Exploring The Potential of Geographic Information System and Agent-Based Model Integration For Urban Land Use Planning

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Abstract

Applications of information and communication technology in urban planning such as the Geographic Information System, the Planning Support System and the Decision Support System have been widely realised by local authorities to enhance the provision of services to their local citizens and improve urban governance. Information systems technology embedded into spatial planning can be viewed as a solution for a local authority to migrate from their conventional working procedures to a computerized and automated systems environment to support the decision-making process. This paper will be exploring the evolution of agent-based modelling integration with geographic information systems technology in urban studies. An exploration of the previous study from various sources shows that research in agent-based model and geographic information system integration in urban studies began in early of 1990s and has continued since then with a significant increase in the 21st century. The usage of geographic information systems in modelling the real situation helps a decision maker with valuable spatial information on the system's behaviour. In addition, the integration of geographic information systems and agent-based models will have a great impact on the process.

Keywords: *Geographic Information System, Agent-based Modelling, Land Use Planning, Urban Modelling, Evolution*

1. Introduction

Interest in implementing agent-based modelling in social science is growing and becoming widely used in urban and regional planning. The use of Agent-based models (ABM) has evolved into one of the key paradigms for urban modelling and comprehending the different processes that shape our cities during the last two decades, with the rise in computational power and data (Crooks et.al 2021). In the context of regional development and urban dynamics, the agents represent the actors that the researcher distinguishes and are deemed relevant in understanding the dynamics (Zhang et.al, 2015). In applying agent-based model, the most significant methodological strength is its ability in considering heterogeneous individual decision-making units and its interactions. Yet, the inconsistency or limitations of the model is the ability of agent-based models to apply individual decision-making rules. There are a great number of ABM applications that have been developed for various aspects of urban planning, which contribute to the

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understanding of its ability to explore urban issues─ the growth of cities and regions, urban growth, transportation, the challenge of slums and changing demographics and urban restructuring (see Crooks et al., 2014 for review). Other recent example in urban studies includes enhancing urban planning and land monitoring model (Haer et.al, 2016), geosocial (Rand et.al, 2015; Wu et.al, 2014; Gomide et.al, 2011), urban growth (Algais & Pullar, 2018; Xie & Fan, 2014; Kim, 2012), regeneration (Jordan et.al, 2014), urban shrinkage (Jiang et.al, 2021; Haase et.al, 2010), gentrification (Sabri, 2012). Many of this research took advantage of ABM's capacity to capture heterogeneity, spatial organisation, and adaptation to generate important new insight related to land use planning issue. Recently, quite several models have been developed and applied in urban planning/regional/spatial planning areas, but most of them have been criticized, frequently because most objects being modelled are not completely understood conceptually (Pinto & Antunes, 2007; Waddell and Ulfarsson, 2004; Cheng, *et al*., 2003). Rakodi (2001) made the argument that improving the quality of planning is an attempt to improve understanding and analyse the interrelated components of urban development processes. Planning and rapid development, especially in the urban centre of trade and tourism, may pose a variety of challenges and problems in the implementation of the plans. This challenge needs to be considered by decision-makers, especially in determining the direction of the development in terms of urban development, in providing a complete infrastructure and as well to raising the country's economy. To ensure the achievement of the plan, the use of ABM is as an approach that might contribute to solving this problem (Crooks et.al., 2014). An agent-based model is a form of computational social science which involves models that are computer programs (Gilbert, 2008). Axelrod and Tesfatsion (2010) also stated that ABM are suited for social science as ABM applied to social processes use concepts and tools of social science and computer science. Previous researchers also have classified ABM as a new wave of urban modelling (Torrens, 2002) due to its ability to address some of the weaknesses of urban planning models.

2. Urban Modelling Evolution

From the early 1990s until most recently, researchers have dedicated their effort to develop comprehensive urban micro simulation models, agent-based models and cell-based cellular automata models, which reflect the dynamic changes in the urban environment (Liu et.al, 2019). These modern era models, building on advances in computing technology, allowed researchers to formulate more complex model structures and handle large amounts of more detailed data, for instance, through the integration with new technology such as Geographic Information System (GIS), to create a new generation of physical models. The chronological development of land use models shows that urban dynamics has extended the scope of conventional land use models, which is reflected in the evolution of the urban spatial structure (Rodrigue et al., 2006). This evolution has led to more complex modelling frameworks with a wider range of components (**Figure 1**).

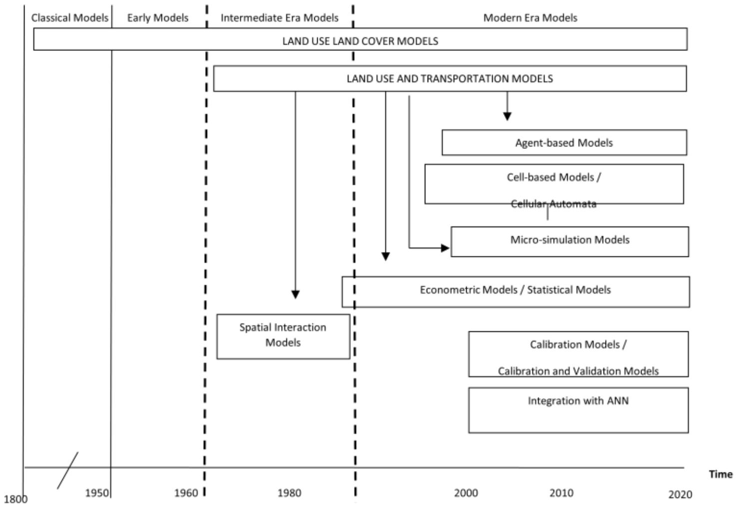

Figure 1: Chronological Development of Urban Land Use models (Modified from Iacono et.al, 2008).

Wegener (1995) provides an evaluation of thirteen contemporary operational urban models from twenty modelling centres from west to east in late 1980's to early 1990's. Later in 2003, Timmermans has categorized the integrated land use and transportation model to three waves; 1st wave: aggregate spatial interaction-based models; 2nd wave: utility-maximizing multinomial logit-based models; 3rd wave: towards activity-based, microsimulation models. Most of models provides by Wagener are initiated under first and second generation's waves. Based on Wagener evaluation, eight types of major urban subsystems are distinguished (**Figure 2**). These eight subsystems concern the urban environment, which is considered as a ninth subsystem.

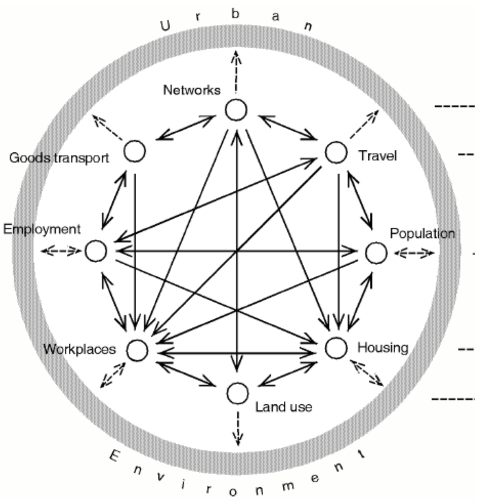

Figure 2 : A model of urban models
Source: Wegener (1995)

All these models can be classified into five main categories (Batty, 2009), Land use-transportation (LUT) models, urban dynamics models, Cellular Automata (CA), Agent-based models (ABMs) and Micro-Simulation. Historically, the revolution of urban systems has developed many different models which are relatively top-down, aggregate or non-interactive. The modern approach such as Microsimulation or ABM approach has most potential such it has sought to rectify the dynamics which elude older models (Wise and Cheng., 2016).

3. GIS And ABM Integration

Several efforts have been made to integrate GIS with ABM, which began in early 1990s for example with the use of software such as Netlogo, Repast and Swarm (e.g. Najlis and North, 2004)) and has continued since then with a significant growth in the 21st century. The agent-based modelling approach is responsive to incorporate the effect of parameter values, rule-based and interactions with environment (Crooks et.al, 2021; Hammond et.al, 2015). The representation of environment involves a description of spatial properties which making GIS is the useful tools for ABM. GIS is thus a powerful tool, which allows mapping, querying, modelling, analysing, and displaying data within a single database. In local planning authorities, GIS is used at various points in the planning process, including analysis and synthesis-oriented tasks such as plan development and evaluation. With its powerful capacity for spatial data management, spatial analysis, and visualization, GIS provides planners with new means to implement their work more efficiently. The use of GIS opens new possibilities for accessing information, more accurate data analysis and help in generating alternative scenarios of development (Batty, 2012). Theoretically, and in practical terms, it would constitute a step forward in modelling if GIS data could be accessed by the ABM. Through the integration, researchers can incorporate detailed real-world environmental data, to simulate agent behaviours and processes as change and movement conditioned by GIS data representations of space and geography, and to visualize the results in 2D or 3D GIS environment (Crooks et.al, 2011). Furthermore, agent-based models can comprise real-time GIS data feeds to simulate and visualize situations unfolding in real time. ABM that incorporates spatial factor for example traffic simulation is more successful because it is easily verifiable, understandable result due to visualization and better confident result (Salamon, 2011). Thus, GIS that incorporating spatial data entity could be easily to be applied with ABM. The multiple representation of spatial data in raster and vector GIS will combine the advantages of spatial disaggregation (raster) and efficient network algorithm (vector) (Schürmann et.al., 1997).

As noted, GIS is already widely used by planning authorities to improve their work. Other components could be added and integrated with GIS to strengthen its capabilities. AB can serve to strengthen two key purposes: simulation and problem solving (Ferrard, 1996). While GIS will provide geospatial information to restrict agents' behaviour to within the study area such as land uses, transportation, amenities and other related data for analysis. The integration of GIS and ABM would enhance the capability of urban simulation techniques (Brown et.al. 2005; Parker, 2005; Torrens and Benenson, 2005). In designing a model for urban land use planning, there are some limitations in designing the models although there are several good reasons in integrating both approaches.

The capabilities of GIS software systems contain effective tools for acquiring, pre-processing, data transformation, visualization/mapping, rendering, querying, and analysing model result (Crooks and Castle, 2012) but, integrating it with ABM is still a difficult and challenging processes. Many considerations and hurdle to overcome of the integration, which is the data. It is traditionally difficult to find good quality data to properly evaluate a complex model (Crooks et.al. 2018). However, nowadays, the emergence of big data and the associated data from social media had directed to the production of sensitive individual-level data (*Mayer-Schönberger* and *Cukier*, 2013) that have the potential to transform the quality of agent-based models. **Figure 3** illustrate the main steps and stages for developing the integration model.

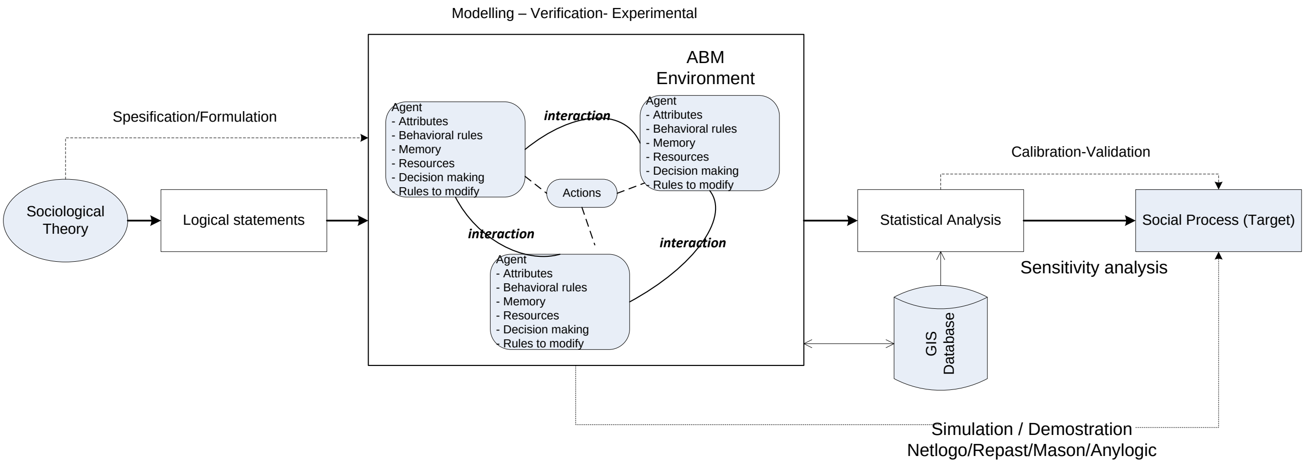

Figure 3: Main steps and stages in develop ABM (Modified from Macal & North (2006), Salgado & Gilbert (2013))

4. Future Research Direction

Currently, the development planning process in Malaysia has no specific tools, which can effectively give an improvement to the traditional approach. Existing processes are paper-based, large-scale, involving various legal aspects as well as cause problems for residents in the area involved. The computational decision-making approach, such as a customized urban growth model could be a good alternative to improve the process because it could give a better solution. A very large number of techniques could be used, each with their own pros and cons. Since 1980's most local authorities in Malaysia have been used ICT, especially Geographic Information System (GIS) in their town planning development. GIS is used mainly for land suitability analysis, data compilation and to generate suitability maps. With the ability of local authority to use GIS in their plan making process, it is a good start and reasonable to develop a new planning model, which could assist decision makers in better decision-making practice. The readiness of staff to use GIS seems they have the ability and are willing to learn to use any other tool, which can assist in decision making process. The use of modern modelling methods and technologies are now important components for developing management decision processes that will enable local authorities to succeed in a rapidly changing environment. It is significant that simulation modelling is now considered an essential feature of decision making for any agency that actively employs modern information technologies (Apăvăloaie, 2014). Thus, how can the integration of GIS and ABM could be implemented? It is quite challenging to identify linking variables and availability of data to link models.

Models, in a case of urban planning, can be used to simulate or mimic the experience of a phenomena and to forecast and predict the development of a city. Modelling provides a particularly important medium for urban planning because of the countless economic, social, and environmental factors that affect the study and management of urban systems but are notoriously difficult to incorporate in urban planning (Torrens, 2000). Therefore, in this case, the model could give an indication on what could be the economic growth trend of the city. The traditional models only focus on aggregate populations, however the issues on balancing the needs of people for housing, transport, education, health, leisure and ethnic diversity are not well suite with the traditional style of urban modelling. ABM could be the best tools in providing alternative of new models of cities. This is because ABM and cities are both operate on a cross-scale basis and are highly dynamic in both space and time (Crooks et.al, 2014). Interaction in cities is spread through urban systems, which involve movements and relationships between individuals in space to a regional scale geography. Thus, it is important for model to be develop as important medium for urban planning because of the countless economic, social, and environmental factors that affect the study and management of urban systems but are notoriously difficult to incorporate in urban planning (Torrens, 2000).

5. Conclusion

Ideally, the successful integration of GIS and ABM will help town planners and decision makers to identify factors that will contribute to growth in a region because human decision making and interaction are the central elements in ABM (Koomen and Stillwell, 2007). Relatively, it also will help urban development actors (policy makers and urban planner) and other professionals and administrators that are involved in the whole process of implementation to understand and make a clear decision in urban planning development. Thus, the integration of GIS and ABM would allow better simulation of urban dynamic development and would have the potential to simulate, display, analyse and present data using a common platform. Traditionally, such support tools have been based on aggregate integrated land use transportation models or on cellular automata models. Agent-based models have the potential advantage that simulations can be more strongly based on the behavioural patterns of the actors as opposed to statistical data related to spatial units of observation. They are two critical issues in coupling agent-based modelling with GIS which are implementing spatial awareness of agents in geographic space and integrating the dynamics of the environment and its impacts on the behaviour of the agents. A study by Cioffi-Revilla et al. (2011) explored the intersection of GIS and ABM for social simulations enables new scientific and policy analyses that exploit the joint, synergistic capabilities of these advanced computational technologies. However, there are no clear principles concerning which level of integration or coupling is best and achievable. As overall, the overview of this paper highlighted the growing array of topics to which ABM is being applied in urban studied, in addition it also began to sketch out numerous various methods in which the methodology might be implemented.

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