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出版情報：Modeling Earth Systems and Environment, 2022-10-07. Springer
バージョン：
権利関係：

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To cite this article: Mohammed, A.M.S., Ukai, T. Agent-based modelling for spatiotemporal patterns of urban land expansion around university campuses. Model. Earth Syst. Environ. (2022). https://doi.org/10.1007/s40808-022-01551-y

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* This is the accepted version of the manuscript published by Springer Nature in Modeling Earth Systems and Environment which is available online at: https://doi.org/10.1007/s40808-022-01551-y

Agent-based modelling for spatiotemporal patterns of urban land expansion around university campuses

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Abstract

University campuses are known to be accompanied by physical and economic spatiotemporal patterns that contribute to the urban land expansion process of their respective cities. Therefore, this paper assesses the impact brought by Kyushu University's Ito campus on the urban land expansion process of Fukuoka City since its establishment. First, ArcGIS software was used to develop urbanity raster maps by aggregating space syntax, spacematrix, and mixed-use index maps. Then, Netlogo software was used to create the simulation model using urbanity maps. Furthermore, agents for simulating the urban land expansion process were created based on developers' behavior retrieved from the literature and real-world observed data. Proposed model has been verified by conducting a sensitivity analysis and checking R-squared value of simulated maps. Then, the model has been used to simulate expected urban land expansion before and after Ito campus establishment. Comparing resulted maps has shown that Ito campus is anticipated to have accelerated the urban land expansion process in the area by 3.3 times on average. Thus, university campuses can be considered as accelerators for the urban land expansion process of their respective cities. The significance of this paper lies in proposing a model that can be used, by urban planners and decision makers, to anticipate urban land expansion to come up with evidence-based research-informed land management plans.

Keywords: Agent-based simulation; campus design; city urbanization; campus development; urban resilience.

1. Introduction

University campuses are known to be a driving force of knowledge. However, due to their physical and economic impact on the surroundings, they started to be recognized as a driving force of urban development as well. Since the beginning of the twenty-first century, research has considered university campuses to be as extensive landholders that are capable of changing the urban morphology of their surroundings in a significant way (Larkham 2000; Bank and Sibanda 2018). Moreover, university campuses have also shown to be accompanied by social, cultural, physical, and economic changes happening in their surroundings (Mohammed et al. 2022). Therefore, the impact brought by university campuses outside their borders, whether deliberate or not, shapes the dynamics of the space where they exist. Furthermore, university campuses have proven to be heavily dependent on the available number and types of services and facilities in their respective cities. On the other hand, cities rely on their universities to address different economic and social challenges (Drucker and Goldstein 2007; den Heijer and Curvelo Magdaniel 2018). Therefore, campus-city relationship is considered as an overlapped interrelated relation that influences urban development of cities in direct and indirect ways. This intrinsic relationship between universities and cities helps cities to develop and urbanize in an accelerated way. As, the capacity needed to cover students and staff's needs encourages various developers and stakeholders to invest in areas surrounding campuses which accelerates city urbanization in a noticeable way (Rugg et al. 2000; Macintyre 2003). Although university campuses' surroundings might be accompanied by negative effects due to the high concentration of students, campuses' role in city urbanization is considered as a vital by-product that transforms cityscape significantly (Munro et al. 2009; Muslim et al. 2013; Moos et al. 2019).

Although city urbanization is fundamentally a process that includes urban land expansion and urban population growth, the interdependencies between different elements of the city (i.e., university campuses, city centres, business districts, industrial zones, etc.) accelerate such a process more rapidly than anticipated (Mahtta et al. 2022). Furthermore, the complexity and incoordination between urban land expansion and urban population growth increase the pressure on decision makers and planners to come up with urban land management plans to be able to cope with the accelerating urbanization trends (Li et al. 2019). As, research has shown that < 70% of urban growth occurring in seventeen different cities in China was consistent with land use management plans (Li et al. 2015). Although urban population growth is the main driver of urban land expansion, building new urban settlements determines, in many cases, the location where such population growth is expected to appear. For instance, building new university campuses is followed by an increase in youth population in the surrounding area which is known as 'studentification' (Smith 2008; Ackermann and Visser 2016; Nakazawa 2017; Visser and Kisting 2019; Gu and Smith 2019; Moos et al. 2019). Gentrification resulted from the existence of large numbers of students may encourage developers (i.e., real estate agencies, business owners, etc.) to invest in campuses' surroundings which, in turn, increases urban development in the area. Although other factors related to campuses' integration and accessibility might play a role in the nature of urban development occurring, the overall impact of building a new university campus can be witnessed on a large scale in the long run (Mohammed and Ukai 2021). So, it became essential to assess the following impact of building large new urban settlements, such as university campuses, on urban land expansion.

The concepts illustrated above are considered as merely theories that explain urban land expansion process and the potential role of university campuses in accelerating such a process. However, it is necessary to provide empirical data to validate such theories and enrich our understanding of how urban land expansion process works (Bonabeau 2002; Brown and Duh 2011). Therefore, many researchers have turned to agent-based modelling (ABM) to understand the essence behind urban land expansion process (Malik and Abdalla 2017). ABM can also represent the complex behavior of agents which is considered helpful in developing hypotheses empirically. Furthermore, modelling, as a concept, is used to explore, describe, or predict changes in land uses or other systems, especially bottom-up modelling approaches (such as ABM) which have shown to reflect more informative accounts compared to any other approaches (Brown et al. 2016). Therefore, various researchers have approached ABM to explore urban scenarios in combination with transport, environment and other economics using models such as TransSim, UrbanSim, REPAST, LUCITA, and SLEUTH. For example, Jackson et al. (2008) have used

REPAST to investigate urban residential dynamics around university campuses. Furthermore, Joshi et al. (2006) have used UrbanSim to investigate the impact of light rail transit systems on household characteristics and future land use. Additionally, Vani and Prasad (2021) have used SLEUTH in a hybrid model with cellular automata (CA) to model urban land expansion in India. Thus, ABM's ability in modelling complex interactions in the urban practice has made it suitable for the problem presented in this research to analyze spatiotemporal patterns caused by university campuses. The following section will investigate campus-city interaction to retrieve agents' behavior to be implemented in the proposed model. Then, following sections will explain, in detail, how proposed model was designed and verified to be used for modelling spatiotemporal patterns of urban land expansion around Kyushu University's Ito campus.

2. Campus-city interaction and socio-economic relations

In order to assess the role of university campuses in the urban land expansion process of their respective cities, it is essential to understand the socio-economic environment in campuses' surroundings. Many universities try to build autonomous self- sufficient campuses. However, due to the fact that the provision of services provided by a university competes against the resources mounted for research and education, universities started to recognize the available types of services and facilities that cities offer. By doing so, developers, stakeholders and decision makers are encouraged to invest in areas around campuses which, in turn, boosts the socio-economic environment in the area creating a solid campus-city functional relationship (den Heijer and Curvelo Magdaniel 2018). Patterns of investments generated by developers in areas around campuses indicate the nature and behavior of urban development taking place (Brennan and Cochrane 2019). For example, restaurant owners might be interested in areas close to the campus to benefit from the high capacity of university students. On the other hand, the increased demand for dwellings in highly populated student areas encourages real estate agencies to invest in accessible areas near transportation hubs to cover the needs of students and residents commuting to work or school (Florida 2004; Jackson et al. 2008). Furthermore, retail and leisure facilities varies in types and locations. For instance, convenience stores and coffee shops may be located near to the campus. On the other hand, large supermarkets and entertaining businesses might exist in accessible areas near transportation stations to serve locals and students in tandem. Therefore, location preferences adopted by developers contribute to the urban development process taking place, especially around campuses built in suburban areas.

Due to the expansion needs of universities and high land prices, universities tend to build their new campuses in cities' peripheries. Consequently, urban development initiated by new campuses built in suburban areas contributes to the urban land expansion process. As, newly built dwellings, businesses, and amenities accelerate urbanization in the area in a visible way. So, suburban areas around new campuses become more urbanized over time (Molotch 1976). Furthermore, the theory of natural urban transformation process offers evidence that deserted suburban areas become more attractive over time; as highly integrated streets stimulate urban density which, in turn, aggregates a mix of land uses that contributes to the urban land expansion process (van Nes and Ye 2014). Previous research has also shown the impact of university campuses on gentrification trends and the following change in urban density and land use mixes (Mohammed and Ukai 2022). However, campuses' impact on urban land expansion has been moderately examined so far. Therefore, this research investigates to what extent a new campus can impact the urban land expansion process. By doing so, locating new university campuses might be considered as a part of land use management plans to help planners and decision makers control macro and micro urbanization trends. In order to assess the role of university campuses in the urban land expansion process, Kyushu University's newly built Ito campus was selected to analyze its surrounding area to assess how urban land expanded over time. Furthermore, the use of agent-based modelling and the availability of historical geographical information system (GIS) data of Ito campus area allow to simulate urban land expansion before and after the establishment of the campus. By simulating urban land expansion without the existence of the campus, we can assess how the process of urban land expansion would have occurred naturally. On the other hand, simulating urban land expansion with the presence of Ito campus enables us to compare and reflect on the impact of newly built campuses on city urbanization. By doing so, urban planners would have the ability to simulate and anticipate expected urban land expansion in the area to take needed measures and come up with research-informed and evidence-based planning strategies.

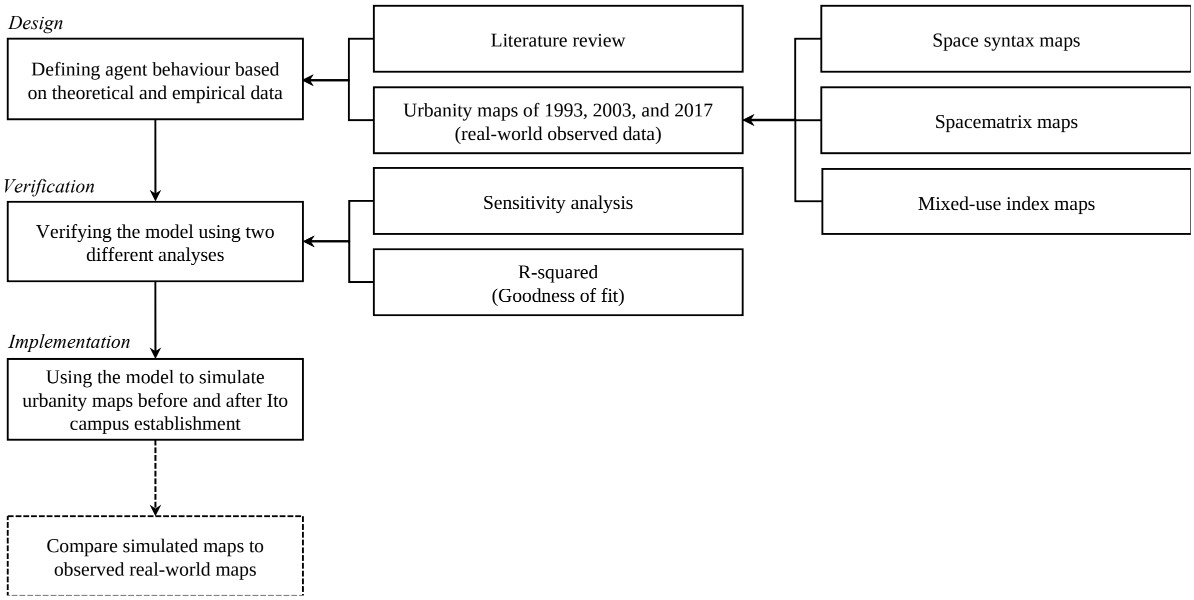


Figure 1. Agent-based simulation workflow

3. Materials and methods

By using developers (i.e. stakeholders, business owners, investors, real estate agencies, retail and leisure businesses, etc.) as agents, an urban land expansion simulation model has been designed through three main steps: design, verification and implementation (Figure 1). First, urbanity raster maps were aggregated from space syntax, spacematrix, and mixed-use index maps using ArcGIS software. Then, agents have been designed based on developers' behavior retrieved from the literature discussed in section 2 and urbanity raster maps. Then, the model has been verified to make sure that the implementation matches the design, and to verify that the process adopted by the model is the same urban land expansion process taking place in the system. Finally, verified model is applied using different datasets before and after Ito campus establishment to compare and reflect on how newly built university campuses affect urban land expansion.

3.1. Study area

Ito campus, which is located in the western part of Fukuoka City in Kyushu Island, is considered as the largest and most advanced campus built in Japan so far (Kyushu University Public Relations 2021). The Engineering School, which is the first school to be built in Ito campus, was established in 2005. Then, soon after other schools moved out from Kyushu University’s original Hakozaki campus one after another till the construction of Ito campus was completed by 2018. The campus was built on the western suburban part of Fukuoka City’s borders with Itoshima City. Ito campus consists of nine different schools built on an area of 2,717,130 m^2 with open borders. The campus is surrounded by two main roads: Route 85 and Route 567. On a 20-minute distance by bicycle, Kyudai Gakkentoshi and Susenji train stations are located which connect the area around the campus with the rest of Fukuoka City and the neighboring Itoshima City as well. Both stations are located along Route 202 which is one of the main routes that goes through Fukuoka City from the east to the west (Figure 2). A 5km radius buffer area was found to include main routes and stations around the campus. Therefore, 5km radius buffer area around the campus was selected in the simulation modelling process. Ito campus was selected due its unique size and location that make it easy to read its impact on the surroundings. The suburban area around the campus is considered as a developing area with Ito campus as one of the first mega projects to exist in it, which makes it easier to visualize the impact of the campus on the urban land expansion process.

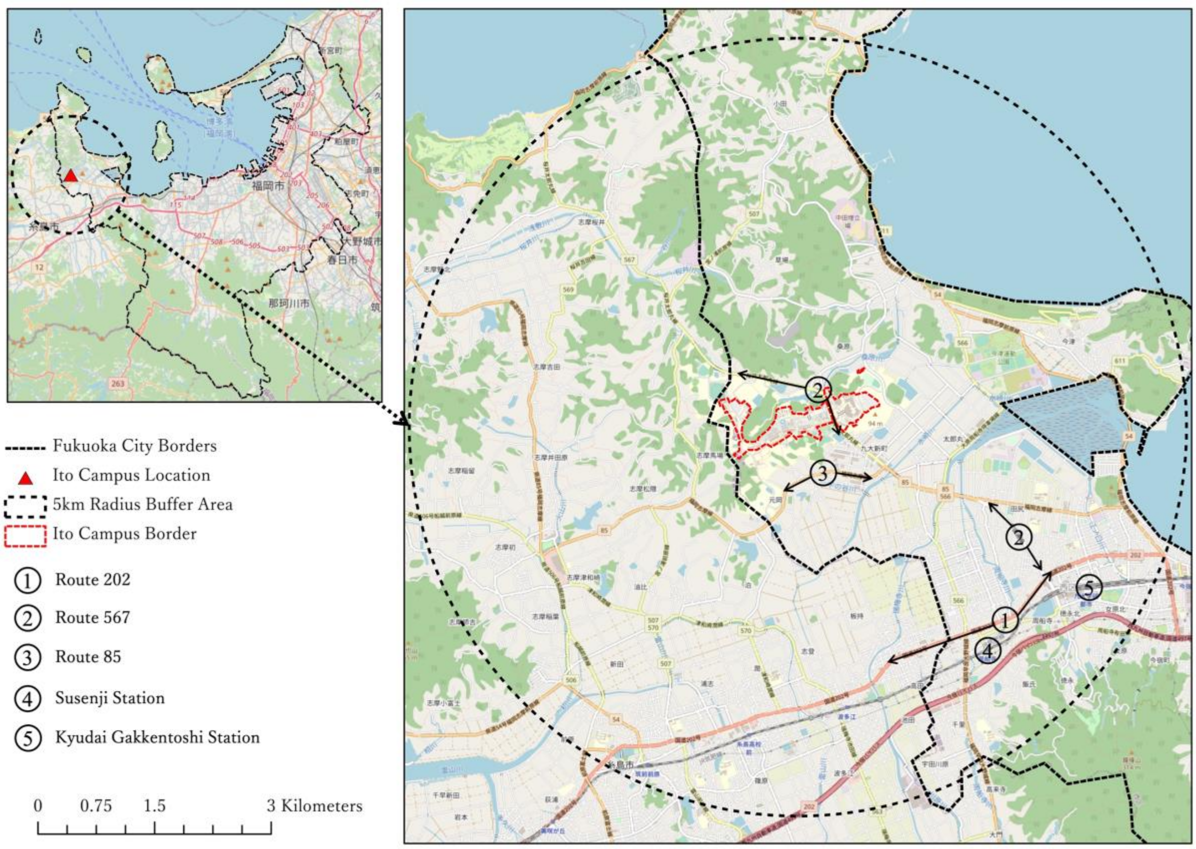


Figure 2. Map shows the location of Kyushu University's Ito campus derived from OpenStreetMap (© OpenStreetMap contributors, CC BY-SA)

View article online at: https://doi.org/10.1007/s40808-022-01551-y

3.2. Urbanity maps

In order to simulate the urban land expansion process, degree of urbanization has to be measured to define agents' behavior. Therefore, urbanity raster maps were created. This paper uses two different keywords simultaneously: urbanity and urban land expansion. Urbanity here refers to the urbanization level of each raster cell from suburban cells to highly urbanized ones. On the other hand, urban land expansion refers to the number of urbanized cells. This paper aims to investigate urban land expansion caused by the existence of university campuses in suburban areas. Therefore, the paper uses urbanity maps to investigate the increase and expansion of urbanized cells as an indication of the occurring urban land expansion process (Figure 3). GIS data provided from Fukuoka City Urban Affairs Bureau in addition to base maps downloaded from OpenStreetMap and Ima Mukashi Map databases were used to produce space syntax, spacematrix, and mixed-use index (MXI) raster maps (OSM Foundation 2020; Kenji Tani 2021). Then, generated maps were aggregated to produce urbanity maps for Ito campus area in 1993, 2003, and 2017 (Table 1). Space syntax methodology was used to produce integration maps for Ito campus area to represent streets with a high potential flow of people (Kim 1999; van Nes and Yamu 2021). Moreover, spacematrix maps were produced to represent urban density in the area around the campus to differentiate between high-, medium-, and low-density areas (Berghauser and Haupt 2010). MXI maps were also produced to represent land use mixes around Ito campus to categorize mono-, bi-, and multi-functional urban blocks (van den Hoek 2010). Space syntax, spacematrix and MXI maps were aggregated to produce urbanity maps using the same methodology developed by van Nes et al. (2012) and Ye & van Nes (2013). Urbanity maps are raster maps that represent urbanization degrees using seven different levels: suburban areas, low urban areas, in-between (low) areas, in-between (middle) areas, in-between (high) areas, middle urban areas, and highly urban areas.

Table 1. Materials and methods used to produce urbanity maps

Method	Platform	Processed Data			
		Data Type	Data Collection Time	Data Source	Data Delivery
Space Syntax	Space Syntax Toolkit (QGIS 3.16.8 software)	Street network for 5km radius buffer area around Ito campus	Late 1980s (1982–86)	Ima Mukashi Map Database	Drawn manually
			Early 2000s (1991–2000)	Ima Mukashi Map Database	
			Early 2020s (2020)	OpenStreetMap (OSM)	
Spacematrix	Spatial Analyst Toolkit (ArcGIS 10.4 software)	Footprint area and number of floors for buildings in 5km radius buffer area around Ito campus	1993	Fukuoka City Urban Affairs Bureau	Provided on request
			2003		
			2017		
Mixed-Use Index (MXI)	Spatial Analyst Toolkit (ArcGIS 10.4 software)	Footprint area and uses of buildings in 5km radius buffer area around Ito campus	1993	Fukuoka City Urban Affairs Bureau	Provided on request
			2003		
			2017		

Urbanity maps for 1993 and 2003 were used to simulate urban land expansion before Ito campus establishment. On the other hand, urbanity map for 2017 was used to simulate urban land expansion after the establishment of the campus (Figure 6.a, e, and h). Using urbanity maps provides us with several advantages. First, they show us urbanization in the area represented in form of urbanity levels which are useful to examine how the area around the campus matured over time. Moreover, urbanity maps are raster maps represented using 100 m × 100 m raster cells, which helps us represent urbanization levels in an abstract way that is easy to compare and analyze. Furthermore, the abstract representation of raster maps is also considered useful to verify the simulation results visually to make sure it matches the design. Additionally, raster maps make it possible to quantify the number and type of each level of urbanization, which would make it more informative when seeking for a quantitative assessment of urban land expansion. Lastly, urbanity raster cells match the nature of agent-based modelling using Netlogo Software which uses patches as units that represent the location of agents. Therefore, urbanity maps were found suitable to be used in the present research.

3.3. Agent-based modelling

Agent-based modelling (ABM) can be defined as a computer system that simulates a certain environment with a set of different rules to enable flexible autonomous actions to meet the objectives of the designed system. ABM process starts usually with defining agents with a certain behavior that allows them to pursuit their objectives that are embedded in their DNA (Wooldridge 1997; Jennings 2000; Macal 2016; Crooks et al. 2018a). In easy words, ABM can be simply defined as a simulation model that contains agents with a certain decision-making framework to examine how agents would behave or interact, which allows to validate observed phenomena, or discover emergent ones. ABM process consists of three main steps: design, implementation, and verification. The design phase begins with setting rules for agents to act upon. These rules could be hypothesized based on empirical or theoretical data or both. However, the aim should be towards simplifying the target system (i.e., the real-world), and any sort of complexity needs to be justified. Therefore, the 'keep it simple, stupid' (KISS) argument is found suitable to represent the system in its simplest form initially and any level of complexity is added if needed to accurately represent the system (Axelrod 1997; Lafuerza et al. 2016). Then, after the model is designed, it needs to be verified to make sure that the designed model works as it supposed to, and to verify that the model follows the same rules found in the target system (Crooks et al. 2018b). Lastly, proposed model can be used with hypothetical data or calibrated with real-world data to discover emergent behaviors or to explain observed ones. One of the main advantages that ABM offers is its integration with GIS, which allows for further spatial analysis of simulated data. Therefore, ABM has had a growing interest in the urban planning community since the beginning of the twenty-first century (Gimblett 2002; Benenson and Torrens 2004).

Furthermore, ABM can represent various different types of agents including developers, businesses, organizations, or citizens that act based on certain constrains and rules. These agents can store and exchange information about their local and global surroundings to decide whether to move, stay, or build. Therefore, ABM has the ability to describe complex interactions happening between entities and their environment better than any other spatial modelling techniques (Benenson 1998; Sengupta and Sieber 2007; O'Sullivan 2008). Many researchers have extensively used ABM models to simulate urban growth and land use change (Jackson et al. 2008; Valbuena et al. 2010b; Valbuena et al. 2010a; Augustijn-Beckers et al. 2011; Jjumba and Dragićević 2011;

Xie and Fan 2014; Zhang et al. 2015; Bakker et al. 2015; Li et al. 2016; Ghosh and Shetty 2017; Motieyan and Mesgari 2018; Li et al. 2019; Zhang et al. 2020; Filomena and Verstegen 2021; Vani and Prasad 2021; Kumar et al. 2021b; Agyemang et al. 2022). However, the focus was mainly on explaining the complex behavior of agents when different policies and scenarios are applied, with a little attention to the impact of urban settlements on urban land growth. Therefore, this research tries to simulate urban land expansion process using developers as agents and university campuses as a factor that stimulates urban land expansion. Netlogo Software (version 6.2.2) has been used to simulate ABM process presented in this research due to Netlogo's user-friendly interface and the availability of GIS extension that allows reading and writing urbanity raster maps (Wilensky 1999).

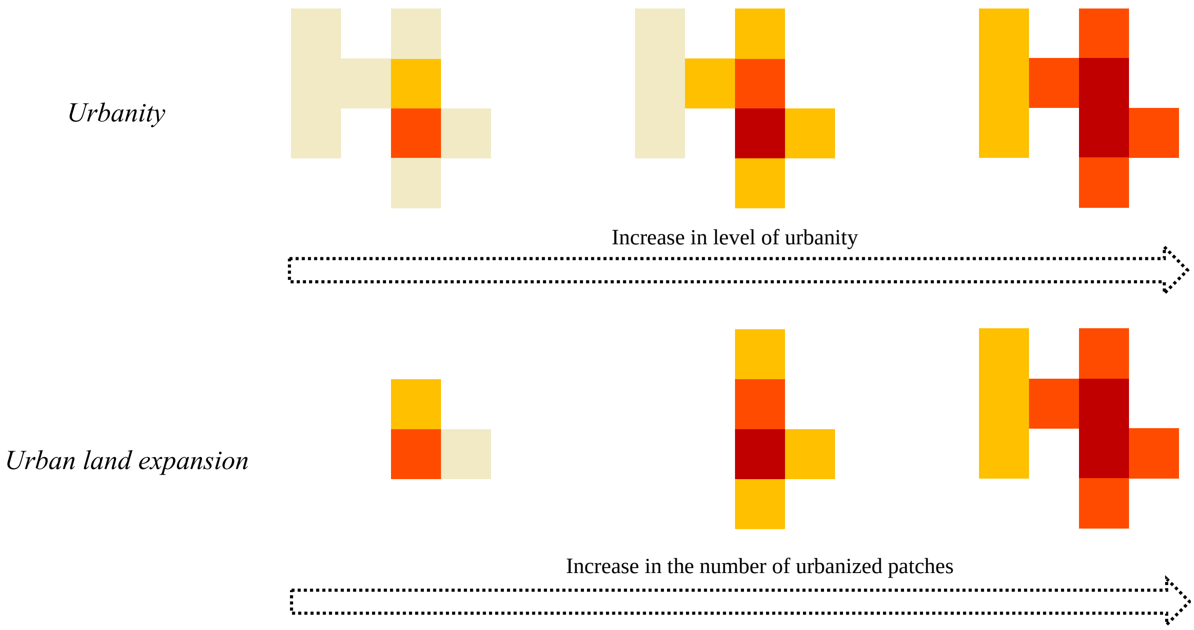


Figure 3. The difference between urbanity and urban land expansion processes as represented through urbanity maps. The darker the cell, the more urbanized it is.

3.3.1. Model design

Based on the literature discussed in section 2, developers (such as stakeholders, business owners, investors, real estate agencies, retail and leisure businesses, etc.) are considered as the main actors of urban land development that usually exist around university campuses. Therefore, developers have been selected as the type of agent to be represented in the proposed model. Although various types of developers may behave differently according to their own interests, the goal of this model is to capture urban land expansion process not developers' behavior. Therefore, using only one type of agent (i.e., developer) was found suitable to simplify the design of the model. Developer agent's behavior can be presumed based on the literature discussed in section 2 and observed urbanity maps shown in Figure 6.a, e, and h. As discussed in the literature some developers may be interested to invest in areas close to the campus, some others may be more interested in investing in accessible areas to serve a wider customer base. However, both types of developers share a common interest in investing in urbanized areas to benefit from the footfall of residents, passers-by, and locals. Moreover, investing in urbanized areas allow developers to attract more customers and buyers due to the social and economic value that highly urbanized areas offer. So, basically most developers won't be encouraged to invest in suburban areas unless space needs require so (Li and Park 2006; Kumar et al. 2021a). Furthermore, investing in any area would encourage other developers to invest as well. Consequently, the more developers invest, the more urbanized the area becomes. Therefore, the urban land simulation model has been designed based on one simple rule, suburban areas become more urbanized by time because of developers' investments. Proposed model also uses similar simulation rules and workflows found in the urban sprawl model proposed by Felsen and Wilensky (2007). However, proposed model is considered more sophisticated as it provides more evidence-based simulation outputs using empirical data found in urbanity maps.

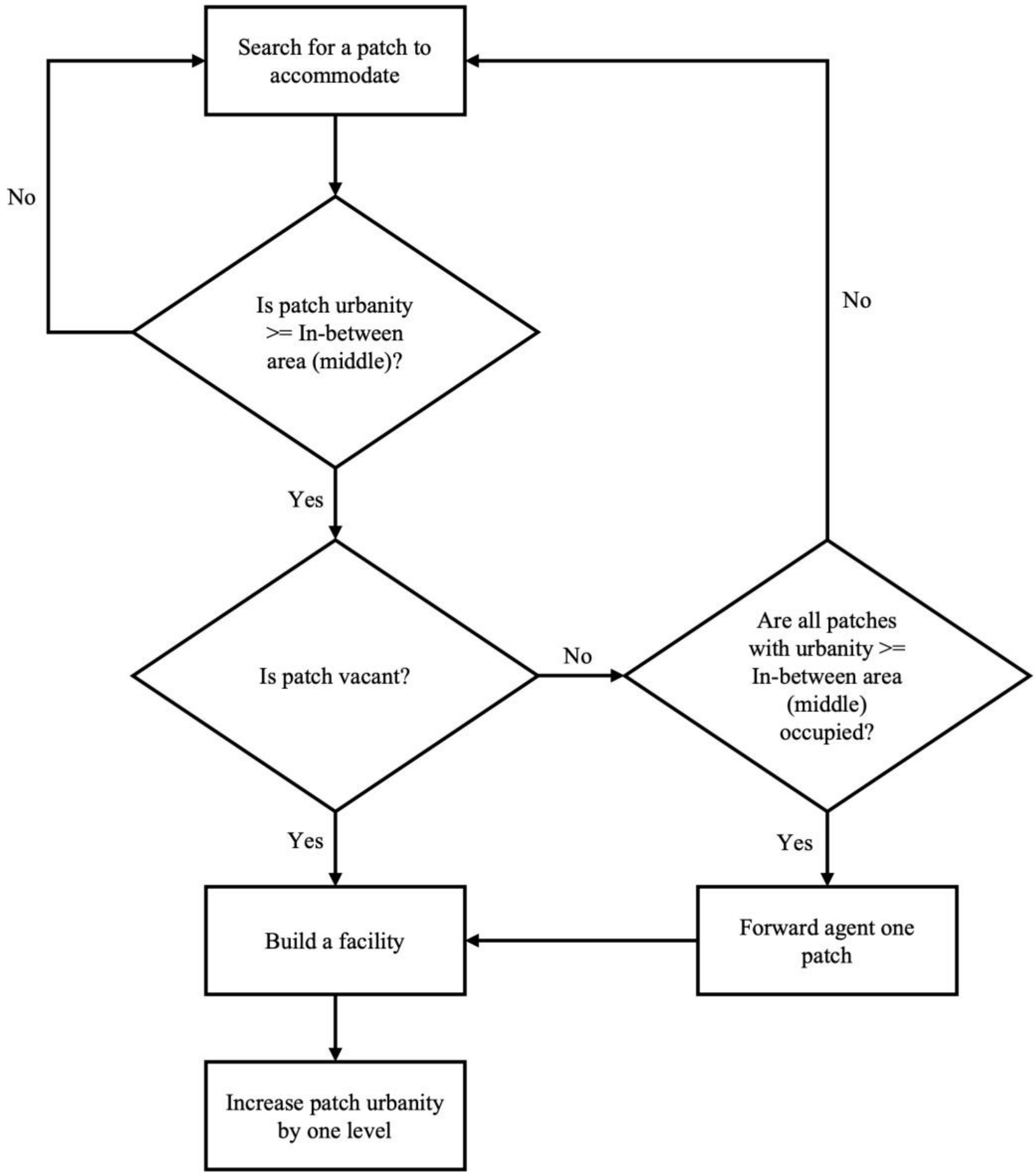
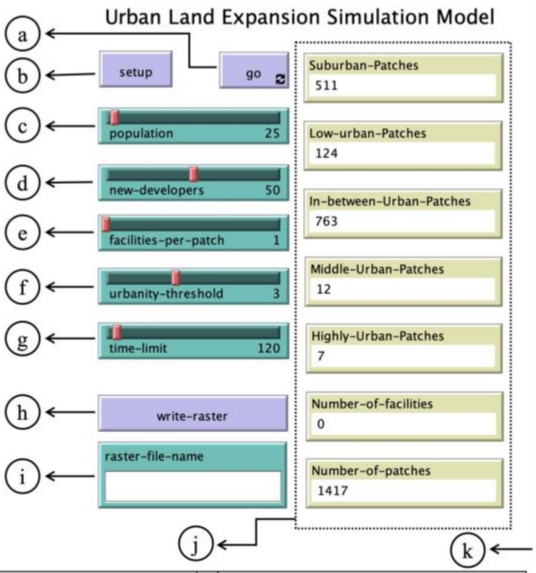
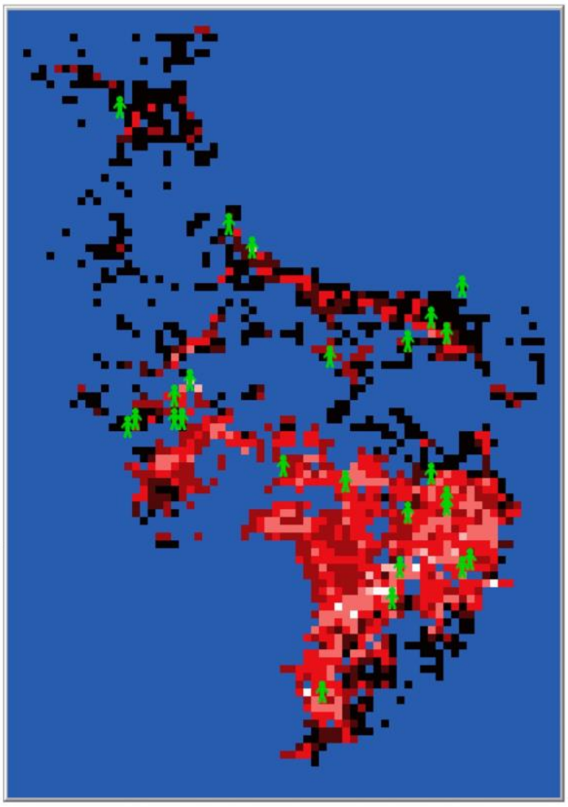


Figure 4. Flowchart illustrates agents' behavior and decision-making process





a	To start simulation	g	Number of ticks which determines when the simulation stops.
b	To setup the model before simulation	h	To write the simulation output into a raster map to be used in the GIS environment
c	Number of developers who enter the system at the beginning of the simulation	i	To name the raster file
d	Number of developers who enter the system every 12 ticks (= one year)	j	Monitors that show the number of patches and agents during the simulation to check its performance.
e	Number of facilities limit per patch	k	Window that shows simulation output before writing it as a raster map in the GIS environment. Green figures represent developer agents. Red patches represent the level of urbanity in each raster cell. The darker the patch, the lower the level of urbanity is.
f	Urbanity threshold based on which the developer agent decides to build a facility		

Figure 5. Urban land expansion model's interface as programmed in Netlogo software

First, developers enter the system to check where to invest. Based on developers' capital, they choose the suitable area that they can afford. Therefore, the investment threshold in the model has been set to make developers invest in patches with an in-between (middle) level of urbanity or higher. If the developer found that the chosen suitable patch is occupied, the agent jumps to the next available patch. Then, once the developer agent settles, its respective patch's level of urbanity increases by one level (Figure 4). Moreover, the model has been designed to allow a certain number of developers enter every 12 ticks (= one year). Number of developers and urbanity raster maps used in the model have been calibrated according to the observed dataset. Once the assigned number of ticks (= number of years) is reached, the model stops to be exported to a GIS environment. The proposed model has been provided with two extra parameters: 'urbanity threshold' and 'facilities per patch'. 'Urbanity threshold' parameter controls the threshold based on which the developer agent decides to invest and build a facility. On the other hand, 'facilities per patch' parameter sets the number of developers who are allowed to settle on the patch and build a facility (Figure 5). Both parameters, 'urbanity threshold' and 'facilities per patch', were included to be used in the sensitivity analysis later in the verification step.

3.3.2. Model verification

In order to verify that the model is behaving as expected, a sensitivity analysis was conducted using 'urbanity threshold' and 'facilities per patch' parameters that were included in the design of the model. As shown in Table 2, sensitivity analysis results show that the model in most cases is working as expected. Test A has shown that 'urbanity threshold' parameter affects the distribution and concentration of newly created patches, which is expected according to the design of the model. Test B has also shown that the number of 'facilities per patch' parameter affects the number of newly created patches, which is expected. However, when the limit of facilities per patch increases, the simulation output shows lower levels of urbanity in most patches. This emergent behavior could be explained according to the relativity of urbanity maps. As urbanity maps show relatives values of urbanity not absolute ones. Therefore, when the limit of facilities per patch increases, facilities are built on a fewer number of patches. So, the urbanity levels of these patches increase, and the urbanity of the rest of the patches remain the same. Then, when the model is rendered, the overall urbanity levels become lower. In other words, high values of urbanity get higher, and lower values of urbanity remain the same. This emergent behavior also shows that land use management plans should provide developers and business owners locational incentives to encourage them to invest on a wider scale. This would help in urbanizing larger areas of rural and suburban lands.

Table 2. Tests carried out to verify the simulation output

Test	Verification parameter	Result	Is this an expected outcome?	Reflection
A	Urbanity threshold increased one level at a time	The lower the urbanity threshold is, the more scattered newly created patches become	Yes	Expected behavior
		The higher the urbanity threshold is, the more compacted and concentrated newly created patches become	Yes	Expected behavior
B	Number of facilities per patch increased one level at a time	The higher the number of facilities per patch is, the less the number of newly created patches become	Yes	Expected behavior
		The lower the number of facilities per patch is, the higher the number of newly created patches become	Yes	Expected behavior
		The higher the number of facilities per patch is, the lower the overall resulted urbanity levels become	No	Emergent behavior

Table 3. Parameters' values used in the simulation

Used dataset	Simulation year	Population	New developers	Facilities per patch	Urbanity threshold	Time limit (Every 12 ticks is equal to one year)	Simulation Period (years)
1993 (Before Ito campus establishment)	2003	16	16	1	3 (= In-between [middle])	120	10
	2017	17	17	1	3 (= In-between [middle])	288	24
	2058	17	17	1	3 (= In-between [middle])	780	65
2003 (Before Ito campus establishment)	2017	16	16	1	3 (= In-between [middle])	168	14
	2058	17	17	1	3 (= In-between [middle])	660	55
2017 (After Ito campus establishment)	2058	17	17	1	3 (= In-between [middle])	492	41

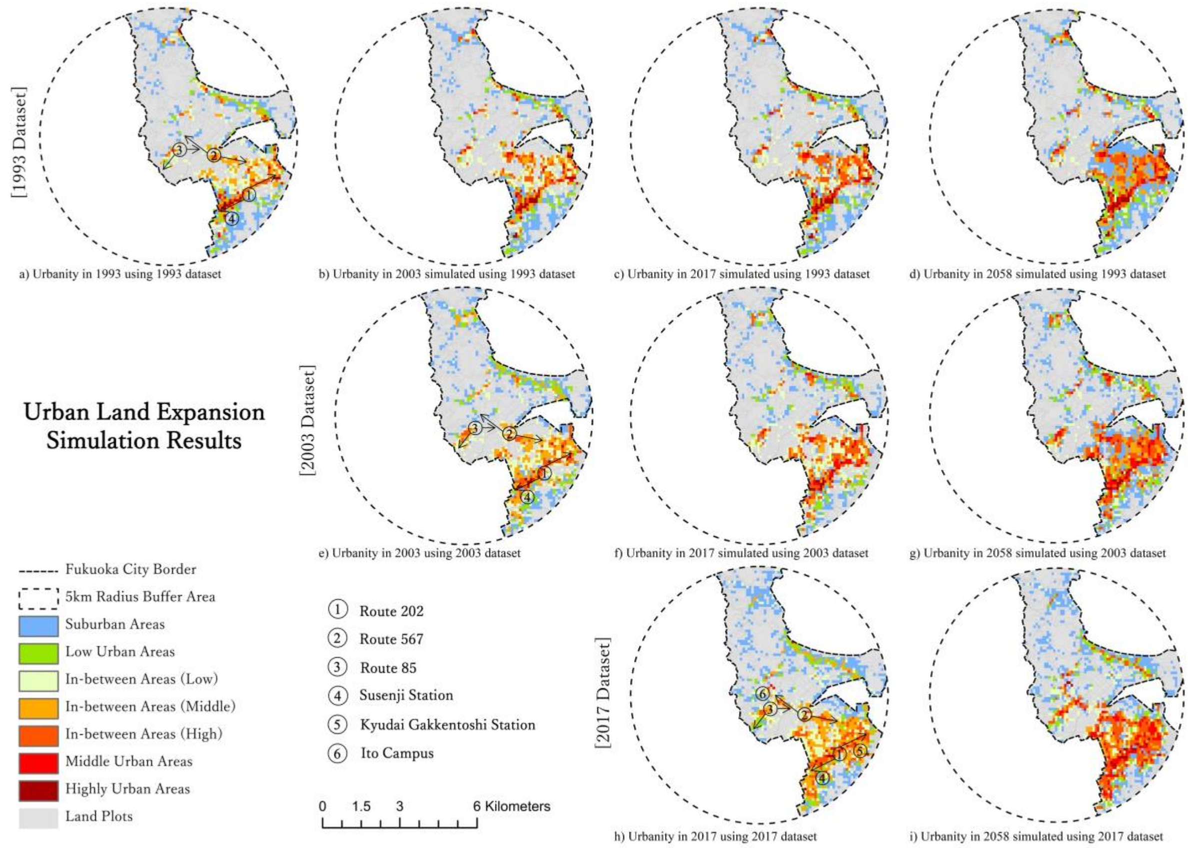
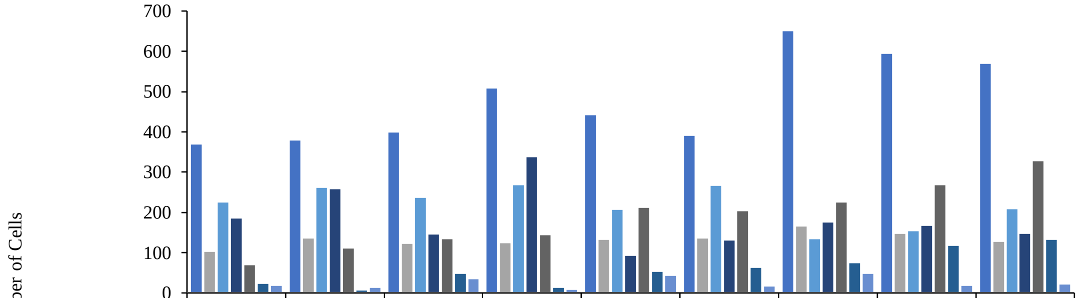


Figure 6. Urbanity maps of Ito campus area

To verify that the process adopted by the model is similar to the one embedded into the system, R-squared (goodness of fit) is used to check how much variation in the observed data is explained by the simulated output (Crooks et al. 2018b; Grekousis 2020). 1993 and 2003 observed datasets were used to simulate urban land expansion in 2003 and 2017. Then, the output number of cells for each level of urbanity was analyzed with 2003 and 2017 observed datasets to check how much variation the output explains (Figure 7). Parameters' values were calibrated with the observed original datasets as shown in Table 3. For instance, the total number of urbanized patches in 1993 was 987 patches and 1161 patches in 2003. This means that a total number of 174 new patches were created. If facilities per patch is adjusted as 1, then this means that 174 new developers entered the system from 1993 to 2003. In other words, around 16 different developers entered the system annually.Other simulation outputs were calibrated following the same method (Table 3). Using IBM SPSS Statistics software Ver. 26, simulated map of 2003 (simulated using 1993 dataset) has shown a R-squared value of 0.86, which means that the simulated model explains 86% of the variation of the original observed model. Furthermore, simulated map of 2017 (simulated using 1993 dataset) has shown a R-squared value of 0.66. Moreover, simulated map of 2017 (simulated using 2003 dataset) has shown a R-squared value of 0.74. This shows that the proposed simulation model exhibits a high percentage of variation of the real-world data, which confirms the validity of using the model to simulate and anticipate urban land expansion process.

3.3.3. Model implementation

In order to assess the impact of university campuses on the urban land expansion process, the model was used to simulate urbanity maps before and after the establishment of Ito campus. Parameters for the simulation were calibrated with real-world data as shown in Table 3. First, 1993 dataset (before Ito campus establishment) was used to simulate urbanity maps in 2003 and 2017 to be compared with urbanity maps as observed in 2003 and 2017. Then, 2003 dataset (before Ito campus establishments) was used to simulate urbanity maps in 2017 to be compared with urbanity maps as observed in 2017. Then, 1993, 2003, and 2017 datasets were used to simulate urbanity maps in the years ahead to see how urban land would expand in the future (Figure 6).



	1993 (observed)	2003 (observed)	2003 (simulated using 1993 database)	2017 (observed)	2017 (simulated using 1993 database)	2017 (simulated using 2003 database)	2058 (simulated using 1993 database)	2058 (simulated using 2003 database)	2058 (simulated using 2017 database)
Suburban Areas	369	379	399	508	442	390	650	593	569
Low Urban Areas	102	135	121	124	131	135	165	147	127
In-between Areas (Low)	225	261	236	267	206	266	134	153	208
In-between Areas (Middle)	184	257	145	337	92	130	174	166	147
In-between Areas (High)	68	111	133	144	212	203	224	267	327
Middle Urban Areas	22	6	47	12	52	62	74	116	132
Highly Urban Areas	17	12	34	7	43	15	47	18	21

Figure 7. Chart shows the number and type of patches in observed and simulated data

4. Results and discussion

Results have shown that the distribution of urbanized cells in 2003 urbanity map simulated using 1993 dataset (before Ito campus establishment) is similar to 2003 map as observed (Figure 6.b and e). Moreover, results have also shown that 2017 urbanity map simulated using 1993 dataset (before Ito campus establishment) is similar in the distribution of cells to 2017 urbanity map simulated by 2003 dataset (before Ito campus establishment) (Figure 6.c and f). Although simulated maps show higher levels of urbanity, the distribution and location of cells are similar to some extent (Figure 7). However, the 2017 observed urbanity map (after Ito campus establishment) has shown a wider distribution of urbanized cells compared to 2017 simulated urbanity maps, especially around the campus peripheries (Figure 6.c, f, and h). If we have a closer look around where the campus is located, we can clearly notice that cells with high values of urbanity in 2017 simulated maps are fewer and more concentrated compared to 2017 observed urbanity map (after Ito campus establishment) as shown in Figure 8.a, b, and c. In other words, if Ito campus has not existed in the area, urban land expansion would have been limited. So, we can conclude that Ito campus has contributed to urban land expansion in the area thanks to the number of services and facilities accompanied its existence. This also offers evidence that university campuses contribute to the urban land expansion as well as the urban transformation of their respective cities.

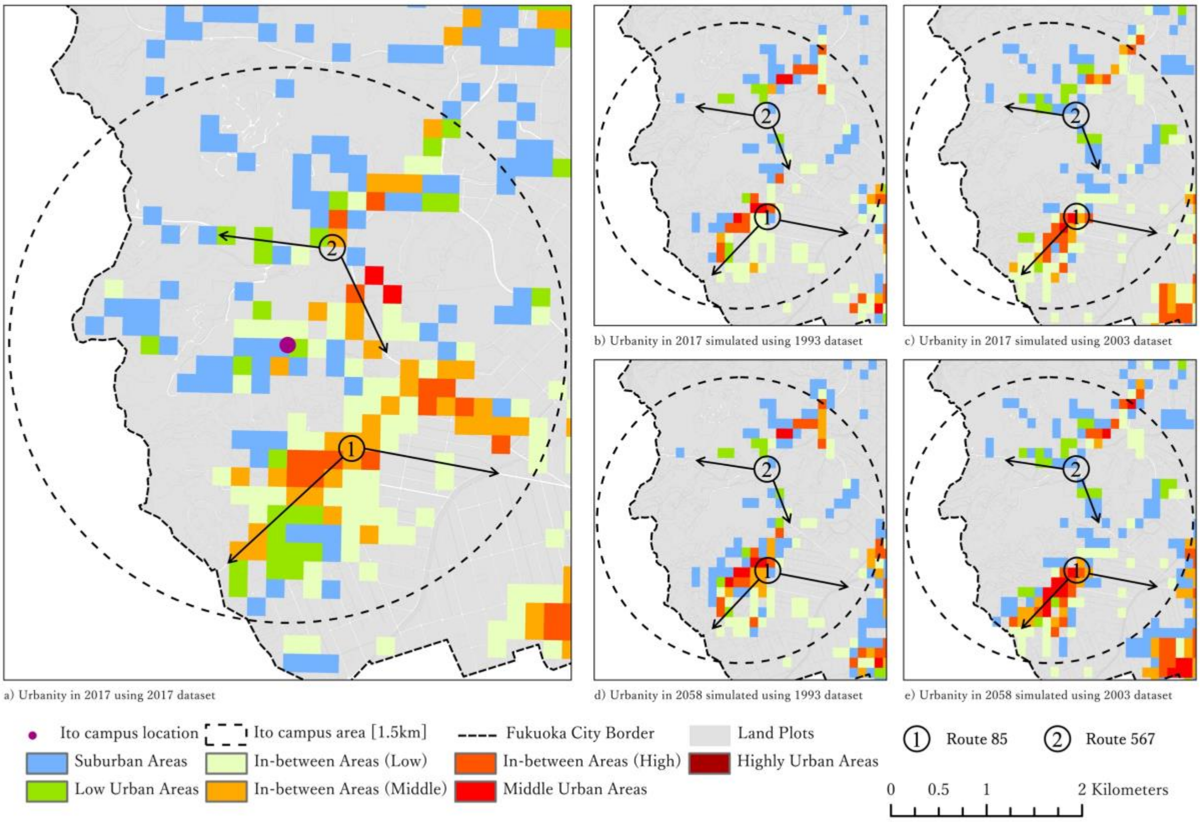


Figure 8. Urbanity maps of Ito campus's surrounding area

Furthermore, for experimental reasons, the number of ticks (= number of months) adjusted in the simulation have been increased one year (= 12 ticks) at a time. Results have shown that the more years are added to the simulation, the more urban land expansion become. However, the area close to the campus has shown to reach its threshold of urban land expansion by 2058. In other words, the model has reached the maximum number of patches that could be added by reaching 2058. After 2058, no matter how many ticks were added, there was no significant change in the number of patches created around the campus. Parameters for 2058 simulated urbanity maps have been calibrated with average values retrieved from observed real-world data as shown in Table 3. 2058 simulated urbanity maps, using 1993 and 2003 datasets (before Ito campus establishment), have shown that urban land expansion has noticeably increased over time (Figure 6.d and g). However, in the area surrounding the campus urban land expansion has slightly increased (Figure 8.d and e). Surprisingly, 2017 observed urbanity map has shown more mature urban land expansion compared to 2058 simulated maps produced using 1993 and 2003 datasets (before Ito campus establishment) (Figure 8.a, d, and e). This also offers evidence that university campuses not only contribute to the urban land expansion of its respective city, but also accelerate the process. Figure 8.a and d show that Ito campus has increased urban land expansion from 1993 to 2017 more than it would have increased in 2058 without establishing the campus. Furthermore, Figure 8.a and e show that Ito campus has increased urban land expansion from 2003 to 2017 more than it would have increased in 2058 without establishing the campus. So, the area would have needed 65 years from 1993 and 55 years from 2003 to expand in urbanization without the existence of the campus. However, the surrounding area has achieved more urban land expansion by 2017 than anticipated thanks to Ito campus establishment. In other words, the existence of Ito campus in the area has accelerated the urban land expansion and maturation process by 2.7 times (from 1993) and 3.9 times (from 2003). So, we can conclude that Ito campus has accelerated urban land expansion in its surroundings by 3.3 times on average. Moreover, Figure 6.i shows that, by 2058, urban land expansion is expected to cover a larger area around the campus starting from Route 202 all the way to Route 567. Compared to Figure 6.d and g, urban land expansion would have happened in two separate locations: in the area near to the campus and around Route 202. However, Ito campus establishment allows the urban land expansion process to connect all the way from Route 202 through Route 567 and beyond.

Although the impact brough by university campuses to their surroundings is dependent on many factors including campus size, campus location, number of students, etc., the existence of a campus in a rural suburban area brings lots of opportunities to the area. As campuses work as nodal points that attract investors and developers due to the high economic potentials that campuses offer. However, building a university campus on city's peripheries might be accompanied with some challenges related to accessibility and studentification. Due to the location of a suburban campus, transportation modes might be limited forcing students to live near by the campus. This, in turn, would create studentified areas around the campus which are known to be associated with social segregation between students and original residents, in addition to other negative impacts such as noise, illegal parking, or students walking home drunk (Allinson 2006; Selwyn 2008). Moreover, suburban campuses suffer from the burden of required resources needed to build their own infrastructure (Misra 2020; Karpińska and Kunz 2021). Additionally, due to the location of suburban campuses away from the city center, campuses face the need to create their own social life and activities to satisfy students' social and physical needs (Hebbert 2018). So, we can conclude that despite the fact that university campuses contribute greatly to the urban land expansion and development process of their respective cities, they still face lots of different challenges that may be burden on the university competing with resources set for education and research. Therefore, university administrators, planners and decision makers need to consider the physical and social impact in addition to the financial commitments brought by building new campuses in suburban areas, especially in the early stages of campus development.

Although the model presented in this paper is built on one simple rule, it provides empirical evidence on how universities shape the urban development of their respective cities. Results have also confirmed that university campuses can rapidly accelerate the urban land expansion process of their respective cities, which is aligned with what universities have been described as extensive landholders (Larkham 2000). Furthermore, proposed model paves the way not only for future research, but also for future policies and planning strategies. As, the model can be considered as a planning tool that provides stakeholders and officials a future vision of how urban land would expand. One more interesting finding that has been presented in this article is that simulated maps have shown that urbanization gets intensified and concentrated around highly urbanized patches which is not the case in real-world observed maps. This shows that developers, especially business owners, may prefer to invest nearby other investors, but not necessarily close to them. As, businesses prefer to protect their sales and competitive profile. So, they choose nearby locations to benefit from the high traffic of customers going to their competitors, but not close enough to damage their sales in case they failed to attract customers. These conclusions have also been confirmed in business location-allocation studies (Karakaya and Canel 1998; Bartik 2012; Kimelberg and Williams 2013). Therefore, business owners as well as investors can benefit from the findings of this research for a better decision making. Furthermore, results have shown that simulated maps show urbanized patches concentrated in clusters around nodal points such as Ito campus, Route 202, and the surrounding railroad stations. Although these clusters are also present in real-world observed maps, they do not look as separated as shown in simulated maps. This captures another interesting well-known behavior of developers that has been investigated in previous research (McDonald 2013). As, some developers may not be able to afford the high cost of land in highly urbanized areas. So, they might prefer investing in areas between highly urbanized clusters, which leads to lines of middle urbanized patches connecting between highly urbanized clusters as shown Figure 6.h. In conclusion, we can sum up that the significance of the proposed model lies in providing empirical evidence of campuses' role in the urban land expansion of their respective cities. Moreover, city officials, urban planners as well as developers can benefit from the proposed model in utilizing research-informed simulation results for a better decision making.

5. Conclusion

Due to the capacity needed to serve students and staff's needs, universities rely heavily on the number and types of services that their respective cities offer. On the other hand, universities help their cities to face social and economic challenges due to universities' role as knowledge and innovation hubs. Therefore, the impact of universities goes beyond their borders to include their surrounding physical, social, cultural, and economic environments as well. As universities work as nodal points that attract developers and business owners to invest and benefit from the high footfall of students and staff. Additionally, studentification resulted from the influx of students to the area around the campus brings several cultural and social changes that can be seen through students' residential patterns or migration trends. Universities' physical impact can also be seen through the role that new universities play in the urban development of their respective cities. Therefore, this paper has conducted an agent-based simulation modelling to assess the impact caused by Kyushu University's new Ito campus on the urban land expansion process. Results have shown that Ito campus is anticipated to have accelerated the urban land expansion process by 3.3 times on average. Although factors related to campus size, campus location, and number of schools and students may affect the scale of the impact brought by a university campus, findings have shown that university campuses, especially suburban ones, contribute greatly to the urban development of their respective cities.

In order to go beyond the limitations of this paper, future research may investigate the impact of other factors, related to campus location, size, or age, on their contribution to the urban land expansion and development process of cities. Moreover, future research may redesign the simulation model to differentiate between different types and behaviors of developers to investigate which type of developers play the biggest role in such a process. Additionally, there have been several detailed cases studies that have shown that land rent dynamics impact where students may live and settle which, in turn, affects the extent of the accompanying social and economic impacts. Therefore, simulating urban residential dynamics around university campuses may help in understanding where studentification and gentrification trends might occur. Designing such simulation models provide planners and decision makers with evidence-based recommendations that help them take more concrete measures and decisions.

Declaration of Competing Interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data Availability

The data that support the findings of this study are available from Fukuoka City Urban Affairs Bureau, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

Acknowledgment

Authors would like to thank Fukuoka City Urban Affairs Bureau for providing the data needed for this research. This paper is part of the PhD thesis of the first author which is funded by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

Ackermann A, Visser G (2016) Studentification in Bloemfontein, South Africa. Bulletin of Geography Socio-economic Series 31(31):7–17. https://doi.org/10.1515/BOG-2016-0001

Agyemang FSK, Silva E, Fox S (2022) Modelling and simulating 'informal urbanization': An integrated agent-based and cellular automata model of urban residential growth in Ghana. Environ Plan B Urban Anal City Sci 49:1–15. https://doi.org/10.1177/23998083211068843

Allinson J (2006) Over-educated, over-exuberant and over here? The impact of students on cities. Planning Practice and Research 21(1):79–94. https://doi.org/10.1080/02697450600901541

Augustijn-Beckers E-W, Flacke J, Retsios B (2011) Simulating informal settlement growth in Dar es Salaam, Tanzania: An agent-based housing model. Comput Environ Urban Syst 35(2):93–103. https://doi.org/10.1016/J.COMPENVURBSYS.2011.01.001

Axelrod R (1997) Advancing the Art of Simulation in the Social Sciences. In: Conte R, Hegselmann R, Terno P (eds) Simulating Social Phenomena. Springer, Berlin, pp 21–40. https://doi.org/10.1007/978-3-662-03366-1_2

Bakker MM, Alam SJ, van Dijk J, Rounsevell MDA (2015) Land-use change arising from rural land exchange: an agent-based simulation model. Landsc Ecol 30(2):273–286. https://doi.org/10.1007/S10980-014-0116-X/TABLES/6

Bank L, Sibanda F (2018) Universities as city-builders: The city-campus development opportunity in East London–Buffalo City, South Africa. Development Southern Africa 35(5):701–715. https://doi.org/10.1080/0376835X.2018.1502076

Bartik TJ (2012) Business Location Decisions in the United States: Estimates of the Effects of Unionization, Taxes, and Other Characteristics of States. Journal of Business & Economic Statistics 3(1):14–22. https://doi.org/10.1080/07350015.1985.10509422

Benenson I (1998) Multi-agent simulations of residential dynamics in the city. Comput Environ Urban Syst 22(1):25–42. https://doi.org/10.1016/S0198-9715(98)00017-9

Benenson I, Torrens P (2004) Geosimulation: Automata-based modeling of urban phenomena. John Wiley & Sons, New Jersey

Berghauser M, Haupt P (2010) Spacematrix. space, density and urban form. NAi Publisher, Rotterdam

Bonabeau E (2002) Agent-based modeling: Methods and techniques for simulating human systems. In: Proceedings of the National Academy of Sciences. National Academy of Sciences, pp 7280–7287

Brennan J, Cochrane A (2019) Universities: in, of, and beyond their cities. Oxford Review of Education 45(2):188–203. https://doi.org/10.1080/03054985.2018.1551198
Brown C, Brown K, Rounsevell M (2016) A philosophical case for process-based modelling of land use change. Model Earth Syst and Environ 2(2):1–12. https://doi.org/10.1007/S40808-016-0102-1
Brown DG, Duh J der (2011) Spatial simulation for translating from land use to land cover. International Journal of Geographical Information Science 18(1):35–60. https://doi.org/10.1080/13658810310001620906
Crooks A, Heppenstall A, Malleson N (2018a) Agent-Based Modeling. Comprehensive Geographic Information Systems 3:218–243. https://doi.org/10.1016/B978-0-12-409548-9.09704-9
Crooks A, Malleson N, Manley E, Heppenstall A (2018b) Agent-based modelling and geographical information systems: a practical primer. SAGE, Los Angeles
den Heijer AC, Curvelo Magdaniel FTJ (2018) Campus–city relations: Past, present, and future. In: Meusburger P, Heffernan M, Suarsana L (eds) Geographies of the University. Springer, Cham, pp 439–459 https://doi.org/10.1007/978-3-319-75593-9_13
Drucker J, Goldstein H (2007) Assessing the regional economic development impacts of universities: A review of current approaches. International Regional Science Review 30(1):20–46. https://doi.org/10.1177/0160017606296731
Felsen M, Wilensky U (2007) NetLogo Models Library: Urban Suite - Sprawl Effect. Center for Connected Learning and Computer-Based Modeling, Illinois
Filomena G, Verstegen JA (2021) Modelling the effect of landmarks on pedestrian dynamics in urban environments. Comput Environ Urban Syst 86:101573. https://doi.org/10.1016/J.COMPENVURBSYS.2020.101573
Florida R (2004) Cities and the creative class. Routledge, New York
Ghosh S, Shetty A (2017) Modelling the land use system process for a pre-industrial landscape in India. Model Earth Syst Environ 3(2):703–717. https://doi.org/10.1007/S40808-017-0329-5
Gimblett H (2002) Integrating geographic information systems and agent-based modeling techniques for simulating social and ecological processes. Oxford University Press, Oxford
Grekousis G (2020) Spatial analysis methods and practice: describe–explore–explain through GIS. Cambridge University Press, Cambridge
Gu H, Smith D (2019) ‘Living off the campus’: urban geographies of change and studentification in Beijing, China. Urban Geogr 41(2):205–224. https://doi.org/10.1080/02723638.2019.1659071
Hebbert M (2018) The campus and the city: A design revolution explained. J Urban Des 23(6):883–897. https://doi.org/10.1080/13574809.2018.1518710
Jackson J, Forest B, Sengupta R (2008) Agent-Based Simulation of Urban Residential Dynamics and Land Rent Change in a Gentrifying Area of Boston. Transactions in GIS 12(4):475–491. https://doi.org/10.1111/J.1467-9671.2008.01109.X
Jennings NR (2000) On agent-based software engineering. Artif Intell 117(2):277–296. https://doi.org/10.1016/S0004-3702(99)00107-1
Jjumba A, Dragićević S (2011) High Resolution Urban Land-use Change Modeling: Agent iCity Approach. Applied Spatial Analysis and Policy 5(4):291–315. https://doi.org/10.1007/S12061-011-9071-Y
Joshi H, Guhathakurta S, Konjevod G, Crittenden J, Ke L (2006) Simulating impact of light rail on urban growth in phoenix: An application of UrbanSim modeling environment. In: ACM International Conference Proceeding Series. pp 135–141 https://doi.org/10.1145/1146598.1146641
Karakaya F, Canel C (1998) Underlying dimensions of business location decisions. Industrial Management and Data Systems 98(7):321–329. https://doi.org/10.1108/02635579810205395
Karpińska D, Kunz M (2021) Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area: A case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. Bulletin of Geography Socio-economic Series (54):137–149. https://doi.org/10.2478/bog-2021-0039
Kenji Tani (2021) Ima Mukashi Map Database. In: Human Geography Laboratory, Saitama. https://ktgis.net/kjmapw/index.html. Accessed 15 Nov 2021
Kim YO (1999) Spatial Configuration, Spatial Cognition and Spatial Behaviour: The Role of Architectural Intelligibility in Shaping Spatial Experience. University College London, London
Kimelberg SM, Williams E (2013) Evaluating the Importance of Business Location Factors: The Influence of Facility Type. Growth Change 44(1):92–117. https://doi.org/10.1111/GROW.12003
Kumar S, Talasila V, Pasumarthy R (2021a) A novel architecture to identify locations for Real Estate Investment. Int J Inf Manage 56:102012. https://doi.org/10.1016/J.IJINFOMGT.2019.09.008
Kumar V, Singh VK, Gupta K, Jha AK (2021b) Integrating Cellular Automata and Agent-Based Modeling for Predicting Urban Growth: A Case of Dehradun City. Journal of the Indian Society of Remote Sensing 49(11):2779–2795. https://doi.org/10.1007/S12524-021-01418-2/TABLES/7
Kyushu University Public Relations (2021) ITO Campus Guidebook. Kyushu University Press, Fukuoka

Lafuerza LF, Dyson L, Edmonds B, McKane AJ (2016) Staged Models for Interdisciplinary Research. PLoS One 11(6):e0157261. https://doi.org/10.1371/JOURNAL.PONE.0157261
Larkham PJ (2000) Institutions and urban form: The example of universities. Urban morphology 4(2):63–78
Li F, Liang J, Clarke K, Li M, Liu Y, Huang Q (2015) Urban land growth in eastern China: a general analytical framework based on the role of urban micro-agents' adaptive behavior. Reg Environ Change 15(4):695–707. https://doi.org/10.1007/S10113-014-0665-1/FIGURES/4
Li F, Xie Z, Clarke KC, Li M, Chen H, Liang J, Chen Z (2019) An agent-based procedure with an embedded agent learning model for residential land growth simulation: The case study of Nanjing, China. Cities 88:155–165. https://doi.org/10.1016/J.CITIES.2018.10.008
Li J, Oyana TJ, Mukwaya PI (2016) An examination of historical and future land use changes in Uganda using change detection methods and agent-based modelling. African Geographical Review 35(3):247–271. https://doi.org/10.1080/19376812.2016.1189836
Li S, Park SH (2006) Determinants of Locations of Foreign Direct Investment in China. Management and Organization Review 2(1):95–119. https://doi.org/10.1111/J.1740-8784.2006.00030.X
Macal CM (2016) Everything you need to know about agent-based modelling and simulation. Journal of Simulation 10(2):144–156. https://doi.org/10.1057/JOS.2016.7/TABLES/2
Macintyre C (2003) New models of student housing and their impact on local communities. Journal of Higher Education Policy and Management 25(2):109–118. https://doi.org/10.1080/1360080032000122598
Mahtta R, Fragkias M, Güneralp B, Mahendra A, Reba M, Wentz EA, Seto KC (2022) Urban land expansion: the role of population and economic growth for 300+ cities. npj Urban Sustainability 2:5. https://doi.org/10.1038/s42949-022-00048-y
Malik A, Abdalla R (2017) Agent-based modelling for urban sprawl in the region of Waterloo, Ontario, Canada. Modeling Earth Systems and Environment 3(1):1–9. https://doi.org/10.1007/S40808-017-0271-6
McDonald JF (2013) Spatial Patterns of Business Land Values in Chicago. Urban Geograpahy 2(3):201–215. https://doi.org/10.2747/0272-3638.2.3.201
Misra D (2020) A path-dependent analysis of the effect of location on the development of new universities. High Educ 80:289–304. https://doi.org/10.1007/s10734-019-00480-7
Mohammed AMS, Ukai T (2021) The impact of university campuses on city urbanization: A syntactic and socio-spatial analysis of Kyushu University campuses in Japan. International Journal of Sustainable Development and Planning 16(7):1209–1220. https://doi.org/10.18280/ijsdp.160702
Mohammed AMS, Ukai T (2022) University campuses as agents for urban change. Environmental & Socio-economic Studies 10(1):22–37. https://doi.org/10.2478/environ-2022-0003
Mohammed AMS, Ukai T, Hall M (2022) Towards a sustainable campus-city relationship: A systematic review of the literature. Regional Sustainability 3(1):53–67. https://doi.org/10.1016/j.regsus.2022.03.004
Molotch H (1976) The city as a growth machine: Toward a political economy of place. American Journal of Sociology 82(2):309–332. https://doi.org/10.1086/226311
Moos M, Revington N, Wilkin T, Andrey J (2019) The knowledge economy city: Gentrification, studentification and youthification, and their connections to universities. Urban Studies 56(6):1075–1092. https://doi.org/10.1177/0042098017745235
Motieyan H, Mesgari MS (2018) An Agent-Based Modeling approach for sustainable urban planning from land use and public transit perspectives. Cities 81:91–100. https://doi.org/10.1016/J.CITIES.2018.03.018
Munro M, Turok I, Livingston M (2009) Students in cities: A preliminary analysis of their patterns and effects. Environment and Planning A: Economy and Space 41(8):1805–1825. https://doi.org/10.1068/A41133
Muslim MH, Karim HA, Abdullah IC, Ahmad P (2013) Students' perception of residential satisfaction in the level of off-campus environment. Procedia Soc Behav Sci 105:684–696. https://doi.org/10.1016/j.sbspro.2013.11.071
Nakazawa T (2017) Expanding the scope of studentification studies. Geogr Compass 11(1). https://doi.org/10.1111/gec3.12300
OSM Foundation (2020) OpenStreetMap. https://www.openstreetmap.org. Accessed 15 Nov 2021
O'Sullivan D (2008) Geographical information science: agent-based models. Progress in Human Geography 32(4):541–550. https://doi.org/10.1177/0309132507086879
Rugg J, Rhodes D, Jones A (2000) The nature and impact of student demand on housing markets. York Publishing Services, York
Selwyn N (2008) "High-jinks" and "minor mischief": A study of undergraduate students as perpetrators of crime. Studies in Higher Education 33(1):1–16. https://doi.org/10.1080/03075070701794759
Sengupta R, Sieber R (2007) Geospatial Agents, Agents Everywhere. Transactions in GIS 11(4):483–506. https://doi.org/10.1111/J.1467-9671.2007.01057.X
Smith D (2008) The Politics of Studentification and '(Un)balanced' Urban Populations: Lessons for Gentrification and Sustainable Communities? Urban Studies 45(12):2541–2564. https://doi.org/10.1177/0042098008097108

Valbuena D, Bregt AK, McAlpine C, Verburg PH, Seabrook L (2010a) An agent-based approach to explore the effect of voluntary mechanisms on land use change: A case in rural Queensland, Australia. J Environ Manage 91(12):2615–2625. https://doi.org/10.1016/J.JENVMAN.2010.07.041
Valbuena D, Verburg PH, Bregt AK, Ligtenberg A (2010b) An agent-based approach to model land-use change at a regional scale. Landsc Ecol 25(2):185–199. https://doi.org/10.1007/S10980-009-9380-6/FIGURES/9
van den Hoek J (2010) The mixed-use index as a planning tool for new towns in the 21st century. In: New Towns for the 21st Century: the Planned vs the Unplanned city. SUN architecture, pp 98–207
van Nes A, Berghauser M, Mashhoodi B (2012) Combination of Space syntax with spacematrix and the mixed use index: The Rotterdam South test case. In: Proceedings of 8th International Space Syntax Symposium. Santiago de Chile
van Nes A, Yamu C (2021) Introduction to space syntax in urban studies. Springer, Netherlands
van Nes A, Ye Y (2014) The theory of the natural urban transformation process: The relationship between street network configuration, density and degree of function mixture of built. In: Proceedings AESOP 2014: Annual Conference. Utrecht, The Netherlands
Vani M, Prasad PRC (2021) Modelling urban expansion of a south-east Asian city, India: comparison between SLEUTH and a hybrid CA model. Model Earth Syst Environ 8(1):1419–1431. https://doi.org/10.1007/S40808-021-01150-3
Visser G, Kisting D (2019) Studentification in Stellenbosch, South Africa. Urbani izziv 30:158–177
Wilensky U (1999) NetLogo Software. Center for Connected Learning and Computer-Based Modeling, Illinois
Wooldridge M (1997) Agent-based software engineering. IEE Proceedings: Software 144(1):26–37. https://doi.org/10.1049/IP-SEN:19971026
Xie Y, Fan S (2014) Multi-city sustainable regional urban growth simulation-MSRUGS: A case study along the mid-section of Silk Road of China. Stochastic Environmental Research and Risk Assessment 28(4):829–841. https://doi.org/10.1007/S00477-012-0680-Z/TABLES/4
Ye Y, van Nes A (2013) Measuring urban maturation processes in Dutch and Chinese new towns: Combining street network configuration with building density and degree of land use. The Journal of Space Syntax 4:18–37
Zhang H, Jin X, Wang L, Zhou Y, Shu B (2015) Multi-agent based modeling of spatiotemporal dynamical urban growth in developing countries: simulating future scenarios of Lianyungang city, China. Stochastic Environmental Research and Risk Assessment 29(1):63–78. https://doi.org/10.1007/S00477-014-0942-Z/FIGURES/7
Zhang W, Kockelman KM, Thill JC (2020) City land use and rent dynamics with location externalities and zoning regulations: A dynamic spatial general equilibrium model. In: Thill J-C (ed) Innovations in Urban and Regional Systems: Contributions from GIS&T, Spatial Analysis and Location Modeling. Springer, Netherlands, pp 185–212 https://doi.org/10.1007/978-3-030-43694-0_9