a discipline that examines the dynamic changes of land system. The interaction between human and natural environment forms our land systems [1]. The survival and development of human society depends on the foundation and services such as food, energy, and resources provided by the land system [2] and human activities change land system. The emerging sustainability science is one form of land use sciences [3] which has seen interdisciplinary research and a great diversity in methodological approaches [1,4,5].

Based on land use science, different disciplines have developed a series of alternative approaches for understanding relationship the natural environment, human factors and technology according to their emphases. For example, urban geography focuses on the organization form and mechanism of natural environment factors and human factors in urban areas [6] and transportation geography focuses on studying the role of transport and mobility in the territorial combination of productivity and the territorial structure of transportation networks [7].

The city is a complex system, it involves social, economic, demographic, transportation, and other aspects [8] and constantly interacts with external systems by population, material, economy and information exchange [9–11]. Urban area is a highly complex and dynamic system of interrelated activities and components with many factors continually change over time.

To understand the mechanism of urban land use changes and represent possible future changes within urban systems, urban models have been developed to describe and analyse the spatial structure of urban areas and the interaction between various urban features by equations. An urban model is a functional formula supported by economics, geography, sociology, and mathematics. It regards the city as a complex hierarchy system which contains multiple subsystems, and the subsystem (e.g., population distribution, transportation and economic)

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can be quantified by using abstract mathematical formulas. As a powerful urban research tool, it has the following features: multi-system collaborative analysis; multi-disciplinary theoretical support; quantitative evaluation [12–15]. For simplicity of understanding and ease of manipulation it can be divided into subsystems [16], for example, transport subsystem and land use subsystem. Usually,urban models are not focused on a certain subsystem, instead, it emphasizes the comprehensive influence of urban subsystems on urban spatial structure and individual behaviour, especially the transportation system and land use system [17].

Cities will always face various problems in the process of development. For example, Fig. 1 shows how the economic performance changes as the city size grows. It shows that although in the initial stage, increasing city size has positive effect on agglomeration economies, the negative effect will appear when it across inflection point [18]. The negative effect can be caused by many factors, such as traffic congestion, infrastructure overwhelming, environmental pollution, deterioration of public health and other urban social environmental and economic issues. For example, high resources consumption with low utilization efficiency, and environmental pollution weaken the urban economic performance [19].

To better understand the mechanism of the negative effect and solve the problem, many studies have examined the relationship between city size, agglomeration economies, urban evolution and decision making (e.g. [20–22]). They argue that there is a relationship between city size and agglomeration economies. However, Capello and Camagni [21] argued that the question of optimal city size tended to be expressed in a misleading way. The real issue is not 'optimal city size' but 'efficient size', which depends on the functional characteristics of the city and on the spatial organisation within the urban system, and has positive effect on urban development [21]. In other word, optimizing the spatial distribution and organisation of urban resources will solve urban negative issues. Therefore, the main task and main challenge of urban modelling is to better understand the mechanism of the interaction, distribution and organization of urban factors.

To better understand the mechanism of the distribution of urban population and solve the problem, urban models have been developed to study on the relationship between city size, agglomeration economies, urban evolution and decision making [20–22]. There are theories and models which study on the mechanism of urban population distribution, and points out multiple factors which impact on urban residents' spatial decision behaviours.

Usually, urban models focus on the relationship between multiple urban fields in order to understand urban system and predict future changes. Although urban models are different in various aspects and details, the purpose of urban modelling is the same. They try to provide a set of practical tools for urban analyses which seeks firstly to understand and describe the mechanism of urban evolution, including govern urban land use and behaviour of urban system, and secondly to predict the consequences of future policy decisions and scenario of urban planning [13,16,23].

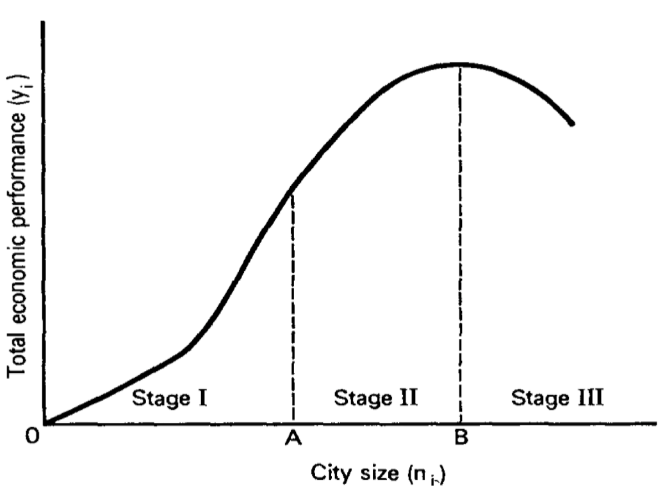

Fig. 1. The relationship between city size and agglomeration economies [18].

Nowadays, with the expansion of city scale and the increase of the number of large and super-large cities, the traditional urban model, which focuses on a particular field, is increasingly difficult to deal with increasingly complex situations. As a result, there is increasing integration amongst different disciplines, leading to the development of new models. For example, the integration of land science and transportation studies has given rise to the land use and transport interaction (LUTI) model. The integration of LUTI model with economics has formed the spatial equilibrium model, and so on. As more and more disciplines are integrated into urban models, the number of parameters and complexity of the models are rapidly increasing. Moreover, in the era of big data, it has become increasingly important to process and analyse large amounts of data. However, the workload of adjusting the models and processing the data using traditional methods too large, and the efficiency and time cost become unacceptable.

With the development of computer technology, especially artificial intelligence (AI), in order to train AI to deal with massive data and complex tasks, the concept of machine learning has been proposed. It uses computers to simulate or implement human learning behaviour [24]. By continualy acquring new knowledge and skills, reorganizing existing knowledge structures, and thus improving its own performance. Therefore, machine learning has become an important tool to deal with complex urban models and massive amounts of data, playing an extremely significant role in urban studies.

This paper reviews the origin and development of urban models, and points out that interdisciplinary integration is the trend of urban model development. The traditional urban models usually approach urban issues form a single prospective, macroscopically (Top-down) or microscopically (Bottom-up). In the future, complex urban multidisciplinary models based on machine learning with massive parameters may achieve macro and micro unification and will become one of the most important directions for urban studies.

In this paper, we briefly introduce the evolution of urban models and associated theories (Sect. 2) to establish a framework and background of urban model developments. We focus on the interdisciplinary models (e.g., land-use and transport interaction models) by providing more details (Sect. 3). We summarize the general challenges for urban models in Sect. 4. New development or applications of urban models are discussed in Sect. 5, and some conclusion and suggestions are proved in Sect. 6.

2. Urban studies and urban models

To a certain extent, the history of human civilization is the history of urbanization. Thus, many researchers devote themselves to urban studies. Urban researchers were trying to identify and analyse the urban development by establishing theories and mathematical models of cities, which describe various aspects of the urban system by conceptions and equations. This sector traces the development of urban models in chronological order and has found that development of urban models is a process from simple to complex, from a discipline to interdisciplinary synthesis.

2.1. Urban studies

In 1937, Mumford argued that the city is a related collection of primary groups and purposive associations: the first, like family and neighbourhood, are common to all communities, while the second are especially characteristic of city life. "*These varied groups support themselves through economic organizations that are likewise of a more or less corporate, or at least publicly regulated, character; and they are all housed in permanent structures, whining a relatively limited area. The essential physical* *means of a city's existence are fixed site, the durable shelter, and the permanent facilities for assembly, interchange, and storage; the essential social means are the social division of labour, which serves not merely the economic life but the cultural processes. The city in its complete sense, then, is a geographic plexus, an economic organization, an institutional process, a theatre of social action, and an aesthetic symbol of collective unity* [25,26]. pp.112)."

In 1950, V. Gordon Childe argues that the essential feature of civilization is a certain size of settlement and population density and "in the case of the Urban Revolution the increase was mainly account for by the multiplication of th0e numbers of persons living together" [27]. He believes the population density is determined by several factors, such as natural resources, transport, technique and economy [27]. Based on that, in 1965, Gideon Sjoberg believes urban evolution is intimately related to three major levels of human organization, each of which is characterized by its own technological, economic, social and political patterns [28]. The main manifestation of urban evolution is mainly refers to the urban sprawl and urban form [27–29].

Urban researchers were trying to identify and analyse the force that push urban development. In 1995, Makse and other researchers argue that population, economic and other urban resources which they called development units are the engine of urban development [30]. In 2003, Yang and others [31] had proposed the concept of geographical potential which is relative predominance, which includes geographic location, spatial interregional differences, regional structure and environmental quality, in geographical location of a region to another region. Such potential is deeply affected by environmental conditions, converted as different historical stages, science and technology development. Urban sprawl is mainly focus on the extent of urbanisation [32], and urban form is mainly focus on the "metropolitan size, activity intensity, the degree that activities are evenly distributed, and the extent that high-density sub-areas are clustered [33]."

Meanwhile, the administrative power also deeply influences on urban development [31,34]. The administrative power mainly depends on the administrative level and policies of local governments. However, how it affects the urban development has not been in-depth researched yet. In other word, a clear correspondence between policy impact and urban development has not yet been established. That has limited the application of urban models in a certain extent.

2.2. The development of urban models

Model development is a process from simple to complex, from a single discipline to a multidisciplinary integration.

In the early age, urban models focus on the site of a city, and argue that the urban development was predominated by the location of a city centre. For example, in the early 1920s, Ernest W. Burgess proposed his famous concentric-zone model which argued that land uses tend to occur in rings around the centre of a growing modern city ([35,36]). In 1929, Burgess outlined an altitudinal-zone model, which argues that there is a positive relationship between socioeconomic status of residents and population distribution [35]. In 1939, Hoyt proposed the Hoyt sector model, which argues that the highest-income residential areas occur in city centres and expanding outward in wedge-shaped sectors and lower-income areas successively, distribute flanked on the sectors' sides [37].

Those three simple models are widely considered as "*the classic models of urban land use*" and "*to be catalysts of research on cities in both developed and developing societies* [38]. " They relate city centre location to urban development, and indicate the relationship between distances, transportation costs (time and money) and population distribution. They argue that transportation linkages significantly influence human activities and their locations [39]. These models have been widely used. For example, based on concentric-zone model and altitudinal-zone model, William B. Meyer proved that the role of amenities is the key factor in residential choice [36], and Dai's group mentioned that from the city centre to the countryside. Some researchers use the Hoyt sector model to explain the outward expansion of cities, for example, [40] use the model to analyse spatial-temporal land use changes of Ruaka town, Nairobi city in Kenya, between the years 1988 to 2019. [41] focused on "*the sector features of the replacement and expansion of functional urban land, similar to Hoyt's sector mode.*"

With the development of urban models, more factors have been involved into the urban models in order to explore the mechanism of urban development from multiple perspectives.

System dynamics is a discipline of crossover and integration which was initially developed by Forrester from MIT [42]. It is a cross-discipline, which uses information science as enter point, and uses organisational theory, control theory, tactical decision-making, cybernetics, system theory and military games to analyse and explore the transmission, exchange, organization and control of information and the casual relationship between decision-making and consequence [43]. System dynamic theory argues that every system has its structure and the organization of the structure decides the functions of the system. Thus, it prefers to focus on the interactions and relationships between the internal subsystems rather than external interference and stochastic events. The subsystems and elements inside regard as stakeholders of system dynamics. It uses a standard causal loop approach to describe the causal relationship and feedback between stakeholders. System dynamic approaches use qualitative Causal Loop Diagrams and quantitative stock-flow models to provide a powerful tool to explain and understand basic structure and the nature of the problem within such systems [43]. It provides an insight for modellers to investigate general dynamic tendencies [43].

In 1959, Hansen proposed a viewpoint that there is a relationship between urban land use and accessibility. Because almost all human activities need to interact through transportation lines, in a certain context, transportation networks determine the spatial separations of human activities and land use, such as the distribution of population, commercial, industrial, etc. [44]. This idea is used as the basis of the Land use-transportation interaction (LUTI) models and laid their theoretical framework. In 1964, Lowry proposed Lowry land use model which includes a residential location model and a service industry location model, and the models are nested with each other [45].

The early LUTI model generally adopted spatial interaction theory as its theoretical basis, but with the intervention of other disciplines, the LUTI model gradually became more and more complex.

In the initial stages, Lee and Batty argued that the theoretical drawback of the urban model, based on the theory of spatial interaction, is that the choices it simulates lack a reliable theoretical basis for behaviour [46,47]. The accuracy of the spatial interaction model mostly depends on the correct selection of key parameters. For example, in the gravity model, attractiveness and distance decay usually are the most important parameters [48].

Then, the Development of Space Economics and the Model of Space Equilibrium provide an opportunity for urban models to simulate individual behaviours and analyse how they influence urban development [49,50]. The combination of space-economy and the LUTI model creates a new type of urban model which is called spatial equilibrium model [51]. The new model has become the most widely used type of urban model in the field of simulating the process of socioeconomic evolution, planning policy evaluation and decision-making support in developed countries [14,52–54].

LUTI models based on the argument that transportation has a major impact on the spatial and economic development of cities and regions. The attractiveness of particular locations depends in part on the relative accessibility, and this in turn depends on the quality and quantity of the transportation infrastructure [55]. Certain factors which influence the growth of urban areas are called urban factors. Almost all urban factors, which include population, land system, economic activities, public service, infrastructure and other urban resources, and urban sub systems are connected and organized by transportation networks. It should be noticed that connectivity is the base rock of interactions between urban factors. Based on that, this paper proposes a hypothesis that the urban factors are connected and organized by transportation networks and created urban potential energy which drives the development of urban areas. The potential energy casts it influences by transportation networks. Their energy will be consumed via transportation. In the end, all the urban factors will form a balanced status and reform the city. Thus, the consumption of transportation determines which region the urban factor can affect. Related researchers present the outcome of research on a sample of 12 European cities and "*The outcome of the research points out that urban transportation infrastructure may have a catalytic effect on the development, redevelopment and regeneration of urban areas but there are a lot of other influencing factors which make such re-urbanization processes a successful or unsuccessful story.*" [56]. So, transportation indirectly works as a catalyst for the development and redevelopment of urban areas as well as the regeneration of declining areas.

System dynamic approaches allow system and policies to interact across space and time. Meanwhile, a feature of Land-use/Transport Interaction Model is that transport and land use systems operate on different time scales, because the respond from transport users may relatively quickly to changes in transport policy or cost, but the respond from land use users may not [43]. Therefore, system dynamics is a ideal for investigating the interaction between land-use and transport, because such system "*contain feedbacks and delays which are often outside of the mental model of the decision maker or where feedbacks cross stakeholder boundaries* [43]."

System dynamics model can be used to predict the consequence of a certain urban planning pattern and they developed related methods to support decision making. There is a growing body of literatures and models which explore and analyse the intercation and spatial organiztion of economy, population, migration, infrastructure, land-use and transportation [43]. They developed urban related methods, such as the dynamic Land Use and Transport Interaction(LUTI) model MARS (Metropolitan Activity Relocation Simulator) and they argue that is part of a structured decision making process [57].

Fig. 2 shows a mental model of commute trips by car in MARS. The "*Employed population, Workplaces, Population, Attractiveness of other zones and Car ownership*" are enter points. The casual chin reactions between them decided "*Attractiveness by car*". For example, with more population and workplaces in a zone, it creates more economic activities and provides more jobs. That increases the "*Attraction*" of the zone and encourage people to commute by car. Therefore, the "*Attractiveness by car*" has been reinforced. If there are multiple zones in a certain region, people may compare conditions, such as travel distances, incomes level and the number of jobs, of those zones and change their destinations of commute. Thus, higher "*Attractiveness of other zones*", lower the attraction of the zone for people to commute by car. Meanwhile, higher the "*Car ownership*", higher the proportion of people who have the option that commute by car. It should be noted that with the increase of employment, more and more people commute by car will caused negative effects on transport. Such as traffic congestion decreases the average velocity of cars and people need more time to search for car parking. So, stakeholders "*Attractiveness by car, Commute trips, Parking search time*" and "Time in car commute" formed negative feedback circle B1, "*Attractiveness by car, Commute trips, Speed by car*" and "*Time in car commute*" formed negative feedback circle B2, and "*Attractiveness by car, Commute trips, Fuel cost*" and "*Time in car commute*" formed negative feedback circle B3. The time and economic cost of commute by car is intolerable for some people. Then they may choose to use other commute modes and that will alleviate negative effects on transport. Therefore, stakeholders "*Attractiveness by car, Commute trips, Speed by car, Time per commute trip by other modes*" and "*commute cost other modes*" formed positive feedback circle B4. All those casual chin reactions and feedbacks will achieve a dynamic equilibrant status.

Fig. 3 shows a simple conceptual structure of traditional general LUTI model. Land use model include current situation of land use and land use policy. Transport model includes traffic infrastructure and travel cost. The accessibility between transport model and land use model forms the spatial organization of a zone. The interaction between spatial organization and population and economic activities reforms the structure of former and impacts on the distribution of the latter, until they achieve a dynamic equilibrant status.

LUTI model is a commonly used mathematical model that is even considered to be the only available model for simulating the urban spatial development process [59]. The main concern of LUTI model is spatial interaction, which regard the location as the main driving force for urban land use and transportation development.

Batty categorize the LUTI models into two categories as follows:

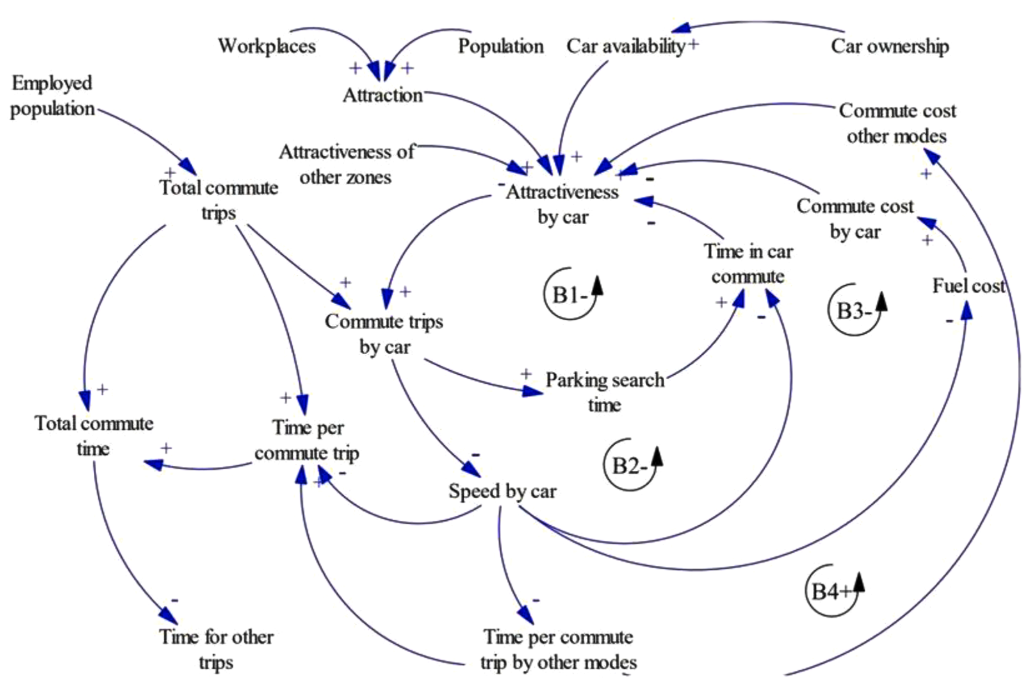

Fig. 2. CLD for the transport model: commute trips by car in MARS [57].

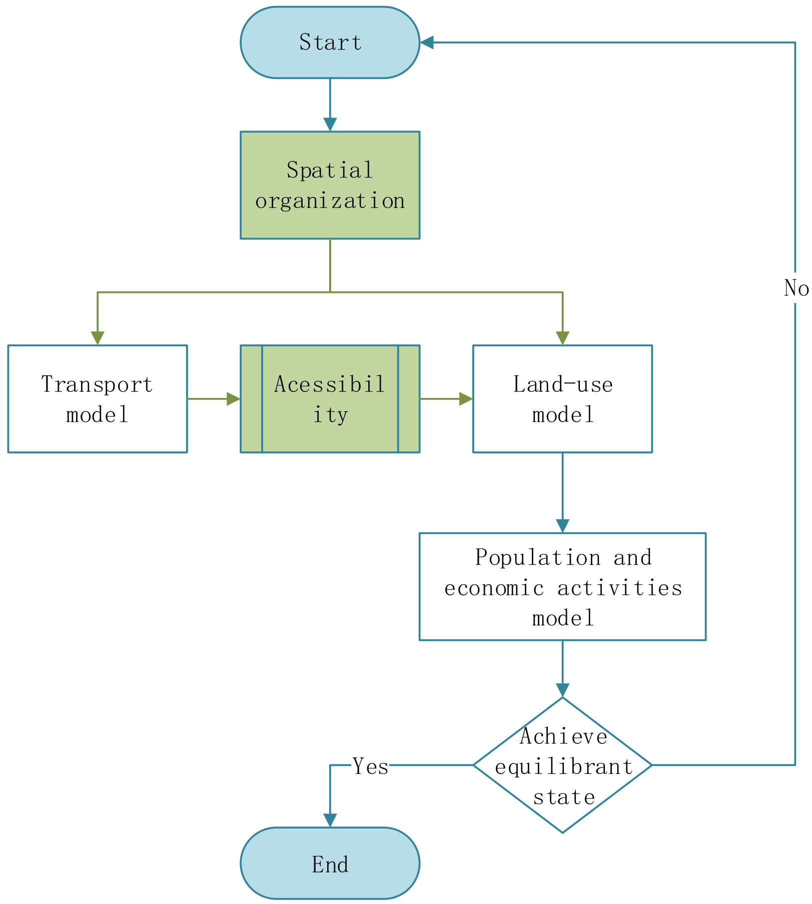

Fig. 3. Traditional general LUTI model(Translated from [58]).

"*various theoretical dynamics associated with equilibrium approaches such as those being developed by Wilson* [60]" and Lowry model [45], and "*more physically based land-development models mirrored around cellular automata and agent-based models*" [15,61]. The main difference between them is that the former is a static model, which assumes that other parameters will not change over time to predict a certain parameter; while the latter is a dynamic model, with in which every parameter can be changed over time. In addition to traditional fields. For example, [62] argues that by integrating land-use and transport models with environmental models of greenhouse gas emissions and climate hazards, LUTI models show promise as powerful tools to analyse and assess the impact of urban policy on climate changes. LUTI models are also applied urban form and energy use [63], and other aspects.

As the interface between human society and the natural environment, the land system is a typical complex system [64]. With the development of computer science, the ability of calculation has been greatly improved, and that provides an opportunity for urban related researchers to explore the urban development from a micro perspective.

The interaction between multiple urban factors and subsystems formed a "*complex system*". It is characterized by path-dependence, critical major mutations, spatial self-organization, and spatial emergence [65,66]. In the system, the interaction between those parts (factors or subsystems), also called "agents" or "cells", often lead to large-scale phenomena and that called "emergence" [66,67]. In an overall sense, the system is hardly "*predictable from a knowledge only of the behaviour of the individual agents*" [13,66].

In the field of modelling complex system, pure top-down modelling methods usually are difficult to attract regional interactions. Whit the development of computer technology, bottom-up methods provides a batter choice to describe complex system [68]. For example, Cellular automata (CA) mode and Agent-based model, which focus on individual behaviours.

Cellular automata (CA) model is a kind of model that simulates spatial and temporal discrete complexity by simple local calculation. This local calculation is based on five elements as follows: Cell, Status, Neighbourhood, Transfer function and Temporal. The basic algorithm of the CA model is that in a moment, the status of a cell depends on its previous status and statuss of its contiguous cells [69]. Such models usually are described as two-dimensional rectangle grid of cells, where each cell has a fixed location and attribute information,for example, land cover, land use or terrain [67], to represent regional land use and "*embodying processes of change in the cellular status are determined in the local neighbourhood of any and every cell* [13]. "

The earliest CA model can be traced back to the original computer science and fractal theory [70]. Researchers usually use CA models to predict or restructure the process of urban growth to compare the consequences of different urban development scenarios. A traditional CA model uses regular square grid and synchronous growth, and is designed for representations of land use change in rural-urban fringe settings. Based on that, related researchers have developed a new CA model that uses spatial data in the form of irregularly sized and shaped land parcels, and incorporates synchronous and asynchronous development in order to model more realistically land use change at the land parcel scale [71].

There are two key components, neighbourhood rules and transition rules, in CA-based models [72,73]. There is an equation to describe the dynamic changes in CA models as follows:

$$S_{ij}^{t+1} = f\left(S_{ij}^{t}, \Omega_{ij}^{t}, T\right)$$

[74]

The parameter S_{ij}^{t+1} represents the status of the cell, where spatial coordinates are (i, j) at time t+1, which is correlated to the current status of cell (i, j) at time t. The parameter Ω_{ij}^{t} represents the influence on its neighbourhood. The parameter T represents the transition rules. All those parameters are in a particular linkage of f [74].

After a period of development, the CA model has developed a series of branch models. In 2016, Li and Gong created an evolution tree to illustrate the development and inheritance of CA models. Although it does not contain all CA models, the most typical models are in the tree (Fig. 4) [74].

Based on the development of the modelling framework or main components of CA-based models, Li and Gong proposed a categorization scheme which divide CA models into two main branches: probability-based models and rule-based models.

The manifestation of probability-based CA models is that the changes of the status of cells are mainly determined by a conjunction of different components as a synthesized probability, and the manifestation of rule-based CA models is that the transition has been determined by five parameters ("i.e., diffusion, breed, spread, slope resistance and road gravity") and "correspond to four types of urban growth patterns, i.e., spontaneous, diffusion, organic and road-influenced [74] ". CA models can be regarded "*as simplifications of agent-based models where the focus is on emergent spatial patterns through time* [13]".

The creation of Agent-based modelling (ABMs) can be traced back to the cellular automaton model. It is an intelligent entity, which incorporates other ideas, including but not limited to game theory, complex systems, emergence, computational sociology, multi-agent systems and evolutionary computation. Because this model requires a lot of calculations, it didn't usher in its prosperous period until computer technology progressed. In 2009, Farmer and Foley defined ABMs as: a computer simulation of a large number of decision-making subjects and institutions interacting through set rules [75]. Subjects in ABMs not only have neighbour interactions, but also have the ability to learn and evolve [68].

Agent-based modelling is one of the most common approach to "*analyse and simulate Land-use/cover change (LUCC) as the result of individual decisions* [76]". The model has been used to test urban policies in urban growth [77], spatial economy [75] and transportation [13,78]. Under guide of its experience and knowledge, it will consider varying related factors and make a decision. As a consequence of the decision, the entity well produces a certain behavioural pattern. Generally, the agent has four main feature: autorhythmicity, spontaneity, sociality and reactiveness [79]. Moreover, urban researchers believe that different modelling problematics can lead to very different solutions. They suggest to use multilevel models, which included macro, intermediate and micro levels, to build a conceptually or causally linked system of grouping objects or processes along an analytical scale in order to help the modeller identify the difficulties peculiar to each of the approaches [80].

As a model which operates from the bottom up, the main focus of an Agent-based model is at the micro-level, elemental or individualistic, to representing behaviours and interactions of those objects through space and time [13]. The model starts from the definition of the rules of subjective behaviours to build the framework in order to avoid the understanding and analyses of the entire system, and makes up for the difficulty of quantitative description of complex systems by traditional mathematical and physical models [81,82].

CA and ABMs have something in common, which is that they both focus on spatial neighbourhood relations and decision making in individual level of subject. The location, spatial accessibility and distribution are very important factors of the land system. Thus, CA and ABMs usually combine with other spatial interaction models to develop new models for specific conditions, for example Land use-transportation interaction models.

The most difference with CA models is that CA models focus on transition rules, but ABMs focus on the emergence which are created by the interaction between different microscopic individuals in the macro-dimension [83,84]. However, both CA and ABMs have their limitation, for example, CA models "*temporally persistent transition probability and neighbourhood effect cannot express the spatiotemporal land use dynamics to generate accurate simulations* [85] ", because in the real world, the rule of land use is usually change over time, but the rule of CA model hardly can change temporally. And ABMs still lack effective solution in the

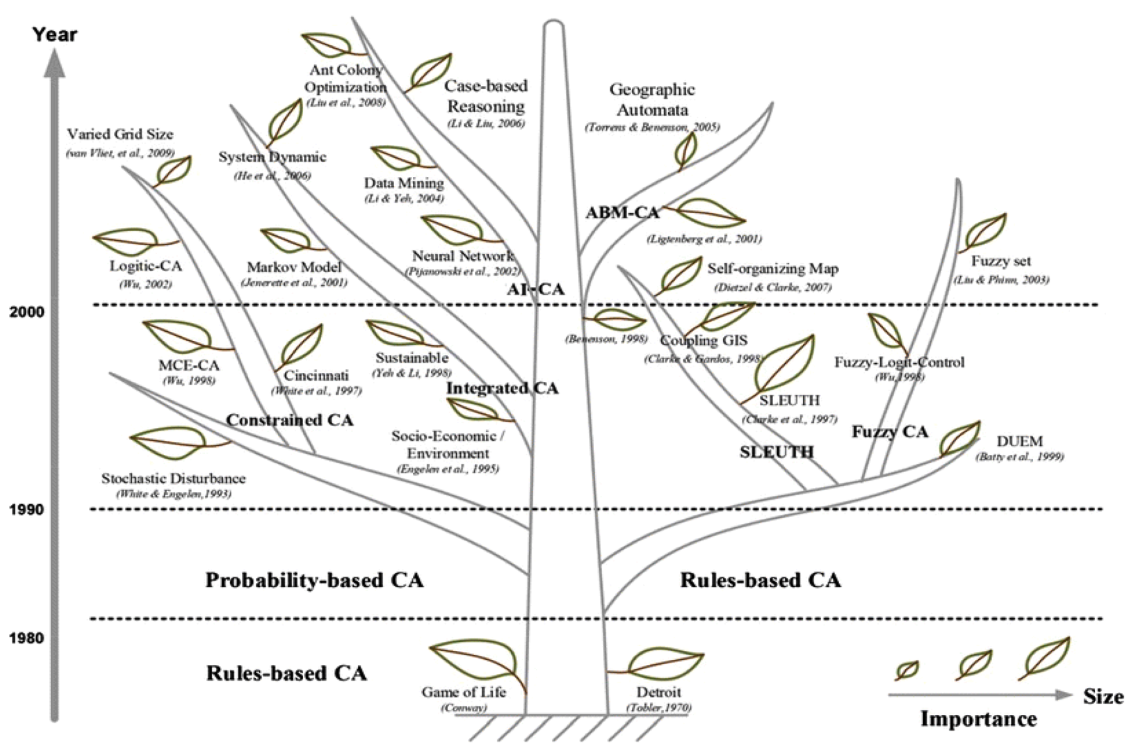

Fig. 4. An evolution tree of CA-based urban growth models [74].

application of large-scale areas [5,86], because "*finding sufficient empirical data about decision making processes and outcomes at larger scales is extremely difficult* [5] ".

Agent-base models and cellular automata models are considered to be ideal methods for studying complex systems and simulating land changes [68,81,82].

With the continuous improvement of new technology and infrastructure, especially information network technology and infrastructure, the era of big data in urban planning research has quietly arrived. Using the massive amounts of data constantly generated in cities, such as bus card data, traffic monitoring data, mobile phone positioning data, and social network data, urban researchers can more directly mine individual behaviour characteristics from real data [87,88]. Furthermore, new computer technology, such as artificial intelligence and deep learning, has been applied in urban research [89,90]. It brings new opportunities and challenges to the development of urban models.

By combining system dynamics with other disciplines, system dynamics approach plays a significant role in understanding and analysis the impact of a certain decision on socioeconomic, policy, population and other human activities, and the consequence that created. For example, by combining system dynamic with geographical information system to consider land use types and transport supplies, [91] used LUTI model to develop an agent-based approach to calculate the impact of Light Rail Transit on touristic suitability in Asia New Bay Area, Kaohsiung, Taiwan, China.

2.3. Classification of urban models

Urban models can be classified according to different criteria. Fig. 5 shows two different methods for the classification of urban models. The first method categorized models by modelling styles and application, and the second method categorized models by modelling methods.

2.3.1. Classification by modelling styles and applications

Batty defined three main classes [92] of urban models by their modelling styles and applications as follows (Fig. 5).

The first class is built around the aggregate static models of economic and spatial interaction. The theoretical roots of this class mainly are socioeconomics, regional economics and urban economics, and location theory, for example, land use and Transportation Interaction (LUTI) models. These models represent the spatial equivalents of classical macroeconomics and microeconomics theory. They are mainly used to understand and predict how urban land use and transportation policies effect on the spatial distribution of urban socioeconomics and transportation activities [93]. In short, this class of models is the most operational [23].

The second class is urban dynamics models. In 1969, JW. Forrester's publication Urban Dynamics [94] introduced an insight "*forming a bridge between engineering and the social sciences* [95]". These models use system dynamics methodology to analyses urban socioeconomic processes [23,95]. BY system dynamics methodology, socioeconomic processes are divided in elements and there are causal relationships between those elements. The change of elements cast their influence via certain causal relationships and triggers chain reactions. System dynamics methodology is usually used to deal with nonlinear growth issues.

The last class is the focus of current urban research which involves models built around representing the action and behaviour of individual agents which linked to spatial location, for example cellular automata and agent-based models. Those models are bottom-up models, which focus on micro-level interactions, for example, the neighbourhood interactions between cells agents through spatial location analysing [23,96,97]. However, the action and behaviour of individual agents are different to quantify and sometimes justify.

Foot provided another classification, which according to their theoretical basis, they can be categorize to the three main types as follows: based on gravity, linear and optimizing mathematics models [16].

The gravity based model, for example, space economic and space equilibrium models, provide an opportunity for urban models to simulate individual behaviors which attractiveness and distance decay usually are the most important parameters [48]. The attractiveness of a factor decays with distance. Therefore, the onset strength of attractiveness and rate of decay dominate the influence area of a factor.

The linear based model usually has been used to deal with the socioeconomic and land use activities in a certain urban area by deriving a set of linear equations [16]. This model regards socioeconomic and land use activities as the independent variables. The information of a variable has collected for each zone in the region to calculate the dependant variable, such as population and employment, in the region.

The optimizing models try to provide an optimal solution for urban development by performing a similar function. For example, simple optimal urban size theories, which based on the main stream economics and focus on the cost-benefit analyses, provide the same optimal size for cities when they have the same production function [98].

2.3.2. Classification by modelling methods

According to different modelling methods, urban models can be classified into two categories: top-down and bottom-up (Fig. 5).

The top-down models are based on spatial interaction models, including gravity model, entropy maximization and etc., which argue that individual behaviours are influenced by the context of macro trends and those individuals are regarded as several groups and the behaviour of each group will show homogeneity on a certain level [99–101]. By setting global behavioural assumptions, the model avoids calibration and calculation difficulties, and reduces the requirement of individual

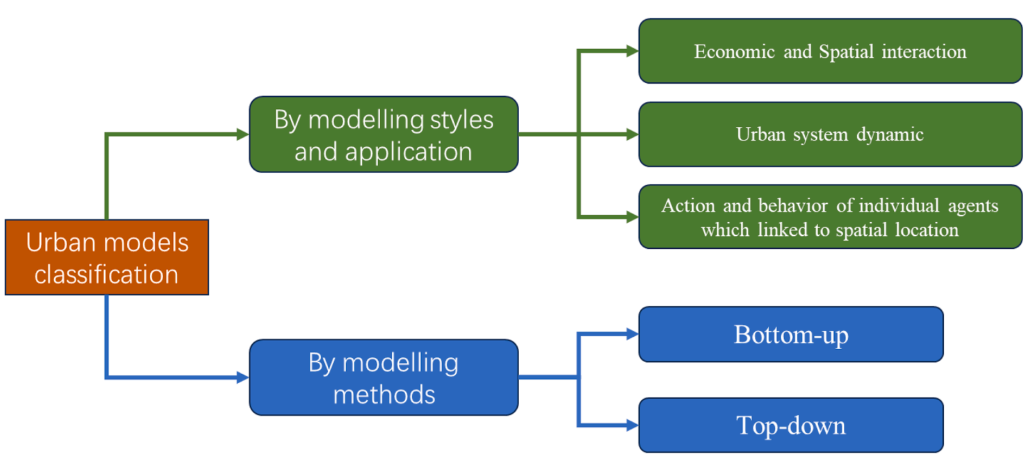

Fig. 5. Classification of urban modelling.

behavioural data. It is helpful for related researchers to reveal the inherent mechanism of selection behaviour from a macro perspective.

With the development of microeconomics and stochastic utility theory [102], bottom-up methods have become an important research direction, and it provides a better choice to describe complex system [68]. The model, which operate from the bottom up, mainly focus on the micro-level, elemental or individualistic, to representing behaviours and interactions of those objects through space and time [13]. The model starts from the definition of the rules of subjective behaviours to build the framework in order to avoid the understanding and analyses of the entire system, and makes up for the difficulty of quantitative description of complex system by traditional mathematical and physical models [81, 82].

In most cases, a land use model is a dynamic general equilibrium model [103]. It emphasizes the autonomy and dynamics of individual behaviour, and believes that individual behaviours depend on their social, economic, political and other conditions [104]. In addition, those behaviours will interact with each other and the context to produce urban form as consequence subconsciously or unconsciously, and related researchers named this process "*self-organization*" [105–107].

3. General challenges of urban modelling

There are two very important concepts, "factors" and "drivers", which will provide a better view to understand the process of land use change. Urban factors, such as population, economic and other urban resources also called development units, which are the engine of urban development [30]. The organization and interaction of factors create drivers, which are certain socioeconomic activities which provide driving forces for land use changes [108]. For example, in many cities, industrial economic activities cause the conversion of agricultural land use into industrial land use in last two centuries.

The aim of urban modelling is trying to simulate and analyse the process of how factors formed the drivers and predict the consequence. Usually, based on the mechanism of modelling, urban models are divided in to data-driven and process-driven approaches [74]. The former is based on historical data to build a relationship between urban development and urban factors. Usually, the historical data is easy to observe and data-driven approaches can capture the main trajectory of urban development by statistical relationships [74]. Thus, the prediction is made with hard empirical experience. However, They "*focus on their correlations instead of their causal relationships* [74]" which only provides weak evidence for urban development mechanism. The latter "*is based on a clear mechanism and is generalized in a conceptual model* [74]". [74] proposed a viewpoint that, theoretically, process-driven approaches can more realistically reflect the socioeconomic activities. However, the process of urban development is influenced by complexed nonlinear and hierarchic interactions between various factors. Any change of any single one of the urban factors will affect other urban factors. Therefore, these complicated relationships are difficult to express based on structural models. Furthermore, "*available datasets in support of the construction of structural models are limited both in time and in space, particularly for detailed socioeconomic datasets* [74]." Because in many cases, the dataset tends to be generalized. Urban systems are very complex. Interactions between urban factors usually are complex and nonlinear. Therefore, in most cases, these two approaches coexist in urban models [109].

In cities, some problems that did not exist before have emerged over time. Thus, urban modelling faces challenges over time. Crooks, Castle and Batty provided a list of the seven main challenges of urban modelling as follows: "*the purpose for which the model is built, the extent to which the model is rooted in independent theory, the extent to which the model can be replicated, the ways the model might be verified, calibrated and validated, the way model dynamics are represented in terms of agent interactions, the extent to which the model is operational, and the way the model can be communicated and shared with others* [110]". Existing urban mobility models have four main limitations as follows: mainly focus on find an equilibrium point [111,112]. For example, general LUTI models are trying to find the equilibrium status of the interaction between land use, transportation, population and economic activities. However, urban system is an opening system and continually exchange resources with outsides. Cities need to output products, services, and consume with the input of resources, energy, and human efforts to maintain their functions. [62] approached the challenges from socioeconomic aspect. They argue that LUTI models need to adopt and integrate external factors and new approaches to socioeconomic simulation of land use and transportation system. Because with the development of technology, new socioeconomic activities, such as online retail, have created new socioeconomic organization forms. That require new approaches to socioeconomic simulation.

Based on the comprehensive philosophical method of analysing urbanization, [113] poses five driving forces of urbanization, "*which are industrialization, modernization, globalization, marketization and administrative/institutional power*". Except the administrative/institutional power, other factors are related to socioeconomic. Socioeconomic is very important for urban development. For example, [34] argue that urban sprawl was significantly associated with urban population density, gross domestic product(GDP) per capita, and industrial structure. Further, when the spatial heterogeneity was considered, the driving forces of urban sprawl exhibited different magnitudes and directions [34]. The results indicate that to formulate effective urban planning and land use policies, decision-makers should seriously consider the differences in urban sprawl depending on region, urban size, and hierarchy [34]. In other word, it is hard to provide a uniform land use policy for every region.

Although they differ in their research focus, Crooks, Castle and Batty analyse the problem in terms of how to build an urban model [110], Xuecao Li and Peng Gong emphasized the role of socioeconomic activities in urban development [74,111,112], they all agree with that those existing urban models have certain of deficiencies in reflecting the complexity of the real world and insufficient to deal with complex urban systems that change over time.

System dynamic models use system dynamics methodology to analyses urban socioeconomic processes [23,95] and can more realistically reflect the socioeconomic activities. However, these complicated relationships between participants of socioeconomic activities are difficult to express based on structural models and collect detailed socioeconomic data. Because in many cases, the socioeconomic dataset tends to be generalized.

In summary, the main challenge of urban modelling has always been around the unprecedented increasingly complex urban system [114].

4. The impact of emerging technologies on urban development

4.1. Geographic information system (GIS) and urban research

Because the huge amount of data that needs to be considered, it had been extremely difficult to predict urban development in the past. Fortunately, with the advance of computer science, computer-assisted technology has been widely used into the study in the field of geography. In 1968, the term "*geographic information system*" was been used by Roger Tomlinson in his paper " *A Geographical Information System for Regional Planning* [115] ". That is the symbol of the emergence of a new interdisciplinary subject, Geographic Information System (GIS). With the popularity of big data, which involves unprecedented volumes of data, GIS in the era of big data has a more powerful tool for data-driven spatial prediction [116]. Related researchers are trying to draw conclusion about the behaviour of complex systems in realistic environments in order to understand and predict the future of specific areas by GIS software. They design a series of GIS model to study urban objects.

There are four mainly different modelling techniques as follows:

Cellular automata (CA) mode, which is a kind of model that simulates spatial and temporal discrete complexity by simple local calculation. This local calculation base on five elements as following: Cell, Status, Neighbourhood, Transfer function and Temporal. The basic algorithm of CA model is that in a moment, the status of a cell depends on its previous status and statuss of its contiguous cells [69]. Traditional CA model uses regular square grid and synchronous growth, and is designed for representations of land use change in rural-urban fringe settings. Related researchers develop a new CA model that use spatial data in the form of irregularly sized and shaped land parcels, and incorporates synchronous and asynchronous development in order to model more realistically land use change at the land parcel scale [71]. CA model usually has been used to predict or restructure the process of urban growth to compare the consequences of different urban development scenarios. This model divided factors into square grid in order to analyse their interactions by spatial neighbourhood relation. However, some urban factors in different cells will organize a tight correlated aggregation under certain conditions, which leads those cells are more influential than others. In addition, under certain circumstances, some cells can influence others without spatial neighbourhood relation. Because of that, a more flexible model is needed.

Agent based model is an intelligent entity, which incorporates other ideas, including but not limited to game theory, complex system, emergence, computational sociology, multi-agent systems and evolutionary computation. Under guide of its experience and knowledge, it will consider varying related factors and make a decision. As a consequence of the decision, the entity well produces a certain behavioural pattern. Generally, the agent has four main feature: autorhythmicity, spontaneity, sociality and reactiveness [79]. Moreover, different modelling problematics can lead to very different solutions. For example, multilevel models, which included macro, intermediate and micro levels, are used to build a conceptually or causally linked system of grouping objects or processes along an analytical scale in order to help the modeller identify the difficulties peculiar to each of the approaches [80]. Although the relationship between various urban factors are well analysed by those models, usually the same type of urban factors will form a subsystem, such as urban traffic networks, retail networks, electricity networks and the like. Not only the interaction of individual urban factors, but also those subsystems will effect on the distribution of urban forms. It is necessary to consider the relationships between urban subsystems.

System dynamics is a discipline of crossover and integration which takes very important meaning in urban research. It argues that every system has its structure and the organization of the structure decides the functions of the system. Thus, it prefers to focus on the interactions and relationships between the internal subsystems rather than external interference and stochastic events. Urban researchers argue that system dynamics model can be used to predict the consequence of a certain urban planning pattern and they developed related methods to support decision making. They developed urban related methods, such as the dynamic Land Use and Transportation Interaction model MARS (Metropolitan Activity Relocation Simulator) and they argue that is part of a structured decision making process [57]. Land-use/Transportation Interaction Model, LUTI is a commonly used mathematical model that is even considered to be the only available model for simulating the urban spatial development process [59]. The main concern of LUTI model is spatial interaction, which regard the location as the main driving force for urban land use and transportation development. However, there are many other important factors which are involved in urban evolution, such as policy, culture, public service, regional structure and etc. Thus, the model needs to be further developed. All those models believe a certain urban pattern will produce the certain urban form as consequence. However, in the process of urban growth, there are a lot of serendipitous and uncertain events. Moreover, all the resources in the urban area are circulating. Therefore, a drawback of such models is they ignore those uncertainty and resource circulation in a city.

Urban metabolism model is a specific type of the Grey Model. The concept was proposed in 1965 by Wolman, and it is fundamental to developing sustainable cities [117]. Kennedy argued that Urban metabolism can be defined as "*the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste*" [118]. Urban metabolism is an organic process in cities which output products, services, and waste with the input of resources, energy, and human efforts. The Grey model is a kind of fuzzy prediction model which flexibly predicts the development tendency of an object in a long-term [119]. The core of the model is to measure input-output ratio and use that to predict the future of a region and find out the confliction between a city's production volume and the needs if the city. So, the urban evolution is an extremely complicated dynamic process. Many factors are involved in urban evolution and the underlying relationship dependencies between them need to be discovered, which is vital to know the whole patterns of the urban issues.

Urban development is an extremely complicated issue. It gets many restrictions of factors, such as economy, population, environment, policy, culture, transportation and etc. Furthermore, the interactions between those factors are extremely complicated and they produce the urban form as consequence. It is a spontaneous process, where a certain order and form are arising from interactions between subsystem factors of the system without external interference in a certain context [120]. Because of constantly changing external conditions, urban factors, which are the components of urban form, are uncertain. They can be increased, decreased, created and destroyed, which will result in constant urban evolution [121].

GIS has provided a powerful tool to analyses and simulate the process of urban development. Based on powerful computing power, constantly changing external conditions and urban factors can be calculated to predict the outcomes of a certain scenario, for example, overlay analysis and buffer zone calculation. Therefore, GIS has been used at multiple fields, such as urban planning, trasnprotation, decision-making support and urban govern. For example, using accessibility analysis of transportation as the starting point, Li et al. employed GIS spatial analysis tools to analyse the impact of urban faciciliteis' distribution, residents' needs, and income on travel behaviour in China, taking into account the country's local contexts. They provided the concept of transport impedance indicator to describe the strength of this impact [122]. Zhou et al. used GIS tools to analyse irregular land use patterns at the urban fringe, providing decision support for urban planners and policymakers [123]. Based on that, smart city that comprehensively assist in urban management,planning and policy making have experienced tremendous development.

Smart city is widely regarded as an effective option to solve urban diseases, for example traffic congestion, infrastructure overwhelming, air pollution [124–127]. It is an emerging strategy aiming to provide better life conditions to support the specific needs of each city for citizens by leveraging technologies to allocate urban resources more wisely [124–126].

The Chinese government introduced a series of policies in order to the promotion of smart city. However, performances of cities where locate in eastern and southern coastal areas have met national government goals more than others, and there are significant differences between them [127]. Liyin Shen and other Chinese researcher [127] believe that the political execution performance of local governments in the practice of policies affects smart city application. However, there "*is little study examining what results have been achieved in practice by applying policy measures* [127]". The participation of departments coordination mechanism and the department barriers of data sharing are still the biggest bottleneck of smart city development [128]. In other word, the divisions between different government layers hampered the development of smart city.

4.2. The impact of ICT based economic organization form on urban development

With the development of the science and technology, communication and computer innovative technologies had been applicated in urban development, and that pose new challenges for urban planning. Those unprecedented technologies are changing the lifestyle of us [129], especially, information and communication technologies (ICT). Based on the use of ICT to integrate urban resources, it presents a new city pattern that urban resources can be allocated across multiple departments [127] which can provide urban planning and management decision-making supporting for decision makers to "*modify urban infrastructures, public and private services and governance activities* [130]".

Digital economy [131] also based on ICT and it has gradually changed the city. Although a growing body of literatures has studied digital economy development, there is a little of theoretical and empirical research to understand the impact of digital economy and migration, which is the one of the key driving forces for urban development, on urbanism. In 2019, Yanliu Lin firstly posed a concept framework of "*E-urbanism*" to divided real world into three interwoven layers by attributes as ICT based economic activitie organisations, socioeconomic relationships, and phsical world, "*namely of ICT infrastructure and production networks, social networks and power relations, and urban form and land use*"(Fig. 6), and she believes that the impact of e-commerce and migration on urbanism is fundamentally revolutionizing social and spatial reorganization of the city [132]. Because digital economy is not totally depending on spatial neighbourhood relationship as those traditional economic activities. For example, the internet is changing our world and the way we living in a city [133], because some socioeconomic and other activities which depend on the internet, they have been called Digital economy [131], have dramatically influence on population distribution.

In the traditional offline economic activities, interactions between participants mainly depends on transportation networks. Exchanges and flows of human power, capital, information etc. need to be done by physical measures. For example, information needs to be passed through the transportation networks in the form of physical letters or messengers. Therefore, the social networks and relations of urban factors are highly consistent with transportation networks. However, e-commercial activities reformed the socioeconomic networks. For example, information can be disseminated via the Internet instead of traditional transportation network based ways.

With the ITC boosting, ITC based activities enable regions to break the location limitation, which triggers a new bottom-up internet process. It has greatly increased the demand for remote work that enforced and accelerated the impact of ICT on transportation. ICT has reorganized the way of economic activities that distribution of economy participants depends on the spatial relationship and social network relationship and ICT infrastructure. Certain economic activities, such as information exchange no longer be limited by spatial distance under the ICT support. It dramatically decreases related transportation needs. It affects the distribution, circulation and exchange of population, and further reforms urban planning, economic organization, and policymaking.

Based on ITC, E-commercial activities enable regions to break the location limitation and join in the national even global industry division, and that trigger a new bottom-up rural urbanization process in China [134]. Related researchers [134] argue that although E-commerce increases the capital and talents back to the rural areas and contributes to rural urbanization, it is still cannot to change the overall trend of population reduction in the entire rural areas in the process of urbanization in China. [134] suggested that local government should establish a governance system that comprehensively considers the demand of market and residences in order to guide the restructuring of rural space. For example, positively increasing the welfare of rural population and coordinating multiple villages or towns joining to the industry chain.

In China, a huge number of villages, rural settlements and villagers who are in the agricultural Hukou group, choice to develop E-commerce by Taobao, a Chinese online trade market like Amazon or eBay. Based on the market requirement and infrastructure conditions, especially ICT related infrastructure, online commerce tradesmen select site to form "*Taobao villages* [135]" by integrating and organizing capital flows, human power, goods flow, technical flow, etc., and that will influence on the surrounding areas of Taobao villages [136]. Wan and other researchers [136] argue that E-commerce villages influence people's spatial decision behaviours which impact on traditional land use change pattern, and they provide a concept "*flow factors* [136]", a characteristic

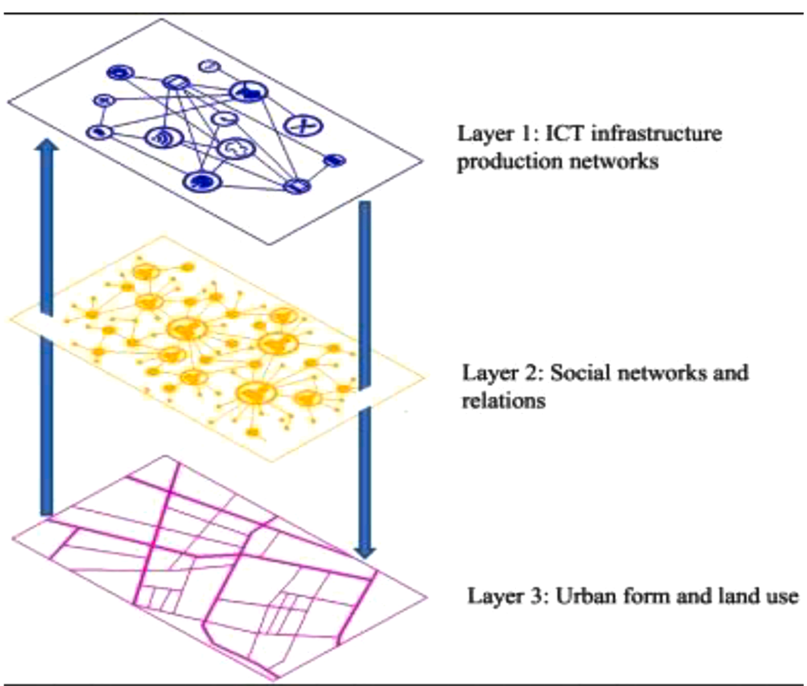

Fig. 6. Three interwoven layers [132].

indicator to describe population flows, cash flows, goods flows, technical flows and etc. They believe the flow factors can be used in digitalized governance system to guide planning and management for rural areas, and fulfil "*the gap in terms of the interaction between E-commerce village and space of flows* [136]". The mechanism of Taobao villages' development shows that ICT based E-commerce activities have reformed population flows in China [132,134,136].

Although ITC decreases the limitation of spatial conditions and is also the key driving force for contemporary urban development [132], most Taobao villages are located in the developed regions of China. [132] believes that the interaction relationship between urban factors is significant as well as spatial distribution. Thus [132] posed a network to describe socioeconomic relations between urban factors, and by comprehensive considering infrastructure, urban form, land use, and transportation network, she proposed a conceptual framework of E-urbanism (Fig. 6) to understand the impact of E-commerce and migration on urbanism. Lin argued that E-commerce activities bring an unprecedent phenomenon that people, who live in different areas, can be involved in the same economic activity at the same time by ICT infrastructure. Therefore, ICT has reformed the relationship between economic activities and population distribution. [132] used the framework to study Taobao villages in Guangzhou city and concluded that E-commerce had changed the city's urban structure, which is the arrangement of land use and the spatial organization of urban factors in a certain urban area, by providing remote coordination and organization of social and economic activities.

Based on ITC, e-commercial activities enable regions to break the location limitation and join in the national even global industry division and increase the capital and talents back to the rural areas and contributes to rural urbanization, and that trigger a new bottom-up rural urbanization process in China [134]. E-commerce villages, such as Taobao villages influence people's spatial decision behaviours which impact on traditional land use change pattern [136].

To understand the impact of e-commerce and migration on urbanism, Lin [132] posed a concept framework of E-urbanism to describe socioeconomic relations between urban factors, and by comprehensive considering infrastructure, urban form, land use and transportation network. Lin argued that e-commerce activities bring an unprecedented phenomenon that people, who live in different areas, can be involved in the same economic activity at the same time by ICT infrastructure. Therefore, ICT has reformed the relationship between economic activities and population distribution. For example, Taobao villages in Guangzhou city provided a conclusion that e-commerce has changed urban structure of the city by providing remote coordination and organization of social and economic activities [132]. Fig. 6 shows Lin's E-urbanism framework.

Spatial organization form of urban factors is reform by ICT based economic activities, and revolutionized social and spatial reorganization of economic activities. Classical urban models are facing unprecedented challenges that social and economic activities not only depend on spatial neighbourhood and distance, but also depend on ICT based socioeconomic relation networks of urban factors.

In 21st century, urban phenomenon is emerging that the networked polycentric mega-city region. Developed around one or more cities of global status, it is characterized by a cluster of cities and towns, physically separate but intensively networked in a complex spatial division of labour. They describes and analyses eight such regions in North West Europe [137]. In many cases, the relationships between urban factors are nonlinear and hierarchic and their interactions produce the urban form as consequence. In other word, city should be regarded as an integral organization.

To solve the problem of population overloading in urban areas and alleviate the development gap between urban and rural areas, Chinese government has implemented a series of measures, including the development of e-commerce in rural areas. For example, many villagers in China are engaged in the sales industry on Taobao, the biggest online sales platform in China. According to the statistical data of Taobao, in China, there are 7023 Taobao villages, that is, more than 10 % of the villagers do Taobao business in the village. Taobao villages have not only created more jobs in rural areas, absorbed part of the urban surplus population, but also narrowed the urban-rural development gap. Meanwhile, the mechanism of Taobao villages' development shows that E-commerce activities have reformed population flows in China [132,134,136].

The concept of E-commerce, ICT based socioeconomic organization, is consisted of land use, population and economic activities sub-models. The basic idea of the concept comes from Lin's E-urbanism framework (Fig. 6). In addition to considering traditional spatial organization, which formed by land use, transportation, population and economic activities sub-models, ICT based organization also influences the equilibrant status of the traditional general LUTI model.

E-commerce continually changing social and economic human activities organization form and population distribution in last decades. Online information and capital flows of E-commerce replace certain traditional human travel needs. The fact that E-commerce work is not limited by geographical location makes it possible to provide job opportunities in places where the cost of living is lower, for example rural areas. It increases the capital and talents back to the rural areas and contributes to rural urbanization. Fig. 7 shows that like traditional spatial organization, E-commerce organization has impact on land attraction.

The classical general LUTI model assumes that people are free to relocate and the interaction between economic participants via transportation networks. However, the situation is changed. Therefore, E-commerce need to be considered in LUTI model practice.

On one hand, Smart city is widely regarded as an effective option to solve urban diseases [124–127]. It is an emerging strategy aiming to provide better life conditions to support the specific needs of each city for citizens by leveraging technologies to allocate urban resources more wisely [124–126].

On the other hand, the Internet, a ICT based communication network, is changing our world and the way we living in a city [133], because some socioeconomic and other activities which depend on the internet, they have been called Digital economy [131] or E-commercial activities, have dramatically influence on population distribution and gradually changed the city.

With the development of interdisciplinary research, urban land use models have been combined with other related models to develop new models. For example, the LUTI model was developed by combining transportation and urban land use models.

Studies on the mechanism of urban development gradually realized the influence of science, technology, economy, culture, site, policy and social structure on urban sprawl [138]. Although urban models differ in various aspects and details, the purpose of urban modelling is the same. They try to provide practical tools for urban analyses that seek firstly to understand and describe the mechanism of urban evolution, including governing urban structures and behaviour of the urban system. Secondly, they aim to predict the consequences of future policy decisions and scenarios of urban planning [13,16,23].

ICT-based economic activities are gradually deeply influencing the organization form of urban factors and people's travel behaviours. For example, some participants in economic activity are freed from geospatial constraints by ICT-based remote working. This significantly influences personal transportation needs and behaviours as well as land attraction and population distribution.

Therefore, urban modelling is facing more and more challenges. To accommodate an urbanizing world population, to provide insights which can help policy makers to solve that problem, a theoretical model that accurately analyses and predicts "*urban evolution* [28]" is needed.

Moreover, in the past two years, after the COVID-19 outbreak, governments worldwide have adopted a series of containment measures for a while to decrease the growth rate of COVID-19. Those strict control

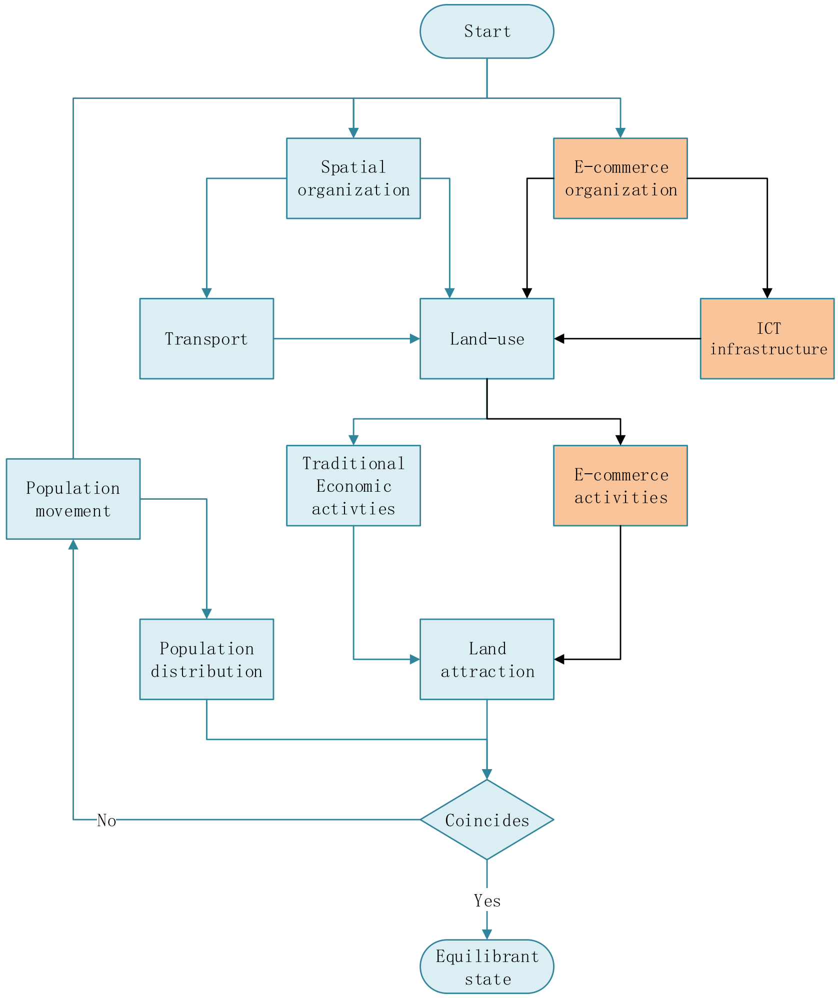

Fig. 7. The impact of E-commerce on land attraction.

measures suspend or reduce public transportation services and limit travel opportunities of the resident to leave home, and the influence of COVID-19 on human travel behaviors becomes a hot point. People are aware that the strict travel control measures effectively mitigated the spread of COVID-19 and significantly decreased transportation activities, especially decreasing public passenger demand ridership. For example, in China and European countries, people are inclined to use "*zero contact*" transportation, such as bicycles, walking, and driving private vehicles to avoid public transportation. Even in Stockholm, Swedish, their local authorities did not implement strict lockdown measures, local public ridership has been decreased 60%. Meanwhile, the World bank's data indicate a significant decrease in the economic growth rate of those main economic entities around the world after the COVID-19 outbreak.

To reduce the negative effect of travel restrictions on the economy, China, the UK, the USA, Germany, and other countries have encouraged people to work at home. That greatly decreases the commute needs of people and increases remote-based economic activities. The Internet, an ICT based communication network, is changing our world and daily lives. They can be communicated and connected without transportation. The only they need is the Internet. Thus, ICT dramatically influenced population distribution and gradually changed the city during the COVID-19 period. It requires analysing the public transportation behaviors at different scales, especially to reveal their underlying mechanism. Therefore, a profound impact and mechanism research of public transportation behaviors under the COVID-19 epidemic warrants further study.

4.3. Machine learning in urban studies and urban models

Nowadays, machine learning plays an important role in urban planning and land use and has been integral to urban stuidies for mutiple aspects [139], for example, urban growth simulation [140], traffic forecasting [141]. Combined with remote sensing, machine learning has been apllied in the field of land-use and land cover-change (LULCC) [142]. Modelling of LULCC effectively expanded the toolbox of territorial and urban planning.Meachine learning has greatly improved the efficiency of urban models. Data is the foundation for urban models. Timely and accurate data is crucial for urban planning and decision-making. Machine learning has significantly improved the efficiency of data production. For example, Satellite remote sensing provides the advantage of quickly and frequently acquiring data in vast urban landscapes. [143] used machine learning models to process urban remote sensing data, and the results showed that compared to traditional data collection methods, the new approach achieved significant efficiency improvements.

Meanwhile, machine learning excels at handling complex models. In the study of urban growth prediction, making accurate predictions is particularly challenging due to the existence of complex topological structures and the high-dimensional nature of datasets related to urban growth [144]. Traditional models often perform poorly when predicting urban growth. [144] conducted a study on urban growth in Florida using machine learning models, and the results showed that machine learning has higher accuracy compared to traditional methods (e.g., Logistic regression).

Machine learning has the ability to analyse massive amounts of urban-related data such as geographical data and urban population data, and to classify, manage, summarize, and analyse various data from different sources. This can help urban planners better understand and meet the living needs of different groups, especially those vulnerable groups that are often easily ignored and concealed behind statistical averages.

Deep neural network models are one of the most important components of machine learning. Their basic structure includes an input layer, a hidden layer, and an output layer. The input layer is responsible for receiving input data, the hidden layer performs nonlinear transformations on the data and feature extraction, and the output layer makes predictions or decisions based on the extracted features [145]. With the improvement of computer performance, the computing power of deep neural network models is becoming stronger, and the scale of data processed and the complexity of tasks are rapidly increasing. After the transformer structure [146] was proposed in deep learning models, the number of parameters in deep learning models exceeded 100 million, which is likely the earliest prototype of large models. Nowadays, the total number of parameters in large models has exceeded one trillion. Large models have the same purpose as traditional models: to assist people in understanding, analysing, and replaying the development process of objective things, and evaluating and predicting their future trends and outcomes. Unlike traditional models, large models have more parameters and more powerful computing power, which can better adapt to large-scale data and complex tasks. When processing complex tasks, they can better capture the potential patterns in the data, thereby improving the accuracy and versatility of the model. Today, smart terminal devices such as smart watches and smartphones have become the most common and frequently used tools in people's lives. With the help of these smart devices and ICT networks, the needs of almost every resident can be accurately reflected to urban planners. Therefore, the task of large models in urban modelling is to help urban planners process massive amounts of resident demand data and assist in making reasonable plans, as well as allocate urban resources more efficiently.

Although machine learning has domenstrated remarkable performance in urban studies, the application of machine learning in urban studies is facing limitations and ethical risks.

On one hand, machine learning requires a large amount of high-quality data for training and annotation. Acquiring such data and ensuring its integrity and accuracy pose significant challenges. Additionally, annotating these data also involves substantial costs, including time and financial resources. These factors pose difficulties and obstacles to the promotion and application of machine learning in urban studies.

On the other hand, the field of urban planning involves a large amount of personal and sensitive data, such as population distribution, income, age, occupation, and so on. Collecting and using these data expose machine learning to ethical and legal risks. Furthermore, if a machine learning model is trained with external interference, its predictions may be biased and unfair, potentially influencing the decision-making process of urban planning unfairly and affecting the overall welfare of society.

5. Summary and conclusion

In this paper, we have reviewed the development of urban models. In the initial stage, location was the root point of urban study. A certain region was dominated by the highest population density gradient zone, which became the urban centre, and the urban centre was regarded as an entry-point to study the relationship between urban centre location and the distribution of urban factors. A series of simple models were created to describe this pattern. For example, in the early 1920s, Ernest W. Burges proposed his famous concentric-zone model [36,147] and "*wedge-shaped sectors*" [37] . However, large cities usually have more than one urban centre. Meanwhile, urban system is an open system, which constantly interacts with external systems by population, material, energy and information exchange. Therefore, basis on those simple models of urban morphology, multiple disciplines, such as transportation and economic, have been involved in urban modelling. Fig. 8 shows the timeline of urban modelling development.

To understand the mechanism of urban development, elements of cities such as natural and socioeconomic resources and population are divided into many urban factors by character, for example educational, medical, financial, working and other factors. The geographical distribution of urban factors has played an important role in urban development [8,138]. Concepts, such as urban structure and urban agglomeration, have been proposed to analyses and describe the distribution and organization of urban land use and urban factors. Those urban factors create driving forces of urbanization [113].

From a macro viewpoint, individual interaction behaviours between urban factors are influenced by the context of macro trends. Those individuals are regarded as several groups and the behaviour of each group will show homogeneity on a certain level. Based on that, top-down models, including the gravity model and entropy maximization, have been proposed.

From a micro viewpoint, those urban factors will interact with others subconsciously or unconsciously and spontaneously produce urban form as consequence. This process is called "*self-organization*" [105–107]. Based on that, bottom-up models, which focus on the micro-level, elemental or individualistic, to representing behaviours and interactions of those objects through space and time [13], have been developed, such as CA and agent-based models.

To reduce resource consumption and increase utilization efficiency, several theories have been proposed. For example, optimal urban form theories explore the relationship between urban size, the organization form of urban factors and driving forces for urban developments. Smart cities try to use ICT-based information systems to promote the level of urban management and solve urban diseases that depreciate driving forces for urban developments.

We expect that in the future, the connection between different disciplines involved in urban studies will become closer, especially in urban planning, where urban land use and transportation planning need to be integrated. Models of economics, transportation, geography, sociology, and management are beginning to be integrated into a complex composite. We believe that adjacent disciplines will merge first, such as land science and transportation science, which will further develop an integrated planning model for land and transportation based on the existing models, such as LUTI models.

With the help of emerging technologies such as smart devices and large models, future urban models may achieve macro and micro unification, and there will no longer be a clear distinction between top-down and bottom-up models. To handle these massive amounts of data, based on the current development situation, we believe that machine learning is the technical foundation for the micro-macro integration of urban models, and the technical foundation for the integration of multidisciplinary knowledge into multi-dimensional urban models.

CRediT authorship contribution statement

Jing Wang: Project administration, Funding acquisition. **Gengze Li:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Huapu Lu:** Validation, Supervision, Project administration. **Zhouhao Wu:** Resources, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

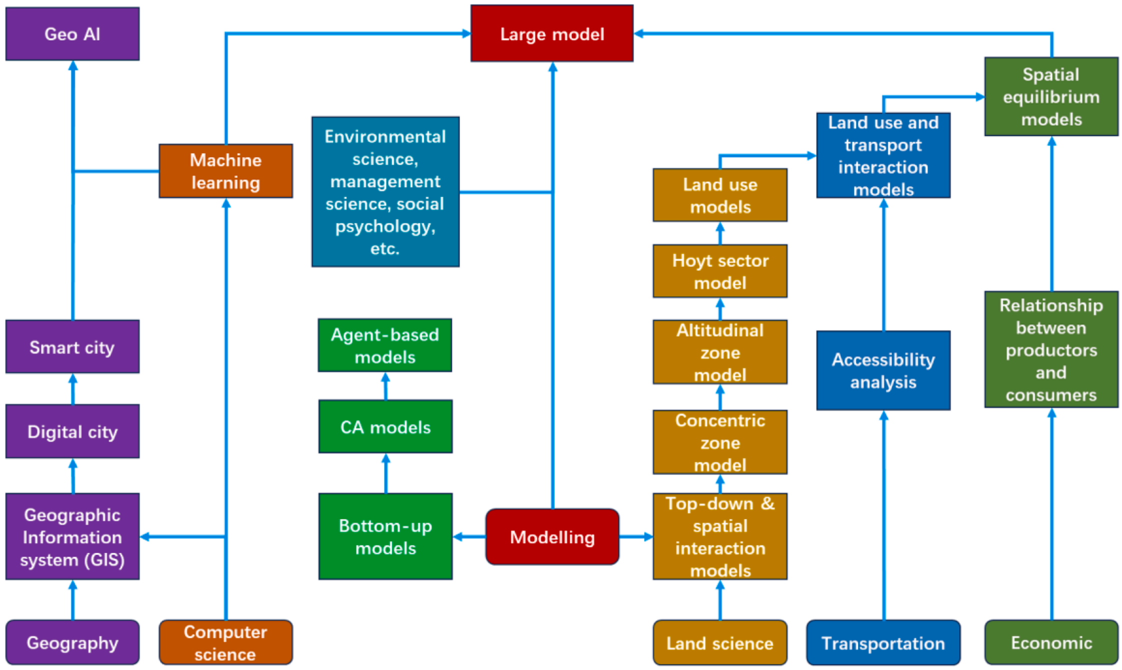

Fig. 8. Urban modelling development.

Data availability

No data was used for the research described in the article.

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