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Multi-agent based simulation for household solid waste recycling behavior

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ABSTRACT

The urban household solid waste (HSW) classification and recycling system is a complex adaptive system (CAS), containing multiple agents and the behaviors between them are interactive. In order to figure out which is the most effective waste management policy for the HSW classification and recycling, this study tried to establish a simulation model combining multi-agent based simulation (MABS) techniques with a social survey questionnaire. The model can simulate the behavior change of the agents in the system under different policy scenarios. Then the proposed model is utilized in Suzhou city in eastern China. The system contains three main agents: (1) the resident agents that generate the HSW, (2) the recycling site and scavenger agents that collect the recyclable materials (paper, metal, plastics and etc.) in the household garbage, (3) the agents in the sanitation department (incineration power plants and landfills) that is responsible for the municipal solid waste collection and terminal garbage disposal. In addition, three waste charge policy scenarios are set and relevant simulation experiments are carried out. The results show that the specific charge policy can improve the performance of residents' separation behavior, which is a more effective way to reduce the HSW and increase the collection rate of domestic recyclable resources (DRR). And there exists certain benefit conflicts between the environmental sanitation agent and the DRR recycling agent at the present stage in Suzhou city. To resolve the issue of the urban HSW management in China, it is necessary to balance the profit of charge point of agents in the system. In addition, it needs to combine the municipal garbage collection network and the renewable resource recycling network together.

1. Introduction

1.1. Research background

Urban household solid waste (HSW) management is one of the enormous challenges around the world. Especially China and most of other developing countries have been experiencing high-speed urbanization and industrialization, which leads to too much consumption of resources and rapid growth of urban solid waste (Mo et al., 2009; Meng et al., 2015; Dong et al., 2016). Waste sorting and resource recycling are considered to be the most efficient ways to solve the problem of "waste city" (Tong and Tao, 2016; Dong et al., 2013).

Since problems of municipal solid waste are getting more serious, the Chinese government has currently made great efforts in the municipal solid waste management (MSWM), especially towards the urban household solid waste (HSW). Eight cities (i.e., Beijing, Shanghai, Guangzhou, Shenzhen, Hangzhou) have participated in the HSW source separation pilot program launched by the Ministry of Construction (MC) since 2000, and 26 cities was chosen as national HSW classification pilots by five ministries (Ministry of Housing and Urban-Rural Development, etc.) in 2015. But the program remains largely ineffective (Deng et al., 2013).

The statistical data show that the amount of MSW clean-up in Chinese urban areas reached 179 million tons, and the amount of urban renewable resources recycling run up to 245 million tons. Among them, there were 60 million tons of domestic recyclable resources (DRR). In China, the DRR are the recycled parts of the valuable materials in the household garbage, which mainly include

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paper, metal, plastic and fabrics (Fei et al., 2016). The recovery rate of DRR was near 25%, which was far lower than that in developed countries (Matsumoto, 2011). Moreover, there is a prodigious disjunction between the construction of HSW source separation system and renewable resources recycling system in the current MSW management in China.

On September 21st, 2015, the Central Committee of CPC (Communist Party of China) and State Council (2015) have announced the *Overall Plan for the Reform of Eco-civilization System*. The plan has stressed the importance and indispensability of waste recycling industry and renewable resources industry and proposed that China would accelerate the establishment of a mandatory HSW classification system and renewable resources recycling directory. Then, on March 17th, 2016, "*The Thirteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China*" was announced. The plan has put forward the primary tasks for the urban solid waste management with the aim to improve the recycle network of renewable resources and strengthen the connection of HSW separation and DRR recovery during the period of the thirteenth five-year.

Therefore, all the above analysis has indicated that it is extremely practical significant to simulate the HSW separation and DRR recovery system and study the evolvement mechanism of the system for the decision making.

1.2. Review of the previous research

There has been some research on the mechanism of recycling behavior (Boonrod et al., 2015). The previous studies have found that main factors influencing the behavior of separating waste and participation namely: (1) knowledge and perception (i.e., environmental awareness and recycling knowledge) (KarimGhani et al., 2013); (2) opportunity costs, such as time costs, distance to recycling facilities (Matsumoto, 2014); (3) economic and policy incentives, such as financial rewards, reward vouchers, laws, regulations and etc. (Timlet and Williams, 2008); (4) social norms such as neighborhoods, publicity and education from the radio and television and signs on buses (Chu et al., 2013).

For the investigation on the cause-effect relationships, there are some commonly used methods such as Fuzzy Cognitive Map (Iakovidis and Papageorgiou, 2011; Kannappan et al., 2011), decision-making trial and evaluation laboratory (DEMATEL) (Ren and Benjamin, 2014; Liang et al., 2016; Ren et al., 2013), and etc. These methods can identify the critical factors and support the decision-makers/stakeholders in the selection of best scenario. However, it is a pity that these studies can neither reflect the dynamic information of space and time in the complex system nor quantitatively predict the performance of the policy implementation.

In this study, the HSW separation and recyclable material collection system is considered as a complex adaptive system (CAS). The theory of CAS was first proposed by Holland in 1995 and the members of the system were considered to have the properties of autonomy, activity, adaptability, communication and reactivity (Holland, 1995). The basis of CAS theory can be generalized that agents' adaptability brings up complexity. In this study, the HSW sorting and recyclable resources collection system is considered as a complex adaptive system (CAS), which is complicated, dynamic and open and contains different elements such as waste disposal management, economics, society and their interplay. Therefore, as a typical complex system, it contains multiple active agents and each agent's behavior will influence others' in the system.

The structure of this complex system is sophisticated and contains a large number of interacting components and frequent interaction process. Therefore, it is difficult to study it well using the traditional analytical method, such as numerical methods or other formula and semi-formula approaches. Recent research has demonstrated that the simulation method is the most effective solution (Green, 2009). And the classic simulation techniques include system dynamics (SD), agent-based modeling (ABM), discrete event simulation (DES), and etc.

SD is a methodology used to model and simulate the complex system. And it represents a system in the form of stocks, flows, time delays, variables and feedback loops (Reddi et al., 2013; Forrester, 1961; Mashayekhi, 1993). Karavezyris et al. (2002) presented a model of waste management systems using the SD to forecast the influence of environmental behavior of the households, and combined fuzzy logic to enhance confidence in the validity of the model. Ulli-Beer (2003) developed a SD model of recycling dynamics in a typical Swiss locality to simulate the interactions between citizen choices and preferences and public policy initiatives. The author emphasized the importance of both individual behavior and the environment. In addition, some scholars (Dyson and Chang, 2005; Antmann et al., 2013; Talyan et al., 2007) used the SD modeling to forecast municipal solid waste generation in a fast-growing urban region to quantitatively evaluate the importance of MSW management. In general, these SD models above have been very mature in forecasting the municipal solid waste management. However, there are some limitations of this modeling technology. For example, the key elements of the simulation system should be defined and quantified as variables, and their influences have to be formulated mathematically (Zhao et al., 2011). But not all the interactions in the complex system can be presented by formulations directly or indirectly.

Agent-based modeling and simulation (ABMS) is a creative method to modeling systems composed of autonomous, interacting agents (Axelrod, 1997; Epstein, 1996). It is generally acknowledged that ABMS is the most significant and prospective technique for exploring dependencies among stakeholders involved in the complex system. This is because ABMS can connect the decision-making agents in microcosmic level together with the macroscopic phenomena of the system, which can help people to study the microscopic mechanism behind the macroscopic phenomena of the complex adaptive system (Wooldridge et al., 2000). ABMS approach and CAS theory have been successfully used in such fields, like United States power market and decision (Vladimir and Koritarov, 2004), economic and social systems (Farmer and Foley, 2009), supply chain research (Ioannis and Athanasiadis, 2005), river basin water resources allocation, carbon emissions trading (Liu, 2013; Li et al., 2014) and assessment of bioenergy systems (Bichraoui-Draper et al., 2015). To date, there are very few reports on comprehensive municipal solid waste management and urban renewable resources recycling system using the agent-based model. An agent-based simulation framework for collaborative decision making of an effective planning for single-stream recycling (SSR) programs was developed in Florida, and it is used by stakeholders for the evaluation of several "what-if" scenarios in their system before reaching a conclusion and making a decision (Shi et al., 2014).

In general, the complexity of urban solid waste management systems has become a controversial issue, but the research on agents' behavior of urban HSW separation and recycling system is limited, and the multi-agent based simulation model for this system is seldom reported in literature. In this paper, we have developed a multi-agent based model to simulate the policy impacts on the waste disposal behavior of three agents including residents, environmental sanitation department and DRR recycling sites. The goal of the model is to provide the decision makers a perspective of the overall HSW recycling and disposal system performance, especially the performance of each individual agent. We develop three policy scenarios: (1) BAU Scenario—Ration charge for the household waste; (2) Simulation Scenario S_1—Specific charge

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