Review Article: Agent-based Modeling and Disaster Management

บทความปริทรรศน์: การสร้างแบบจำลองบนพื้นฐานพฤติกรรมผู้กระทำและการจัดการภัยพิบัติ

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Abstract

Social simulation is usually used to analyze issues in social science and to study behaviors of people in specific events. Unlike scientific experiments in other hard sciences, which can be tested in a closed environment or in a laboratory, social simulation applies computation methods to examine social phenomena.

In urban planning, understanding stakeholders—which include residents, businesses, factories, and local governments—is one of the important factorsin a successful project. In many cases, these stakeholders are heterogeneous individuals who may have different behaviors. Thus, to effectively solve issues in urban planning, planners need to understand stakeholders. Agent-based modeling (ABM) is widely used to analyze behaviors of stakeholders under implementation of urban policies, especially in the events of natural disasters, which are considered as complex systems. In these analyses, spatial structures of affected areason which stakeholders are located and interact are a crucial ground of ABM. Together with the development of geographic information systems (GIS), the database systems and analyses of ABM become more accurate and reliable, especially on phenomena with the complexity of spatial structures.

This review article explains the development and definition of ABM and introduces software and toolkits for building an agent-based model, as well as reviews articles and research that use ABM to analyze the issues in theoretical testing and urban planning. Schelling's Segregation and Hotelling's Law models are discussed as examples of theoretical testing while robbery and driving behavior models are selected as the implications of ABM in urban planning. This article also focuses on the use of ABM on natural disaster policies and management using case studies of Japan and the United Kingdom.

บทคัดย่อ

การจำลองสถานการณ์ทางสังคมศาสตร์ (Social Simulation) โดยใช้การคำนวณบนคอมพิวเตอร์ เป็นวิธีการที่นิยม ในการวิเคราะห์เหตุการณ์และพฤติกรรมของบุคคลในสถานการณ์ต่าง ๆ ซึ่งไม่สามารถทดลองได้จริงในสังคมเหมือนกับการ ทดลองทางวิทยาศาสตร์อื่น ๆ ที่สามารถกระทำในระบบปิดหรือในห้องทดลองทางวิทยาศาสตร์

ในการวางผังเมือง การทำความเข้าใจผู้มีส่วนได้ส่วนเสีย (Stakeholders) ซึ่งรวมถึง ผู้อยู่อาศัยในเมือง ธุรกิจ โรงงาน หน่วยงานของรัฐ และผู้วางนโยบาย เป็นองค์ประกอบที่สำคัญที่สุดในความสำเร็จของโครงการ ซึ่งผู้มีส่วนได้ส่วนเสียนี้มี ความเป็นปัจเจกบุคคลที่มีความต้องการและพฤติกรรมที่อาจจะแตกต่างกัน (Heterogeinity) ดังนั้น ในการวิเคราะห์ปัญหา ของเมืองจึงจำเป็นจะต้องทำความเข้าใจกับพฤติกรรมของผู้มีส่วนได้ส่วนเสียดังกล่าว อีกทั้งปฏิสัมพันธ์ของผู้มีส่วนได้ส่วน เสียในพื้นที่และเมืองนั้นมีความซับซ้อน (Complexity) ซึ่งแบบจำลองบนพื้นฐานพฤติกรรมผู้กระทำ (Agent-Based Modeling) นั้นสามารถนำมาใช้ในการวิเคราะห์พฤติกรรมของผู้มีส่วนได้ส่วนเสียจากนโยบายต่าง ๆ ของเมืองได้ โดยเฉพาะใน สถานการณ์ภายใต้ภัยพิบัติทางธรรมชาติ ซึ่งนับว่าเป็นระบบซับซ้อน (Complex System) อีกทั้งการพัฒนาของระบบ สารสนเทศภูมิศาสตร์ (Geographic Information Systems) ทำให้ระบบฐานข้อมูลและการวิเคราะห์โดยใช้แบบจำลองบน พื้นฐานพฤติกรรมผู้กระทำนั้นมีความถูกต้องและน่าเชื่อถือมากยิ่งขึ้น โดยเฉพาะกับปรากฏการณ์ทางสังคมที่เกิดขึ้นจาก การผสมผสานกับความซับซ้อนของระบบพื้นที่ (Spatial Structure)

บทความปริทรรศน์นี้อธิบายที่มาและลักษณะของแบบจำลองบนพื้นฐานพฤติกรรมผู้กระทำแนะนำโปรแกรม คอมพิวเตอร์สำหรับการสร้างแบบจำลอง รวมถึงการรวบรวมบทความและงานวิจัยที่นำแบบจำลองดังกล่าวมาใช้ในการ ทดสอบทฤษฎีทางสังคมศาสตร์ โดยแบบจำลองการแบ่งแยกของ Schelling และแบบจำลองกฎของ Hotelling ได้ถูกเลือก มาใช้ในการทดสอบทฤษฎี อีกทั้งแบบจำลองพฤติกรรมการโจรกรรมและพฤติกรรมการขับรถได้ถูกยกมาเป็นกรณีศึกษาใน การวิเคราะห์ปัญหาทางด้านการผังเมือง บทความนี้เน้นการใช้ประโยชน์ของแบบจำลองในการวางนโยบายภายใต้สถานการณ์ ภัยธรรมชาติและการจัดการภัยพิบัติ โดยใช้กรณีศึกษาจากประเทศญี่ปุ่นและสหราชอาณาจักร

Keywords (คำสำคัญ)

Agent-based Modeling (การสร้างแบบจำลองบนพื้นฐานพฤติกรรมผู้กระทำ)

Disaster Management (การจัดการภัยพิบัติ)

Geographic Information Systems (ระบบสารสนเทศภูมิศาสตร์)

Introduction

A model is a simplified representation of some aspect, events, and phenomena. It can be created as a physical or theoretical representation. For better understanding of the aspect, some details can be excluded from the model. One of the best examples of a model is a globe which can represent some aspect of the Earth, for instance, geography and political boundary.

In architecture, a model is usually referred to a physical representation of built environment—such as spaces, enclosures, and building envelopes—which allows architects and designers to materialize and communicate their thoughts and ideas. Likewise, in social science, a model is usually a theoretical framework of socio-economic processes defined by a set of parameters and variables as well as mathematical techniques. The model is simplified to illustrate complex processes of social activities.

Experiments in social science, including urban design and planning, are difficult to perform in closed environment or in a laboratory. Social modeling or social simulation is used as a tool to study social phenomena, where we might not be able to observe the outcome in real life, by applying computational methods, which are originated from physics and artificial intelligence. It can bridge the descriptive approach usually used in social science with the scientific experiment approach used in other hard sciences (Takahashi, Sallach & Rouchier, 2007). The topics that have been studied using social simulation include social norms, institutions, reputation, knowledge transmission, elections, economics, and urban planning.

The development of social simulation can be tracked back to a thought experiment of a physical self-replicating machine of von Neumann (1966). This idea of von Neumann was developed by Stanislaw Ulam as a collection of cells on a grid, which later was developed by von Neumann as cellular automata. Later in the 1970s, John Conway developed the *Game of Life,* a two-dimensional cellular automation which is operated by simple rules in a virtual world in the form of a checkerboard. The game was first publicized in Gardner (1970).

The idea of von Neuman'scellular automata had been introduced to a social model of biological agents by Craig Reynolds, a computer scientist. Social models were developed for large scale agent model by Joshua M. Epstein and Robert Axtell. Their model, Sugarscape, can be used to examine the dynamics of social phenomena such as migration, pollution, transmission of disease, evolution, marital status, and sexual reproduction (Epstein & Axtell, 1996).

Social simulation generally consists of social agents, interactions among agents, and effects of interactions. Broadly speaking, it can be categorized into four types: (1) system level simulation, (2) system level modeling, (3) agent-based simulation, and (4) agent-based modeling. While system level simulation studies a social phenomenon as a whole by using theoretical outlooks and information in order to predict what should happen to a society under some specific conditions, which are set by variables, system level modeling use a set of mathematical equations and computer programing for specifically prediction of social phenomena. Agent-based simulation aims to study interactions of artificial agents and translate the results of simulation into the outcomes of social phenomena. Agent-based modeling (ABM) is an experimental tool for theoretical research on complex social phenomena to understand behaviors of agents and their interactions under specific events. In this article, we will focus on the studies of ABM, especially on the complex system of natural disasters.

Introduction to Agent-Based Modeling

Agent-based modeling is a relatively new approach to examine complex systems that emerge through interactions among autonomous agents (Macaland North, 2010). By modeling the system from the ground-up (i.e., agent-by-agent and interaction-

by-interaction), patterns, structure, and behaviors can be observed. Agent-based models are used across a wide range of disciplines, including computer science, biology, sociology, and economics. The analysis of Complex Adaptive System (CAS), which is one of the applications of the agent-based modeling, focuses not only on behavior emerged from agents' interactions but also the agents' capability to adapt in response to their previous interactions.

A typical agent-based model consists of three basic components: agents, agent's relationship, and agent's environment. An agent is an autonomous, self-contained, and uniquely identifiable individual who may be adaptive, goal-directed, or heterogeneous (Tontisirin, 2013). The agent relationship specifies the neighborhood of an agent-based on its localized environment and the interaction mechanisms among agents, meaning that an agent interacts with the subset of all agents as oppose to the entire agents. For example, an agent may only interact with its neighbors located nearby in geographic environment or with its most socially-connected. The agent environment provides spatial context of agent's locations in relation to other agents. The environment can be represented in hypothetical two-dimensional space such as grids or cellular as well as in actual geographic representation such as Geographic Information Systems (GIS).

Software and Toolkits for Building an Agent-Based Model

In general, agent-based models can be built on programming languages or on specific ABM software and toolkits. ABM can be done on a laptop, desktop, or in large-scale computing clusters depending on a size of ABM. Following are examples of software that can used to build an agent-based model (Macal & North, 2009):

- Dedicated Agent-based Prototyping Environments: NetLogo, Repast Simphony, StarLogo

- General Computational Mathematics Systems: Mathematica, MATLAB
- General Programming Languages: C++, Java, Python
- Spreadsheets: Microsoft Excel using Visual Basic Application (VBA)
- Large-scale Computing Environment: AnyLogic, MASON, Repast, Swarm

As discussed earlier, agent-based modeling has been applied in a wide range of studies in social science. Following are selected examples of ABM that highlight its application in social science studies.

ABM Application on Theoretical Testing

Schelling's Segregation Model

One of the prominent examples of ABM explaining urban planning issues is the neighborhood segregation model of Tom Schelling, one of the Laureate in 2005 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel. This initial attempt of ABM application show that residents with different races choose to live in the grid spatial structure. He shows that a neighbor prefers to live near people with the same color or have a mixture "up to some limit", and this phenomenon of complete local separation of distinct groups could lead to total segregation (Schelling, 1972).

Wilensky (1997) presents the Schelling's segregation model in NetLogo software (Wilensky, 1999), a multi-agent programmable modeling environment. Figure 1 illustrates the segregation pattern of neighborhood with residents of two different races, shown in green and red colors. The initial state of the model represents random locations of residents in the neighborhood, shown in Figure 1 (A). After a period of time, residents can choose to move to live near people of the same race or different race, depending on their individual preferences defined by a certain parameter. At the equilibrium, the pattern of segregation is shown in Figure 1 (B). Results of the Schelling's modelhas been regarded as a strong
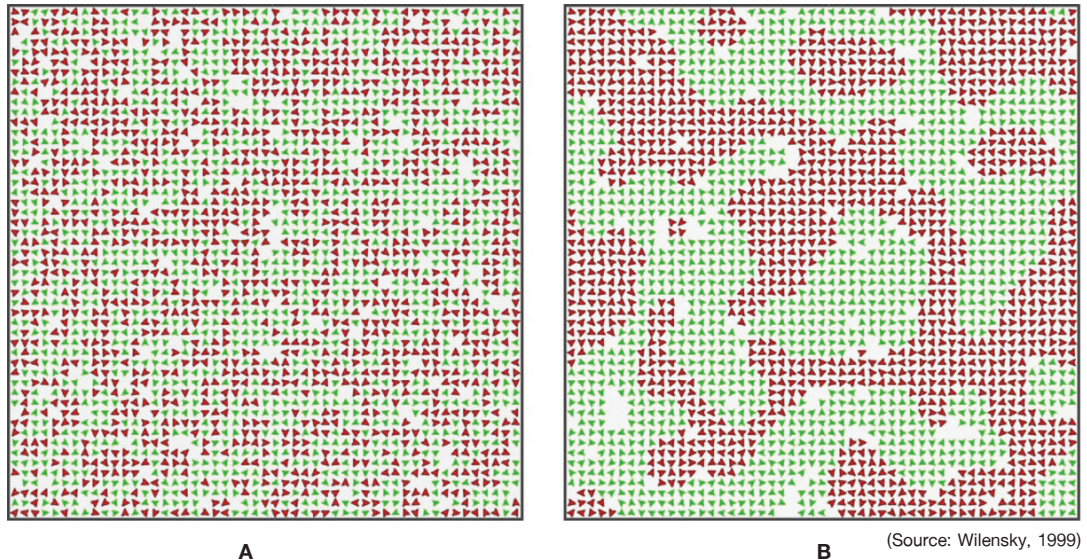
A **B**

Figure 1. Schelling Model at the initial stage (A) and after equilibrium has been reached (B), with the parameter of percent-similar-wanted 50%.

evidence that, regardless of their initial locations of residence, people more incline to live closer to others with certain similar characteristics—a race in this example.

Hotelling's Law Model

Another widely known ABM in social science is the Hotelling's Law model developed in NetLogo by Ottino et al. (2009). Hotelling (1929) studies the optimal placement of storesand pricing of their goods in order to maximize profits. In this model, Ottino et al. (2009) apply this idea of Hotelling's Law by allowing the movement of stores into a two-dimension plane, instead of a single dimension in Hotelling's original study. In addition to movement, stores in this model can change their prices to draw customers, who are spread equally in the plane and always choose to go to the nearest shop if the prices of goods are exactly the same because products and quality are not different.

In this model, in order to maximize profit, each store moves location and changes the price of goods several times to gain larger market. A decision is made without any knowledge of strategies of the competitors. On the other hand, each customer considers the price and distance from each store, and prefers to go to the store that offers the lowest sum. Figure 2 illustrates the before and after stores' movement and price adjustment under Hotelling's Law. In each figure, there is a map showing locations and market areas of three stores, and three graphs showing (1) price of goods at each store (top panel), (2) market areas of each store (middle panel), and (3) revenue of each store (low panel). The initial state of the model represents random locations of three stores in the neighborhood, shown in Figure 2 (A). In every period of time, each store makes a decision to move and adjust the price of goods. As shown in Figure 2 (B), after a certain period of time, stores adjust their prices to compete for customers. One store's best interest (violet store) is to locate far away from other stores (red and blue stores) so it faces less competition from others.
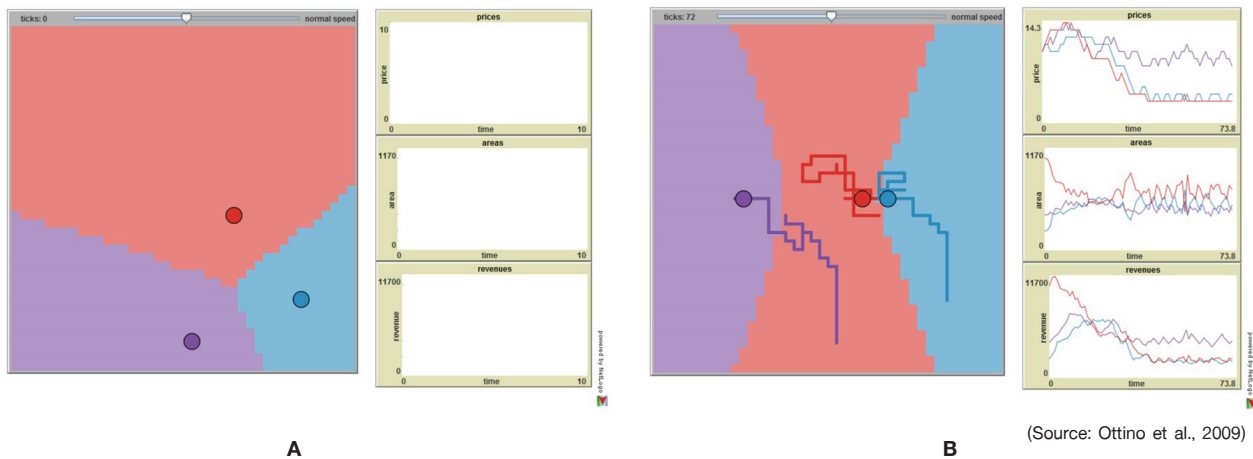
A

B

Figure 2. Hotelling's Law Model at the start (A) and after tick 72 (B).

ABM Application on Urban Planning

Repast Simphony Virtual City Model

This example is the application of ABM on studying behavior of burglary in a part of a city. The model is built on Repast Simphony software developed by Malleson (2011). It consists of agents (burglars), city context (houses and roads), and agent's behavior (burglars' decision to travel and to commit burglary into a random house). The model also examines the role of road network on patterns of burglary. The geographic information systems (GIS) data of the part of the city of York in the UK is used as the city context. This simple model shows that the road closures affect the pattern of burglary in the suburb and the city center of York. Figure 3 illustrates the Kernel Density Algorithm maps of the burglary rates before and after the road closures. This study is one of the first few attempts that integrate GIS spaces in a simulation to represent actual physical context in an agent-based model.
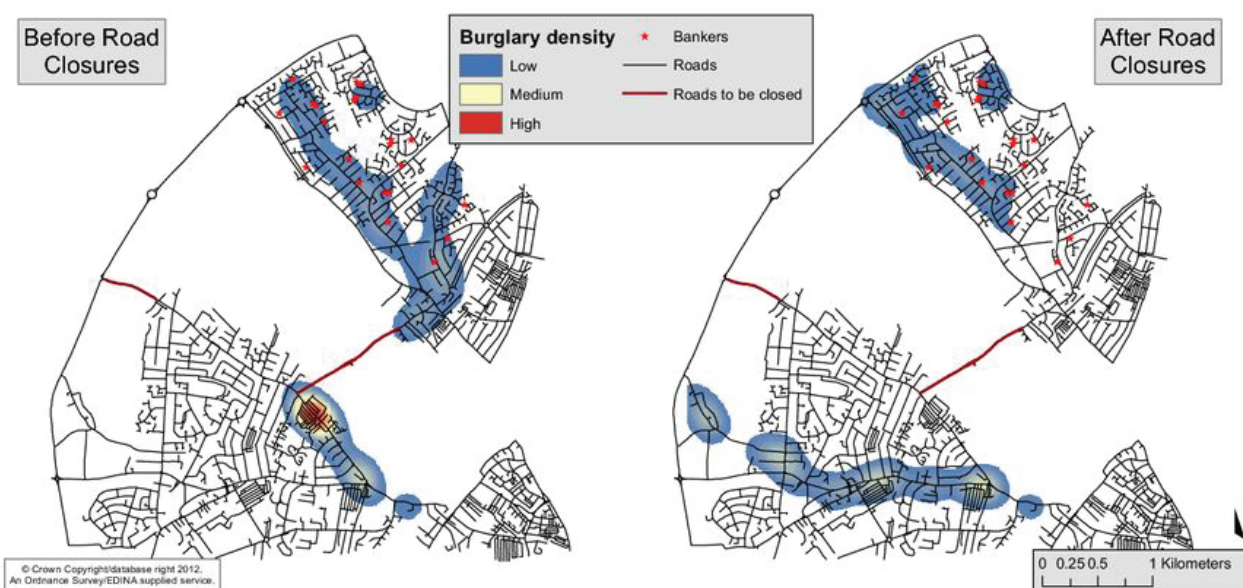
Figure 3. Repast Simphony Virtual City before road closures (A) and after road closures (B).

Evolutionary Prisoner's Dilemma of Motorists Model

In the case of ABM application on the context of urban planning in Thailand, Tontisirin (2013) develops the conceptual framework of evolutionary prisoner's dilemma (EPD), based on the RepastCity model, to examine road users' behaviors in the setting of roads in Bangkok city center. Prisoner's dilemma is one of the classic examples in game theory. It is a phenomenon when two individuals pursue their own interests can lead to a worse off outcome for them. EPD introduces a time dimension to prisoner's dilemma. Thus, two individuals can adjust their interaction strategies. Using micro-behavioral foundation simulation and the extension of the evolution of an n-person prisoner's dilemma within an actual geographical space, this model is the integration of ABM and GIS. It is one of the few attempts to contextualize an evolutionary prisoner's dilemma.

In the EPD framework, the model is assumed that all motorists (players) are rational and know perfectly the values of one's payoff matrix as well as each other's. There are four strategies: always cooperating (ALLC), Tit-for-Tat (TFT), Anti-Tit-for-Tat (ATFT), and always defecting (ALLD). In this model, ALLC motorist is a person who follows traffic rules and regulations. On the other hand, ALLD is a person who violates traffic rules and regulations. TFT is a person who cooperates in the first move and then does whatever the opponent does in the last encounter. ATFT is the opposite of TFT. Figure 4 illustrates the simulation interface at time 0 and 50. As shown in Figure 4 (A), four types of motorists start to travel in the city center of Bangkok at tick 0. Figure 4(B) shows that ALLD is the dominant strategy of the motorists.

Figure 5 illustrates average travel time for each initial condition, ALLC, ALLD, and mixed strategies. It shows that a condition with all ALLD agents overall has the highest average travel time. The result presents that motorists in Bangkok violate traffic regulations because of the belief that doing so save travel times. Paradoxically, if enough motorists share the belief the traffic is even more congested. Congestion, thus, emerges as a result of strategic time-saving behavior.

Disaster Management

Disaster Management as a complex system

Complex system is defined as "those [systems composed] of a set of heterogeneous agents whose
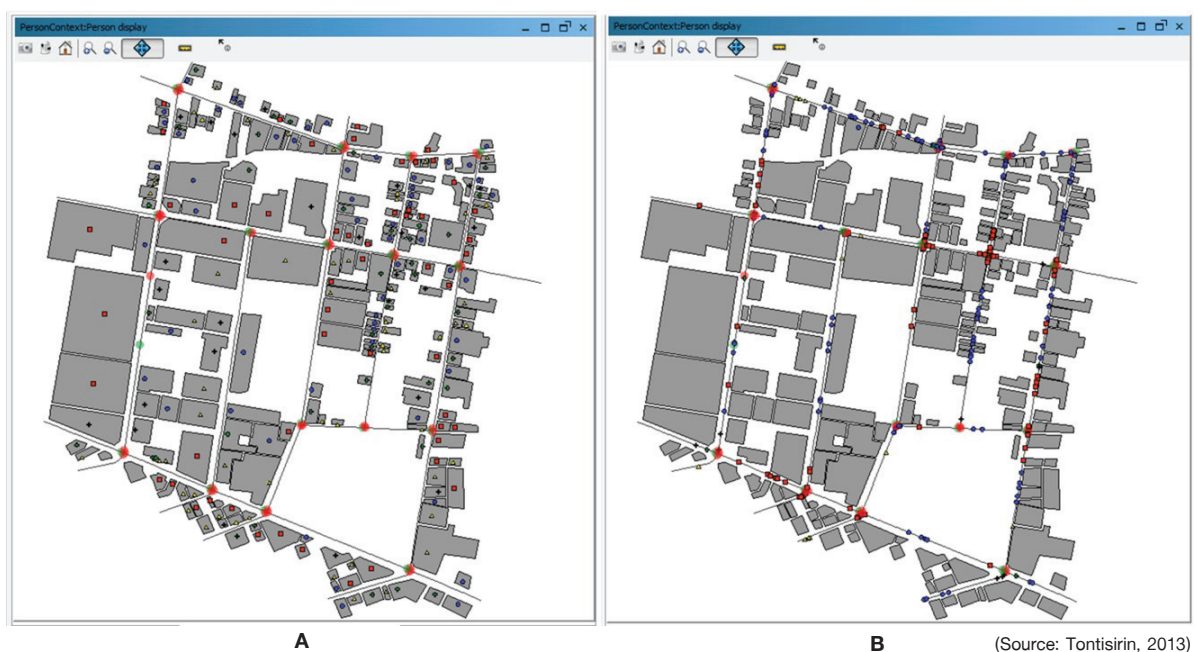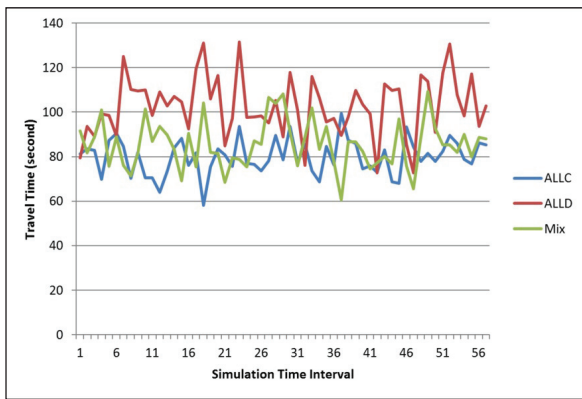

| A | B | (Source: Tontisirin, 2013) |

Figure 4. Simulation interface of motorists' behaviors at tick 0 (A) and 50 (B).

(Source: Tontisirin, 2013)

Figure 5. Average travel time with three different initial conditions.

behavior is interdependent and may be described as a stochastic process" (Durlauf, 2005). Disaster management—in terms of immediate response to disaster and recovery operations—is a dynamic process that changes not only spatially but also temporally. The immediate responses, such as rescue missions to save lives and help disaster victims, are urgently needed right after a disaster. Recovery operations, on the other hand, require a rather long-term planning process that involves issues of housing, unemployment, business operations, and other assistance. As a result, different needs should be met at different points in time of disaster management, which can be described in four different phases: mitigation, preparedness, response, and recovery (Comfort et al., 2004). In addition, parties involved in disaster are often heterogeneous, both in terms of characteristics and needs. Thus, their ability to cope with the disaster varies and should be taken in disaster policy analysis. As such, disaster management should be considered as a complex system, and an effective analytical method for disaster management should be able to handle such complexity. One particular approach to policy analysis for disaster management is to use a computational simulation technique such as an agent-based modeling, which can explain complexity of spatial phenomena of natural disaster via "behaviorally informed instruments" (Mansury, 2013).

## ABM Application on Disaster Management

Agent-based Flood Evacuation Simulation of Life-threatening Conditions Using Vitae System Model

Liu et al. (2009) study the effectiveness and limitation of the Vitae System (VS) model in the life-threatening situation. The VS model is a new conceptual framework for integrated disaster management fundamentals—survivability, vitality, and communication (Okada, 2006). It is a systematic logic to interpret an evacuation decision-making in a critical situation where people have to survive first, maintain vitality, and then communicate with other people to determine self-help and mutual aid.

This study presents a new approach to evaluate the evacuation from a flood incident for the case study of the Oike underground space in Kyoto, Japan. The model combines a hydrodynamic simulation with an agent-based model of evacuation decision-making and the facility management. Figure 6 illustrates the overview structure of the evacuation simulation system in the critical situation used in this study.

The Oike underground space—a shopping mall, a subway station concourse and platform, and parking lots—has three underground floors, located near the Kamo River. It is likely that the 100-year flood may occur in the Kamo River basin, and the underground space can be overflown by the flood. The hydrodynamic simulation shows that the water depth can rise very quickly. The inundation of the underground space may take only 15 to 20 minutes. The underground space is likely to be submerged after 21 minutes. The simulation interface and the floor plans of Oike underground space are shown in Figure 7.

The simulation represents the results of three scenarios: (1) evacuation in a standard arrangement near a staircase, (2) in the left corner arrangement which is far from the staircases, and (3) in the scattered set in the lowest basement B3F. Figure 8 shows that the enduring time for the standard arrangement and scattered set are almost the same. The enduring time of the left corner setting, however, is shorter
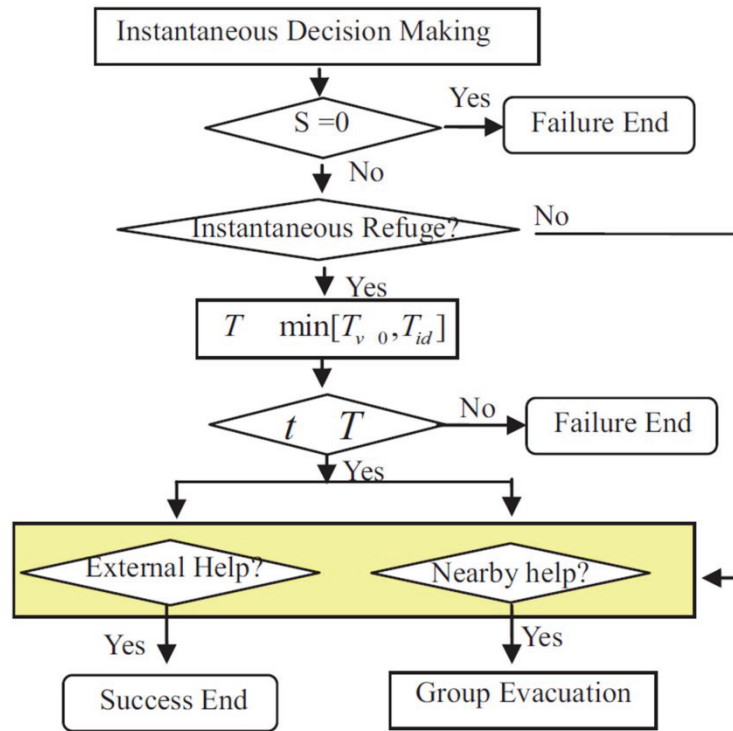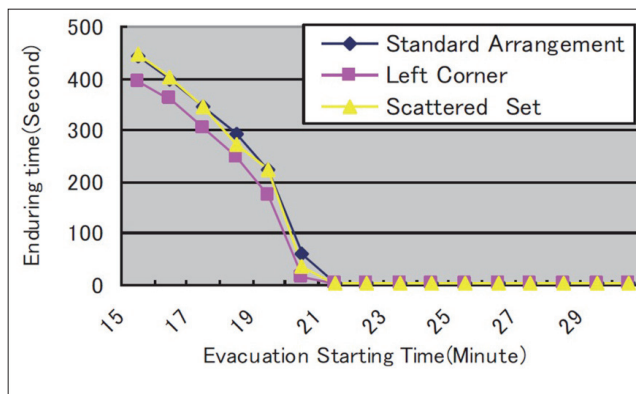
(Source: Liu et al., 2009)

Figure 6. Structure of the model for evacuation in critical situation.
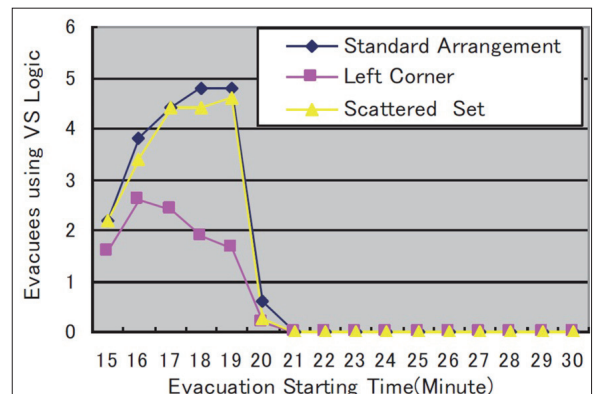

(Source: Liu et al., 2009)

Figure 7. Floor plans of Oike underground space and the interface of Vitae System based evacuation simulation system.

(Source: Liu et al., 2009)

Figure 8. Simulation results for enduring time.


(Source: Liu et al., 2009)

Figure 9. Simulation results for evacuation with Vitae System logic.

because of the distance to staircases. The simulation of evacuation strategy under VS logic assumes that people evacuate in an adaptive way. As shown in Figure 9, the enduring times of all scenarios increase, which means that more people take adaptive action in the evacuation.

### *An Agent-Based Model for Risk-Based Flood Incident Management*

This example is the application of ABM on flood incident management using the case study of the coastal town of Towyn, UK by Dawson et al. (2011). This study presents a novel approach to evaluate flood event management. The model combines a hydrodynamic simulation with an agent-based model of interaction of people, the flood emergency plans, and the appraisal of flood incident management. It simulates the operations and interactions of multiple agents with macro level system behavior emerging form of interactions of each agents and the environment. Figure 10 illustrates the overview structure of the risk analysis system for flood incident management used in this study.

The result of the case study show the effectiveness of flood event management measures such as flood warning and the location of evacuation shelters, which can be used to quantify the impact of flood defense failure on the residents of Towyn. Figure 11 illustrates the histogram of number of agents exposed to flood where for half of agents were given a flood warning and acted on immediately at approximately an hour before the flood defense failed and where for the other half did not received the warning. The result
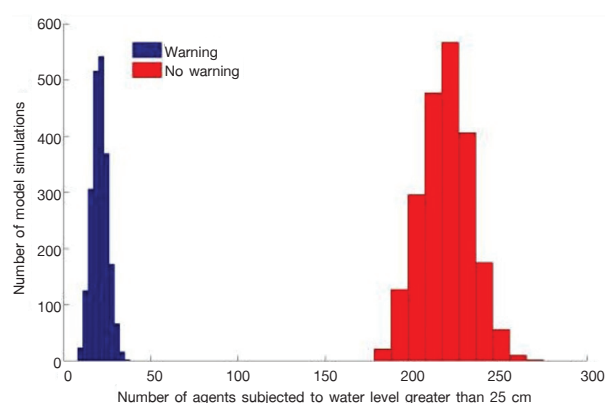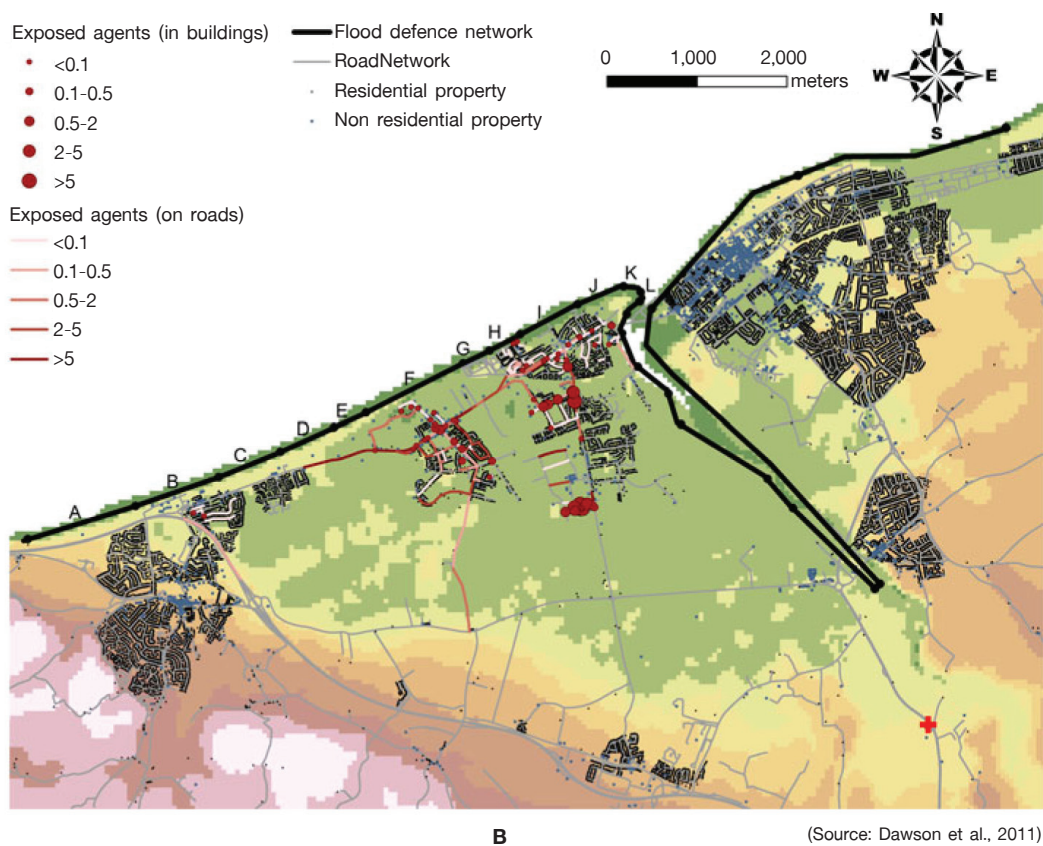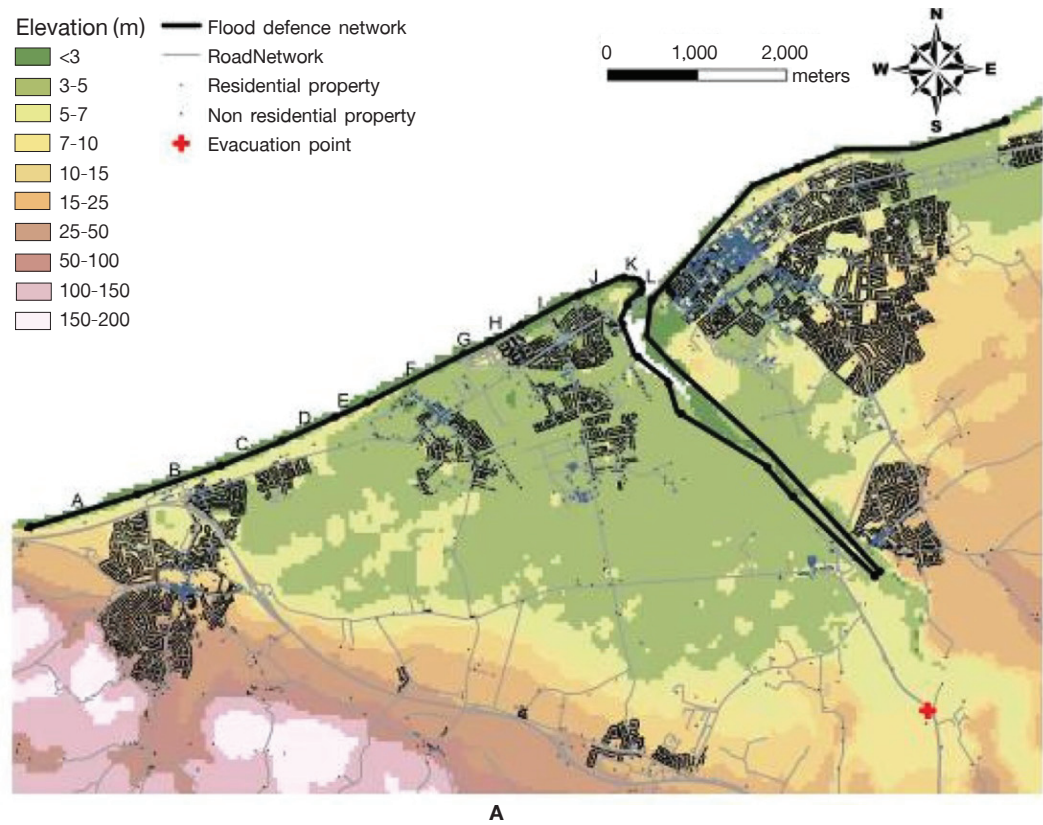

(Source: Dawson et al., 2011)

Figure 11. Histogram of number of agents exposed to flood where for half of agents received a flood warning and where for the other half did not.
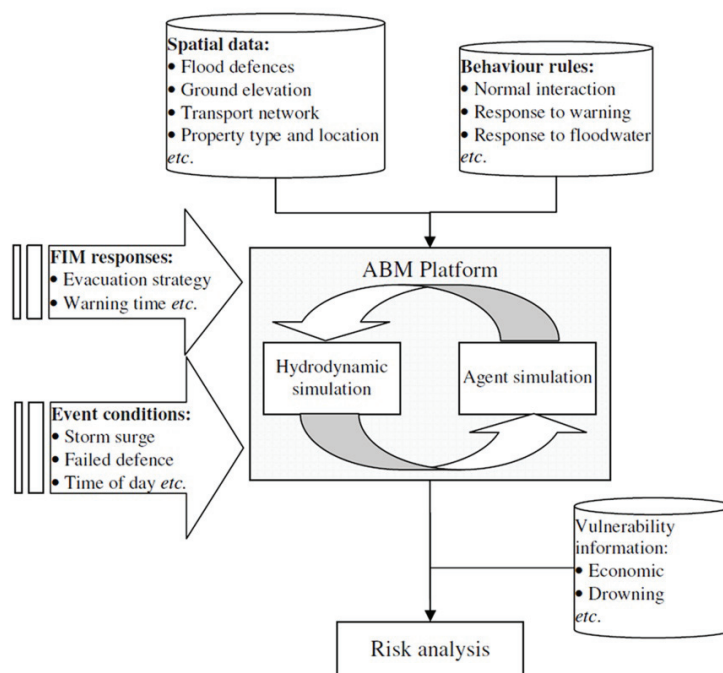
(Source: Dawson et al., 2011)

Figure 10. Structure of the risk analysis system for flood management.

Figure 12. Map of Towyn in the UK, flood defense network, topography, road network, and the locations of residential properties and the evacuation shelter (A); the location of road network, and number of agents exposed to flood when the flood defense fails (B).

shows that the effectiveness of flood warning and immediate action is necessary for the flood management in the study area. In addition, the results can be used in policy analysis such as the increase of flood frequency, flood protection infrastructure investment, and land use planning. The methodology used in this study is ready to apply to analyze the flood management policy where spatial and demographic data sets are available, especially in the UK.

Figure 12 (A) shows the flood defense network, topography, road network, and the locations of residential properties and the evacuation shelter in the town of Towyn. Figure 12 (B) presents the results of simulation of the event when the failure of flood defense occurs. It shows how many people in buildings and on roads are affected by the flood.

Conclusions

The applications of ABM have been widely usedin studies in social science. Several theories and thought experiments has been tested in ABM. Wilensky (1997) tests dynamic models of segregation (Schelling, 1972) in the framework of ABM. Ottino et al. (2009) builds a simple agent-based model to test Hotelling's Law (1929) on how stores find the optimal placement and adjusting prices of goods to maximize their profits. In urban planning, ABM has been used to analyze social dynamic in a city and region. Malleson (2011) studies the impact of road network on burglary behavior using a simple agent-based model. Tontisirin (2013) combines ABM, GIS, and the framework of evolutionary prisoner's dilemma to study the behaviors of motorists in Bangkok. In the complex system of disaster management, the integration of ABM and other analytic methods are applied to examine the dynamic of social phenomena under the critical situations of disasters. The combination of a hydrodynamic model and an agent-based model sheds the light on the social phenomena and related policies of flood incidents for a micro-scale, such as an enclosed space or a building, as shown

in Liu et al. (2009) as well as for the city-and regional-scale as shown in Dawson et al. (2011).

The advantage of agent-based modelling is an ability to represent important information about social phenomena not easily to capture with other traditional modeling. Agent-based models can examine the heterogeneous behavior of agents with different information, rules, and environment to the macro behavior of the overall system (Lampert, 2002). In the case of disasters where the future is unpredictable, decision and policy makers do not rely on forecasts. Thus, ABM becomes an increasingly powerful tool for policy makers because it can give robust solutions from multi-scenario simulation scenarios and adaptive policies.

Although ABM is a powerful tool for simulating social dynamics and policy analyses, many challenges of using ABM remain in social science studies, in particular on modeling complex systems. These challenges are thoroughly discussed in Donaghy (2009). As ABM allows policy makers to simulate social systems under several counterfactual scenarios to test implications of certain policies, one important question arises as what "stylized facts" or "empirical regularities" are to be explained in the model (Donaghy, 2009). Firstly, if there are uncountable scenarios possible, one should ask which scenario(s) are to be chosen and simulated. Secondly, structural relationship of agents should be identified, rather than simply mimicking passing phenomena. Third, a model should be validated through fair comparisons of competing explanations of such social phenomena. Finally, one should maintain the integrity of ABM model builders and keep in mind the goal of ABM simulation, being objective rather than subjective. As the late Walter Isard, the founding father of regional science, concerned, ABM is "much more flexible than rigorous but restrictive axiom-theorem-proof approach." It has "too many degrees of Freedom", which can be used to manipulate the model like cooking by "adding more ingredients until we get what we want" (Mansury, 2013).

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