An agent based environmental impact assessment of building demolition waste management: conventional versus green management

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Abstract: Waste materials generated from building demolition have become a great challenge to sustainable urban development due to its consumption of the limited landfill spaces, water pollution, energy consumption and harmful gas emissions. Proper management of demolition waste (DW) is a complex process and requires systematic thinking and analysis. Many methods have been proposed to study the environmental impact assessment of demolition waste management (DWM). However, it is found that the currently available studies pay little attention from the perspective of complex adaptive system (CAS) to consider the attitude and interaction of the heterogeneous stakeholders as well as the importance of green DWM which has a great influence on the effectiveness of DW management. The aim of this research is to simulate and explore how the change of attitude and the dynamic interaction among heterogeneous stakeholders can influence the environmental performance of DWM. To achieve this aim, a model for evaluating the environmental impact of DWM was developed by using an agent-based modeling (ABM) approach. The main factors considered in the model are the ratio of green deconstruction (i.e., building deconstruction) managers vs. conventional demolition (i.e. building destruction) managers, the ratio of green design managers (i.e. design for deconstruction) vs. conventional design managers, and the interaction behavior of heterogeneous stakeholders following the herd theory. In the model, the environmental impact assessment was quantified into four categories i.e. land resources, water resources, air resource and energy resources. The proposed model is demonstrated by using the data drawn from the Chinese construction industry. The results reveal that if the deconstruction method and the deconstruction oriented design are widely adopted by architects and engineers, the negative environmental impacts generated by DW can be reduced by at least 50%. Furthermore, the results provide valuable information for government departments to make decisions on how to improve environmental performance of DWM.

Keywords: demolition waste, demolition waste management, agent-based modeling, environmental impact assessment, deconstruction

1. Introduction

It is widely acknowledged that construction industries around the world not only consume a large amount of natural resources and energy, approximately reaching 40% of total consumption, but also generate huge construction and demolition (C&D) waste. Taking China as an example, with the acceleration of urbanization and urban renewal, C&D waste has become a major source of urban solid waste and accounts for 30-40% of the total municipal solid waste in China (Ding, 2015; Lu and Yuan, 2010; Tam, 2016). According to government statistics, the amount of C&D waste is still in rapid growth and is becoming the largest waste streams estimated to reach 90% of municipal solid waste in the near

future (Yuan and Shen, 2011). Moreover, 90% of the C&D waste was generated from the building demolition and the quantity of demolition waste (DW) is up to 200 million tones each year in China (Wang et al., 2014). Furthermore, demolition activities often produce more than 39 times as much waste materials per square meter as construction activities (Wang, 2012). Therefore, building demolition has become an important source of C&D waste and has received increasing attention from both practitioners and researchers worldwide.

Faced with the substantial amount of DW, significant efforts have been made to their management over the last two decades. However, until now, only less than 10% of DW was reused or recycled and the rest is simply landfilled or dumped illegally (Wu, 2016). It is widely recognized that the demolition activities bring significant adverse impacts to the natural environment. First, the landfilled and dumped DW occupy lots of land spaces and reduce the soil fertility (Yuan, 2013; Zhang et al., 2012). According to the official statistics, approximately 6000 m³ of land spaces are needed to landfill 10,000 tons of DW. Second, the illegal dumping may bring the potential risk to the groundwater and surface water due to the DW leachate (Delay et al., 2007; Yuan et al., 2011). Third, the demolition activities incur a waste of huge building materials since many of them still have high residual value but remain unrecycled, and this also increases the energy consumption for transportation and landfilling (Marzouk and Azab, 2014). Fourth, the transport and disposal machinery used in the demolition process may bring negative effects to the air such as dust and gas emission, noise pollution (Bravo et al., 2015). Therefore, the large amount of DW imposes a serious pressure on the urban and regional sustainable development and demolition waste management (DWM) becomes an urgent issue.

It is a global hot topic deserving comprehensive exploration on how to accurately assess the environmental impact of DWM. Based on a review of the literature, it is found that the major evaluation approaches include environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle assessment (LCA), system dynamics (SD) and mixed assessment method. EIA is an environmental management tool aiming at encouraging more environment friendly protection from planning and decision-making to the ultimate implementation (Mondal et al., 2010). EIA is a procedure oriented method. For instance, to assess EIA of the Russeifa landfill, seven steps were followed, namely, screening program, scope, assessment, mitigation measures, monitoring, reporting and reviewing (El-Naqa, 2005). Normally, EIA is used to evaluate and compare environmental impacts of different DWM alternatives or scenarios so that the most promising program could be identified (Ortiz et al., 2010; Trankler, 1996).

SEA is described as a systematic process of evaluating the environmental consequence of proposed policies, plans or program initiatives in order to ensure that it is appropriately addressed at the earliest stage of the decision-making process on a par with economic and social considerations (Josimovic et al., 2015; Partidário, 1996). Therefore, SEA has become an instrument to implement sustainable development strategies in planning, which can be used not only in sectoral planning but also in other areas such as waste management planning. For example, SEA was adopted to develop a regional waste management plan in an Austrian case study (Salhofer et al., 2007), identify the potential problems of DWM in Kuwait to the environment (Kartam et al., 2004) and design waste management alternatives in Ireland (Desmond, 2009).

LCA is a popular tool for analyzing the sustainability of DWM and has gained tremendous benefits to develop environmentally sound DWM strategies in the past few years (Buratti et al., 2015; Yay, 2015). Three types of LCA models were utilized to conduct environmental impact assessment including process LCA (P-LCA), economic input-output LCA (EIO-LCA), and hybrid LCA. For example, a LCA

methodology was applied for valorization of building demolition materials and products from an eco-sustainability point of view, completing a comparison of different environment impact categories between demolition-valorization system and traditional system (Sara et al., 2001). A hybrid LCA model integrating EIO-LCA with P-LCA was developed to assess the net carbon, energy, and water footprints of different DWM strategies e.g. recycling, landfilling, and incineration (Kucukvar, 2014).

SD is a systematic approach that is particularly useful for considering the dynamic interrelationship among the variables within the social and economic system (Zhang et al., 2014). Therefore, it would be appropriate to use SD as a tool to understand a complicated C&D waste management system from a holistic perspective when assessing its environmental impact. For instance, based on a case study in the construction industry in China, a model was developed to evaluate the environmental performance of construction waste management by using SD method (Ding et al., 2016; Ye, 2012). In order to evaluate the environmental impacts of two alternatives i.e. recycling and disposing, a SD model was established to complete the evaluation with STELLA software (Marzouk and Azab, 2014). The simulation results provide valuable information for decision makers to improve the environmental performance of DWM.

Mixed assessment method is a combination of multiple methodologies which are complementary to each other so that the environmental impact of DWM can be better assessed. For example, a combination of different approaches including material flow analysis (MFA), LCA, environmental life cycle costing (ELCC), and best available technology (BAT) was applied to evaluate the overall environmental and economic performance of the Finnish DWM system (Dahlbo, 2015). It is obvious that the findings would be useful for analyzing the environmental performance of a system from different perspectives before decision-making.

Although a number of methods to assess environmental performance of construction and demolition activities are available as discussed above, it should be noted that there is a lack of empirical studies for evaluating the environmental impact of DWM covering the following three important aspects: (1) an analysis in view of DWM as a complex adaptive system (CAS); (2) the heterogeneity, autonomy, adaptability of the stakeholders and the dynamics by the interaction of the various stakeholders; (3) the difference between conventional and green management process (Ding, 2014). DWM will affect land, water, air and energy consumption and it is affected by a number of internal and external factors including government policy, law and regulation, market demand and supply, demolition technology and skill, land, space and environmental constraints, public and society perception, as well as cost-benefit trade-off. Hence, DWM should be examined from a complex adaptive system perspective (Ding, 2014). Even though SD methodology is a systematic approach that deals with the complexity and dynamics of a social and managerial system, it seems to be inadequate when a deep interpretation for the driving forces between adaptive stakeholders' attitude or behavior is needed. Furthermore, SD is a top-down modeling methodology which fails to explain how the macro phenomena could emerge from the microscopic agents' behavior and the homogeneity between stakeholders in SD were assumed, which may cause a significant inconsistency between theoretical models and reality (Jo, 2015). So far no research has been done to explore the effect of the stakeholder heterogeneity on DWM. Moreover, the construction industry has viewed "green" development as one of the project management objectives to minimize environmental impacts (Zhang et al., 2015). However, there is no research considering the benefits from the implementation of green DWM. For example, green demolition methods or design concepts adopted by demolition or design companies will affect the amount of DW generated in different project stages, and have a positive effect on the environment. Therefore, in order to assess the environmental impact of DWM from a CAS perspective, it is necessary to consider the attitude and interaction of the

heterogeneous stakeholders within the system. Meanwhile, the difference between conventional and green DWM process should be fully taken into consideration. Only by acknowledging the complex adaptive nature of the demolition waste management system (DWMS) is it possible to better assess its environmental impact and subsequently improve it. Hence, this study applied the agent-based modeling (ABM) approach to evaluate the environmental impact of DWM.

In the following sections, first the ABM approach is briefly introduced. Next, the design and implementation of the proposed model is delineated in detail. Then, the simulation results were analyzed and discussed. Finally, the paper concludes with a summary of the key findings.

2. Research methodology

2.1. ABM approach and its application

ABM, also referred to as individual-based modeling (IBM), is a new paradigm in the modeling and simulation of dynamic systems, which has gained increasing attention over the past decade. It is a bottom-up modeling method that is particularly useful for analyzing social and economic complex systems and complex adaptive systems (Holland, 1995). There are three basic ABM elements, namely, agents, an environment and rules of action & interaction. ABM is a computational method that enables researchers to build, analyze and conduct experiments with models composed of autonomous and heterogeneous agents that interact with each other and their local environment in order to identify the mechanisms that bring about some macroscopic emergent phenomenon of interest (Du, 2016; Liu and Ye, 2012). Compared with other modeling methods, ABM has the following advantages: (1) ABM can be adopted to describe a CAS; (2) ABM can model a large number of simple and heterogeneous agents and cover the interactions between them; (3) Unlike the top-down modeling such as SD and Discrete Event Simulation, ABM presents a highly disaggregated view of the system in which behavior emerges by inductive reasoning (Jo, 2015).

Since its origination in the 1970s, ABM approach has been applied for investigating a wide range of systems in various disciplines including social, ecology, economics, political science etc. (Grimm et al., 2006). For example, a multi-objective ABM framework is developed for the effective planning of single-stream recycling programs for municipal solid waste. The proposed framework is a powerful tool that can be used by stakeholders for the evaluation of several different alternatives or scenarios in municipal solid waste management system before making a decision (Shi et al., 2014). For facilitating the backfill reuse in the C&D waste management, a centralized optimization model and a distributed ABM are proposed and implemented to compare their performances in the dynamic supply chain. The comparative study indicates that ABM is more capable of investigating the dynamic backfill supply chain due to its decentralization of optimization and fast reaction to unexpected disturbances (Gan, 2015). In order to analyze construction stakeholders' behavior and decision-making regarding recycled mineral construction materials in the Switzerland construction material market, the ABM agent operationalization approach combined with analytical hierarchy process (AHP) were adopted to quantify stakeholders' decision-making process and analyze its consistency with their behavior. The results demonstrated the importance of stakeholders' interaction for recycled mineral construction materials i.e. most stakeholders decide which material to adopt based on the interactions with other stakeholders (Knoeri et al., 2011a, b).

2.2 Modeling framework and software platform

A standard and widely understood descriptive protocol is needed for ABM to be an effective and reliable CAS research methodology. Thus, different modeling frameworks have been proposed by various

researchers. For instance, Grimm et al. have proposed a standard protocol (i.e. Overview, Design concepts, and Details (ODD)) for describing ABM in ecology (Grimm et al., 2006). The ODD model protocol was applied to 19 ecological models to evaluate its effectiveness (Grimm et al., 2006) and was tested by 28 modelers who cover a wide range of fields within ecology (Grimm et al., 2010). Dam introduces ten steps for creating an ABM of a socio-technical system: (1) problem formulation and actor identification, (2) system identification and decomposition, (3) concept formalization, (4) model formalization, (5) software implementation, (6) model verification, (7) experimentation, (8) data analysis, (9) model validation, and (10) model use (Dam et al., 2013). Teo proposed the primary steps and stages to build an ABM for social science research including (1) specification and formalization, (2) modeling, verification and experimentation, (3) calibration and validation (Teo, 2013). Based on the above studies, this paper proposes a five-step modeling framework for ABM (see **Fig. 1**):

Fig. 1. The framework for developing an agent-based model

With many ABM toolkits available, it is important to make the best choice according to the research objective. A comprehensive list of ABM toolkits was gathered by Nikolai, and five characteristics including language required to program a model and to run a simulation, operating system required to run the toolkit, types of license that governs the toolkit, primary domain for which the toolkit is intended, and types of support available to user were examined (Nikolai, 2009). Furthermore, Object Oriented Programming (OOP) languages such as Java and C++ are ideal for the implementation of ABM because the OOP language enables a close mapping between the concepts of agent and class. Therefore, a modeling environment, Repast Symphony 2.2, is selected for the modeling and simulation in this research. Repast stands for Recursive Porous Agent Simulation Toolkit. Repast Symphony—often abbreviated as Repast S—is part of a family of Repast modeling tools. Repast S is a sophisticated modeling environment that supports not only the OOP of models by Java but also their visualization and data analysis (Barnes, 2010).

3. Model development and simulation

The objective of this research is to build a dynamic model by applying ABM methodology to capture the adaptive and interactive nature of various stakeholders in DWM. The proposed model is able to simulate the various stages of waste generation and evaluate environmental impact of DWM. To achieve this objective, the procedure shown in Fig.1 was followed. The proposed framework is described in the following sections.

3.1 Research question identification and confirmation

3.1.1. Problem Formulation and Actor Identification

Rapid economic growth and urbanization in China lead to extensive demolition activities which generate huge amount of DW inducing a great adverse impact on the environment. Hence, how to implement effective DWM has received increasing attention from government and researchers. Furthermore, how to accurately assess the environmental impact of DWM plays an important role to conduct an effective DWM. Therefore, this research analyzes the DWMS from the perspective of CAS, explores how various stakeholders' attitudes and behaviors affect DWM and builds DWMS model to conduct the environmental impact assessment of DWM.

A large number of buildings are demolished each year due to various reasons such as demographics, new construction, type and size of the settlement, low safety standards and natural disasters etc. (Saghafi, 2011). However, few buildings are demolished due to the end of design working life (Huuhka and Lahdensivu, 2016). Therefore, most materials still have high residual value that can be reused or recycled (Rahman et al., 2014). There are two demolition methods in practice. One is conventional demolition method using explosives, top-down demolition procedure that introduces a huge waste of materials (Shi, 2009). It is currently the primary method for building demolition due to different reasons such as the low cost, time constraint and influence of other stakeholders. As a result, a large amount of DW are generated causing the waste of resources and serious environmental pollution. The other method is deconstruction (also named selective demolition) which stands for the careful dismantling of building elements so as to make as much recovery of construction materials, promoting reuse and recycling as much as possible (Rios, 2015; Tam, 2016). Furthermore, materials reuse and recycle have provided an option to reduce the total amount of waste landfilled, save natural sources, prolong the life cycle of particular types of materials. Therefore, the deconstruction of buildings have emerged as an alternative to the conventional demolition because it may be more profitable (Akbarnezhad et al., 2014). The selection and decision of demolition/deconstruction methods depend on demolition companies so they play an important role in the DWMS.

To enable a well-planned deconstruction, efforts must be taken by architects and engineers right from the design stages. Therefore, the concept of designing for deconstruction (DfD) has to be mentioned. In contrast to the conventional design with little consideration for building relocation and component reuse, DfD is an innovative way of designing a building to maximize its flexibility so that it can be disassembled or deconstructed for various reasons such as aged community or obsolescence (Akinade, 2015; Khalili, 2011; Wang et al., 2015; Zhang et al., 2012). The essence of DfD is to design building components to be easily disassembled or deconstructed. Therefore, design phase is closely linked with the demolition phase and has a significant indirect effect on the reusing and recycling of DW. Meanwhile, designer's behavior and attitude play an important role to the waste minimization design (Wang et al., 2015). However, conventional design concept is adopted by most designers due to designer's capability and external environment even though they have realized the incontrovertible advantage of DfD.

Designers make the final decision for what kind of design concept should be adopted in design process. Hence, designers also have significant influence in DWMS.

There has been many published research about stakeholders' attitudes and behaviors regarding C&D waste management. It is acknowledged that the attitudes and behaviors are crucial to understand how C&D waste management problems might be resolved (Al-Sari et al., 2012; Begum, 2009; Knoeri et al., 2011b; Kulatunga, 2006). Therefore, this paper intends to provide insights on how various stakeholders' attitudes and behaviors affect DWM. Government as one of the key stakeholders has the obligation and ability to guide and implement effective DWM. The findings could support government to make reasonable decisions for DW minimization and sustainable DWM. Based on a literature review and the status quo of DWM, the agents involved cover, besides the government, the demolition companies and design companies as well as several essential agents in the waste material generation and management chain such as demolition projects, transportation companies, material reusing companies (mainly refers to construction companies), recycling companies, landfill site and assessment agencies (mainly refers to the Urban Management Bureau or agency). Please note that the research data were drawn from the City of Shenzhen, the fourth largest city in China.

3.2. Specification-Formalisation

3.2.1. System Identification and Decomposition

From the perspective of complexity science, DWMS is a CAS involving economic, environmental and social stakeholders who interact with each other and with the local environment (Ding, 2014; Marzouk and Azab, 2014; Ye, 2012). There are four subsystems contained in the framework of DWMS i.e. subsystem of DW generation, subsystem of DW disposal, subsystem of DWM policy, and subsystem of DWM assessment (see **Fig. 2**).

Fig. 2. The framework of demolition waste management system (DWMS)

The subsystem of DW generation is to quantify DW generated from demolition activities. Firstly, demolition projects are the source of DW generation and the project agent was included in the system. Furthermore, demolition company managers play an important role as direct participants so they are represented by demolition agents in simulation. Two types of demolition managers are classified according to the two demolition methods being adopted. The ones using the conventional demolition

method are referred to as the conventional demolition managers and denoted by a fuschia icon in Repast S. The others using the deconstruction method are viewed as green deconstruction managers (Zhang et al., 2015) and shown by a green icon (see **Fig. 5** (a)). In addition, design companies play a vital role in DWM to effectively achieve the deconstruction so they are represented by design manager agents in simulation. Considering design managers have the right to adopt a different design concept, design managers can also be divided into two categories. The ones following the conventional design concept are the conventional design managers and represented by a red icon (see **Fig. 5** (a)). The others implementing the DfD concept are green DfD design managers (Zhang et al., 2015) and shown by a blue icon in simulation. By following the basic modeling and simulation principle, i.e. “start simple” and “keep focused”, only the interactions and the attitude changes among the above two types of agent, namely, demolition managers and design managers were considered. The other agents in the remaining three subsystems were assumed to have no interactions and attitude changes and they are responsible for calculating statistics for the amount of DW and assessing the environmental impact of DWM. Moreover, the attitude and behavior of each demolition or design manager toward different demolition method or design concept have a threshold value which sets the rules to transform a conventional demolition or design manager into a green deconstruction or DfD design managers following the herd theory (Gu et al., 2015; Sun, 2013). Finally, the social space represented by a two-dimensional grid is the local environment for all the agents in the DWMS.

From the perspective of waste generation & management chain and environmental impact assessment, the demolition phase covers a series of waste management activities and results in the positive or negative environmental impacts. Therefore, a conceptual model illustrating the waste chain and environmental impact assessment is shown in **Fig. 3**. The parameter values used in the model and the important indicators assessing the environmental impact have been collected and extracted from the literature, websites, specification, and through surveying the DWM market of Shenzhen (Akbarnezhad et al., 2014; Marzouk and Azab, 2014; Qin, 2012; Shen, 2011; Shen et al., 2016; Tam, 2015; Xie, 2013; Ye, 2012; Yuan, 2011; Yuan and Wang, 2014; Zhang et al., 2014).

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- Demolition Site**
- The Number of Demolition Project=102^[1];
- Demolition Waste Generation**
- Waste Generation Rate^[2];
 - 1- Collecting Percentage;
- Waste Collection and Storage (Quantity)**
- Incentive to manage waste $\in (0,1)$;
 - Collecting percentage ≥ 0.6 ^[4];
- On-site Sorting (Quantity)**
- 1-Illegal dumping percentage;
 - 1-Reusing percentage-Recycling percentage;
- Source Reduction (Quantity and EIA)**
- Source reduction rate^[3];
 - Reusing percentage=28%^[4];
- Reused Waste (Quantity and EIA)**
- Recycling percentage;
- Recyclable Waste (Quantity and EIA)**
- Recycling percentage;
- Non-recyclable Waste (Quantity)**
- Transport distance of Illegal Dumping = Random (5km, 10km)^[3];
 - Transport distance of Landfill = Random (10km, 20km)^[3];
 - Transport distance of Recycling Centers = Random (15km, 25km)^[3];
- Demolition Waste Transportation (Quantity and EIA)**
- 1-Reusing percentage-Recycling percentage;
- Landfill (Quantity and EIA)**
- 1-Collecting Percentage;
- Illegal Dumping (Quantity and EIA)**
- 1-Collecting Percentage;
- Reclamation/Recycling Centers**
- 1-Collecting Percentage;
- In-site**
- 1-Collecting Percentage;
- Market**
- 1-Collecting Percentage;
- Environmental Impact Assessment (EIA) Index**
- Land Resource Index
 - Water Resource Index
 - Energy Resource Index
 - Air Resource Index
- Land Resource Index**
- Landfill Space
 - Land Fertilizer
- Water Resource Index**
- Ground - water
- Energy Resource Index**
- Oil
 - Natural Gas
 - Coal
- Air Resource Index**
- GHG
 - CO
 - SO₂
 - NO_x
 - PM
- Source Reduction, Reusing, Recycling**
- Transportation, Landfill, Illegal Dumping**
- 1 - Conventional Manager (Conventional Demolition/Design Manager); 2 - Green Manager (Green Demolition/Design Manager)
- [1] Housing and Construction Bureau of Shenzhen Municipality-Open Data Platform; [3] Interview in demolition industry of Shenzhen;
- [2] Technical code for construction waste reduction, 2011, Shenzhen; [4] Yuan, H. P., 2011; Xie, K., 2013;

Source Reduction Intention / Source Reduction Behavior: double

- Source Reduction Rate by Demolition Company / Percentage of DW Collection / Percentage of DW Illegal Dumping / Percentage of DW Sorting: double ≥ 0 and ≤ 1
- DW Generation / DW Source Reduction / DW Generation after Source Reduction: double
- DW Collection / DW Illegal Dumping / DW Sorting : double
- Vision of Neighbors: integer ≥ 0

Design Company Agents (instantiated as Conventional Design Manager with conventional design concept / Green DfD Design Manager with DfD concept) have:

- Project ID / Role: String
- Attitude Toward Waste Reduction Behavior / Subjective Norm / Perceived Behavior Control / Source Reduction Intention / Source Reduction Behavior: double
- Source Reduction Rate by Design Company: double ≥ 0 and ≤ 1
- Vision of Neighbors: integer ≥ 0

Project Agents have:

- Project ID / Project Type: String
- Area / Start Time / End Time: double
- Distance to Illegal Dumping / Distance to Recycling Center / Distance to Landfill: double

Reusing Agents (instantiated as contractor) / Recycling Center Agents / Landfill Agents have:

- Project ID: String
- Percentage of DW Reusing / Percentage of DW Recycling / Percentage of DW Landfill: double ≥ 0 and ≤ 1
- DW Reusing / DW Recycling / DW Landfill: double

Transporter Agents have:

- Project ID: String
- Possibility of Failing to Provide Manifest Form: double ≥ 0 and ≤ 1
- DW Transportation: double

Government Agents have:

- Penalty Paid due to Illegal Dumping / Unit Cost of Landfill: double
- Constraint on DW Generation / DW Recycling Driving Factor / Regulation Influence / Enforceability / Completeness of Regulation / Effectiveness of Supervision / Effectiveness of Regulation Execution: double
- Probability of Receiving Penalty: double ≥ 0 and ≤ 1

Assessment Agents have:

- Total actual amount of DW generation: double
- Total Amount of Construction Materials Saving: double
- The Occupation of Landfill Space / The Loss of Land Fertilizer: double
- The Loss of Water: double
- The Consumption of Oil / The Consumption of Coal / The Consumption of Natural Gas: double
- The Emission of GHG (Greenhouse Gas) / The Emission of NO_x / The Emission of SO₂ / The Emission of CO / The Emission of PM (Particulate Matter): double

3.2.3. Model Formalisation

As the model is being developed, there should have a “story” of how agents act and interact, thereby giving rise to emergent patterns. Model formalization consists of two sections. The first one is to develop a model narrative that is an informal description of the generative theory of the system under study. The

other one is the expression of this narrative in pseudo-code which is a description of an algorithm written in human-readable form, providing an insight into the structure of the algorithm while omitting computer specific details.

Model Narrative:

- **Conventional Demolition Managers / Green Deconstruction Managers do:**

Waste material generation is the starting point of DWM. Large amount of DW is generated as a result of various demolition projects done by demolition companies. The approaches of demolition are classified into the conventional demolition method and the deconstruction method.

Waste source reduction is a process to take measures for avoiding waste generation from the possible origins (Wang et al., 2015). At the beginning of each demolition project, some of the waste material will be reused or recycled by the demolition workers to a certain extent. The source reduction rate mainly depends on two aspects: one is the demolition method adopted and the other is the design concepts followed by the designer manager who may or may not consider the green deconstruction when the project is in the design phase. From the perspective of environment protection, the source reduction should be paid much more attention.

Waste collection is a part of the process of DWM which has a significant effect on the quantity of landfilled waste because the more DW could be collected, the fewer DW will be landfilled. So waste collection has an indirect influence on the environment due to the fact that landfill process will bring serious environmental pollution. The percentage of waste collection is influenced by the laws, policies and other regulation factors for waste management.

Waste illegal dumping refers to dumping waste illegally instead of using an authorized method. In order to avoid the cost of landfill or other high disposal cost, waste is dumped to a site with no licence to dispose waste e.g. rural areas, uncultivated land and roadside. This illegal method not only consumes a lot of land spaces but also incurs a negative impact on the land fertilizer and groundwater. The percentage of illegal dumping is affected by regulations and landfill charge.

Because mixed and contaminated waste is not suitable for reuse or recycling but generally disposed of at landfills, waste sorting is encouraged before further processing in order to ensure a higher rate of reuse or recycling (Lu et al., 2016). On-site sorting is usually done by hand and it has little impact on the environment compared to the illegal dumping and landfill. So the environmental impact of sorting will not be discussed in this paper. The percentage of waste sorting also depends on the regulation for waste management.

Each demolition manager in the two-dimensional grid space can interact and communicate with others due to project collaboration, project bidding and related industry conferences/workshops etc. The information exchange and communication can often greatly affect their attitude and decision-making with respect to DWM.

- **Conventional Design Managers / Green DfD Design Managers do:**

The architectural design for a building by a designer has an important influence on the demolition of the building. Its importance is reflected by the source reduction at the beginning of the demolition. If implementing DfD in the original design, such as adopt prefabrication and recycled materials as well as consider the effective demolition for better reusing the valued waste materials, the majority of materials and resources will be saved by this behavior. The source reduction rate is influenced by designers' attitude toward waste management, capability and external environment. Like demolition managers, design managers can also interact with each other.

- **Project Agents do:**

The different structures of buildings influence waste generation. The demolition projects could be divided into the four categories, namely, residential, commercial, public and industrial building demolition projects. Different projects have diverse floor areas and the distance to the non-designated areas, landfill sites and recycling companies.

- **Reusing / Recycling / Landfill Agents do:**

Waste materials reusing means reuse of the same material in construction more than once including the material being used again for the same function or a new-life reuse where the material is used as a raw material for a new function. This process is mainly carried out by contractors. Another environmental friendly treatment is recycling where waste materials are reprocessed into products, materials or substances for the original or other purposes (Rodriguez et al., 2015). These two disposal methods have a positive effect on the environment compared to the landfill and illegal dumping (Bravo et al., 2015; Xuan et al., 2015).

Waste landfill is the final option for waste disposal where all the wastes are disposed of in landfill by taking into account the types of waste such as the inert waste, non-special waste etc. The environmental impacts of waste landfills include the occupation of landfill space, energy consumption and air pollution.

- **Transporter Agents do:**

Waste transportation refers to transporting waste from the demolition site to the illegal dumping places, recycling plants or landfills. It has a negative impact on the environment due to the consumption of energy and pollution emissions during the transportation.

- **Government Agents do:**

Government plays a leading role in DWM who can improve and implement effective DWM through the development of regulating policies and measures. For example, landfill fees and illegal dumping fines are considered as effective ways to reduce the amount of illegal dumping and landfill. Therefore, government can promote a large amount of wastes into the recycling enterprise, or for reuse by proper regulation.

- **Assessment Agents do:**

The environmental impact assessment covers the following two aspects. The first one is the positive environmental impacts that associated with implementation of DWM including waste reduction, reusing and recycling. An effective DWM is important to reduce the occupation of landfill space, avoid the loss of land fertilizer and groundwater as well as the energy consumption and pollution emission savings. Conversely, the negative environmental impacts related to the overall process of waste management cover waste illegal dumping, transportation and landfill. Their impacts on the environment were taken into account from the following aspects such as landfill resource, water resource, energy resource and air resource.

Pseudo-code:

Pseudo-code is a straightforward and understandable method that uses mathematical and logical descriptions of what and how agents are supposed to behave by combination of the model narrative and formalised concepts. For example, demolition waste source reduction activity is described in pseudo-code in **Table 1**. The other model narratives could be turned into pseudo-code in a similar fashion.

Table 1 Model pseudo-code example.

Algorithm 3.2.3 Model pseudo-code example – demolition waste source reduction activity

- 1 all Demolition/Design Manager
 - 2 set Demolition/Design Manager ID
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3  set Source Reduction Rate by Demolition/Design Manager
4  set Source Reduction Rate
5  set The amount of DW generation
6  set The amount of DW source reduction
7  Calculate-Source Reduction Rate by Demolition/Design Manager
8      If Demolition Manager is Green Deconstruction Manager
9          Do Source Reduction Intention = Function (Attitude Toward Waste Reduction Behavior,
10              Subjective Norm, Perceived Behavior Control)
11          Do Source Reduction Behavior = Function (Source Reduction Intention, Perceived Behavior
12              Control)
13      If Source Reduction Behavior belongs to a Certain Range
14          Do Source Reduction Rate by Demolition/Design = Random Function
15          Else Source Reduction Rate by Demolition Manager = Function (Source Reduction
16              Behavior)
17          Else Source Reduction Rate by Demolition/Design = Random Function
18      End if
19  Get Source Reduction Rate by Demolition/Design Manager
20  Calculate- Source Reduction Rate
21      Source Reduction Rate = (Source Reduction Rate by Demolition Manager + Source Reduction
22          Rate by Design Manager)
23  Get Source Reduction Rate
24  Calculate- The amount of DW source reduction
25      The amount of DW source reduction = The amount of DW generation * Source Reduction Rate
26  Get The amount of DW source reduction

```

3.3. Modeling-Verification-Experimentation

3.3.1. Software Implementation

After the formulation of the model narrative and pseudo-code, the model could be programmed in an appropriate modeling or programming environment. The model with 15,000 lines of source code is written with Java in Repast Symphony 2.2. The model consists of four packages and fifteen classes as shown in **Fig. 4**. Empirical data in the model were collected from literature, websites and official statistics published by the Shenzhen environment department, and six semi-structured interviews conducted in the Shenzhen construction industry covering design companies, demolition companies, construction companies and recycling companies as shown in **Table 2**. Interviewees include two structural designers, two architects, two demolition project managers, four construction project managers and four recycling managers. The interviews were conducted between November 2015 and February 2016 with each lasting about 45-60 minutes. Interviewees were selected through academic and industry social networks. All of them possessed a considerable amount of DWM related experience. The aim of the interviews was to collect more in-depth information to supplement the data collected from the literatures and websites so as to appreciate the status quo of DWM in Shenzhen and build the model. As shown in **Fig. 4**, there are three classes, namely, Constants class, Project Data class and CWMUtils class in the cdwmmodel.common package. Their functions are to define model constants, to store attribute data of the project and to reserve common utility functions in the model. It should be noted that the data collected from the literature and interviews were placed in the model constants class which can be called and transferred by all the agents

in the model.

Fig. 4. Model implementation

Table 2 Quantitative variable values.

Variable	Value	Unit	Source(s)
Total demolition projects	102	-	(Housing and Construction Bureau of Shenzhen Municipality, 2015)
Residential waste generation indicator	1.45	T/m ²	(Wang, 2012)
Commercial waste generation indicator	1.38	T/m ²	(Wang, 2012)
Public waste generation indicator	1.48	T/m ²	(Wang, 2012)
Industrial waste generation indicator	1.13	T/m ²	(Wang, 2012)
Attitude toward waste reduction behavior	0.7	-	Interviews and (Li, 2014, 2015)
Subjective norm	0.3	-	Interviews and (Li, 2014, 2015)
Perceived behavior control	0.5	-	Interviews and (Li, 2014, 2015)
Regulations associated with DW disposal	10	-	Interviews and (Yuan and Wang, 2014)
Unit landfill charge	30	Yuan/ton	Interviews
Unit penalty paid due to illegal dumping	80	Yuan/ton	Interview and (Yuan, 2011)
Unit land occupation	0.68	m ³ /ton	Interview and (Qin, 2012)
Unit loss of fertilizer	3.5	kg/ton	(Qin, 2012)
Unit loss of water	100	ton/ton	(Qin, 2012)

Unit oil consumption by landfill	0.857	kg/ton	(Xie, 2013)
Unit oil consumption by transportation	0.718	kg/ton • 100km	(Xie, 2013)
Unit coal consumption by landfill	0.031	kg/ton	(Xie, 2013)
Unit coal consumption by transportation	0.026	kg/ton • 100km	(Xie, 2013)
Unit natural gas consumption by landfill	0.00005	m ³ /ton	(Xie, 2013)
Unit natural gas consumption by transportation	0.00004	m ³ /ton • 100km	(Xie, 2013)
Unit GHG emission by landfill	2.01	kg/ton	(Xie, 2013)
Unit GHG emission by transportation	1.81	kg/ton • 100km	(Xie, 2013)
Unit NOx emission by landfill	0.043	kg/ton	(Xie, 2013)
Unit NOx emission by transportation	0.031	kg/ton • 100km	(Xie, 2013)
Unit SO2 emission by landfill	0.001	kg/ton	(Xie, 2013)
Unit SO2 emission by transportation	0.002	kg/ton • 100km	(Xie, 2013)
Unit CO emission by landfill	0.091	kg/ton	(Xie, 2013)
Unit CO emission by transportation	0.015	kg/ton • 100km	(Xie, 2013)
Unit PM emission by landfill	0.0007	kg/ton	(Xie, 2013)
Unit PM emission by transportation	0.0004	kg/ton • 100km	(Xie, 2013)

3.3.2. Model Verification

Model verification is to ensure the model free of errors prior to the execution of simulation runs. In order to verify the model, several tests were taken including recording and tracking agent behavior, single-agent testing, interaction testing in a minimal model, multi-agent testing (Dam et al., 2013). A typical example examining the interaction between the agents in a minimal model is illustrated in **Fig. 5**. Since there are multiple types of agents in the model, the minimal model constructed should contain at least two of each type so that the basic agent interactions as laid out in the model narrative can be examined.

Taking two residential building demolition projects as an example, the minimal model include two demolition managers and two design managers. One project has a conventional demolition manger and a conventional design manager, and another has a green deconstruction manager and a green DfD design manager. As shown in diagram (a) **Fig. 5**, four managers are created in the simulation environment with the model initialization completed. The demolition areas of the two projects are 176,687 m² and 192,434 m² respectively. Based on the empirical data, the time that the two demolition projects entered into the simulation should be separated in the 24th and the 49th time step. The completion time of the two demolition projects are in 245th and 290th time step respectively with an average demolition progress of 100 m²/1h (Coelho and de Brito, 2011). With the residential building waste generation rate of 1450kg/m², the total amount of DW generation should reach 535,225.45 tones when the two demolition projects are

completed.

The amount of DW generation and agents' interaction over time can be accurately reflected in the diagram. On the diagram **Fig. 5(b)**, blue and green lines respectively represent the amount of DW generation and the amount of DW after Source Reduction i.e. the total actual amount of DW generation. The red line represents the amount of DW source reduction. On the diagram **Fig. 5 (c)**, blue and red lines represent the count of green design manager and the count of conventional design manager respectively. The green and pink lines represent the count of green deconstruction manager and the count of conventional demolition manager. As the simulation and interaction between the two types of agents progressed, agents' behavior and attitude began to change at the 110th and the 160th time step when all conventional demolition managers transformed into green deconstruction managers and all conventional design managers converted to the green DfD design managers. It can be seen that the trend of generated DW is consistent with expectation. In the mean time, after 110 time steps, the trend of generated DW after source reduction gradually slows and the amount of DW source reduction shows a rapid upward trend. The key reason for this phenomenon is the change of demolition managers' behavior and attitude. Similarly, the change of design managers' behavior and attitude at the 160th time step also influences on the DW amount. Therefore, agents and relationships from the conceptual model have been translated into the computational model correctly by the verification simulation runs.

(a)

(b)

(c)

Fig. 5. An example of model verification-Interaction testing in a minimal model

3.3.3. Experimentation

When the model has been verified, experiments could be conducted to study the research questions in 3.1.1. Three steps will be followed in this section, namely, experiment design, experiment setup and experiment execution. The most important step is the experiment design that starts with selecting the right type for the hypothesis, choosing a suitable time frame and defining scenarios and the space. The simulation is scheduled in an experimental setup of 1100 runs with 11 scenarios. All the parameters except for Ratio of Green Manager (includes Green Deconstruction / DfD Design Manager, Range is 0-1) are fixed to assess the environmental impact of DWM. In all experimentations, a single simulation run consisted of 575 time steps with each time step representing one day of real-world time. Simulation output data related to the indicators of environmental impact assessment are collected for each time step during each run.

Experiment design – Explore the environmental impact assessment of DWM

- Setup
 - Ticks [575]: the duration time of 102 demolition projects.
 - Repetitions [100].

- Parameter settings
 - Attitude toward Waste Reduction Behavior [0.7].
 - Perceived Behavior Control [0.5].
 - Subjective Norm [0.3].
 - Regulations associated with DW Disposal [10].
 - Unit Landfill Charge [30].
 - Unit Penalty paid due to Illegal Dumping [80].
 - Degree of Neighbors [4].
 - Ratio of Green Deconstruction and DfD Manager [0-1, Interval 0.1]: The green deconstruction and DfD manager's market share.
- Output at each tick
 - The tick.
 - Random seed used (to be able to reproduce the results).
 - Number of Conventional Demolition Manager and Green Deconstruction Manager.
 - Number of Conventional Design Manager and Green DfD Design Manager.
 - Total actual amount of DW generation.
 - Total Amount of Construction Materials Saving
 - Total amount of Landfill Space Occupation / Land Fertilizer Loss.
 - Total amount of Water Loss.
 - Total amount of Oil Consumption / Coal Consumption / Natural Gas Consumption.
 - Total amount of GHG (Greenhouse Gas) Emission / NO_x Emission / SO₂ Emission / CO Emission / PM (Particulate Matter) Emission.

3.3.4. Data analysis

During the course of a simulation, all data generated were saved in txt files and later transferred to an Excel document. Then the simulation results can be analyzed in conjunction with R and Matlab scripts. In the following sections, the results of environmental impact assessment indicators are shown in graphs.

Explore the environmental impact assessment of DWM

The environmental impact assessment covers the following four aspects:

(1) Land resource

Based on the output analysis of 1000 simulations, the total landfill space occupation and the total land fertilizer loss are shown in **Fig. 6** and **Fig. 7**. It can be seen that during the period of 575 days the amount of landfill space occupation and the amount of land fertilizer loss generated by 102 demolition projects vary in a certain range with the change of green manager ratio. Both of them showed a significant decrease with the growth of green deconstruction manager ratio. As shown in **Fig. 6** (a) and **Fig. 7** (a), when the ratio of green deconstruction manager is 0 i.e. all the demolition companies utilize the conventional demolition methods and the design companies follow the conventional design concept, about 7.49 million m³ of landfill space will be occupied and 6571.37 tons of land fertilizer will be lost. Correspondingly, when the ratio of green manager is 1 i.e. all the demolition companies use the deconstruction methods and the design companies follow the DfD concept, approximately 3.60 million m³ of landfill space will be occupied and 3155.89 tons of land fertilizer will be lost. It can be seen that the amount of landfill space occupation and the amount of land fertilizer loss will decrease by 3.89 million m³ and 3415.48 tons in the 102 demolition projects, reaching 51.94% and 51.98% reduction respectively.

Fig. 6. Total landfill space occupation and curve of density function (The ratio of green manager=0-1, N=0-1000; tick=575)

As shown in **Fig. 6** (b) and **Fig. 7** (b), R is used to produce the curve of density function of the landfill space occupation which illustrates the distribution of the total landfill space occupation of 1000 simulations. The curves show the pattern of “high on both sides, low in the middle” and “higher on the left end”, which means lower landfill space occupation and lower land fertilizer loss appears more frequently due to the interaction between stakeholders and the growing ratio of green deconstruction managers. The occupation of landfill space is mainly incurred by the amount of landfilled waste which includes the non-recyclable waste and uncollected waste. Therefore, efforts should be made to enhance the ratio of reusing, recycling and source reduction as well as encouragement of on-site waste collection. The loss of land fertilizer was resulted from the leachate and other pollutants from illegal dumping waste. Hence, the supervision and regulation must be further improved.

Fig. 7. Total land fertilizer loss and curve of density function (The ratio of green manager=0-1, N=0-1000; tick=575)

(2) Water resource

According to the 1000 simulation results, the total water loss caused by the 102 demolition projects is shown in

Fig. 8. The total water loss shows a great decrease with the growth of green deconstruction manger ratio. As shown in the

Fig. 8 (a), when the ratio of green manager is 0, about 187.75 million tons of water will be polluted. In constrast, when the ratio of green deconstruction manager is 1, appropriately 90.17 million tons of water will be polluted. It can be seen that the water loss will decrease by 97.58 million tons, reaching 51.97% reduction. A similar pattern is found in the

Fig. 8 (b) which shows 90 million tons of water loss is more likely to occur compared to the 187.75 million tons. Since the loss of water is caused by the illegal dumping, the supervision and regulation must be further improved.

Fig. 8. Total water loss and curve of density function (The ratio of green manager=0-1, N=0-1000; tick=575)

(3) Energy resource

There are three types of energy consumption: coal, oil and natural gas. The 1000 times simulation results are shown in **Fig. 9** and **Fig. 10**. These charts show the different range of energy consumption with the change of green manger ratio. A sharp decline in the amount of energy consumption for three resources can be identified according to **Fig. 9**.

Fig. 9. Total coal, oil and natural gas consumption (The ratio of green manager=0-1, N=0-1000)

Fig. 10. Curve of density function of total coal, oil and natural gas consumption (The ratio of green manager=0-1, Tick=575)

As shown in diagram **Fig. 9** (a) and **Fig. 10** (a), when the ratio of green manager is 0, about 335.97 tons of coal will be consumed. In contrast, when the ratio of green manager is 1, appropriately 161.29 tons of coal will be consumed. It is concluded that 174.68 tons of coal will be saved, reaching 51.99% reduction. The density function curve of the coal consumption is produced by R which illustrates the distribution of the total coal consumption. It shows a similar trend with the landfill space occupation.

Fig. 9 (b) and **Fig. 9** (c) show that appropriately 16541.18 tons of oil and 537.97 m³ of natural gas will be consumed when the ratio of green manager is 0. Around 7941.63 tons of oil and 258.27 m³ of natural gas will be consumed when the ratio of green manager is 1. It can be seen that 8599.85 tons of oil and 279.7 m³ of natural gas will be saved, reaching 51.99% reduction. The density function curve of the oil consumption and the natural gas consumption shown in diagram (b) and diagram (c) of **Fig. 10** are

similar to that of the coal consumption.

The waste landfill and transportation will consume a large amount of energy. The energy consumption during transportation come from three parts, namely, transporting to landfill, transporting to recycling plant and transporting to the illegal dumping site. Hence, reusing and source reduction on-site should be highly emphasized in DWM so that the transportation could be reduced. Meanwhile, reasonable arrangement of the landfill sites and recycling plant is also vital for reducing the energy consumption.

(4) Air resource

DWM is a process accompanied by a variety of polluting gas emissions including GHG, NO_x, SO₂, CO and PM. The outputs of each gas are shown in **Fig. 11** and **Fig. 12**. These diagrams show the different range of gas emission with the change of green manger ratio. It is obvious that a dramatic decline of the five types of gas emissions can be clearly noted.

Fig. 11. Total GHG, NO_x, SO₂, CO and PM emission (The ratio of green manger=0-1, N=0-1000, tick=575)

Fig. 12. Curves of density function of total GHG, NO_x, SO₂, CO and PM emission (The ratio of green manager=0-1, Tick=575)

As shown in **Fig. 11** (a), when the ratio of green manager is 0, about 22035.53 tons of GHG will be emitted. While the ratio of green manager is 1, appropriately 10578.69 tons of GHG will be emitted. It can be seen that the amount of GHG emission will decrease by 11456.84, reaching 51.99% reduction.

Fig. 11 (b) and **Fig. 11** (c) show that appropriately 455.77 tons of NO_x and 13.19 tons of SO₂ will be consumed when the ratio of green manager is 0. Around 218.80 tons of NO_x and 6.33 tons of SO₂ will be consumed when the ratio of green manager is 1. It can be seen that 236.97 tons of NO_x and 6.86 tons of

SO₂ will be reduced, reaching 51.99% and 52.01%.

As shown in **Fig. 11** (d) and **Fig. 11** (e), when the ratio of green manager is 0, about 862.01 tons of CO and 7.21 tons of PM will be emitted. In contrast, when the ratio of green manager is 1, appropriately 413.84 of CO and 3.46 tons of PM will be emitted. It is concluded that 174.68 tons of coal will be saved, reaching 51.99% reduction. It can be seen that the amount of CO emission and the amount of PM emission will desperately decrease by 448.17 tons and 3.75 tons, reaching 51.99% and 52.01% reduction.

Similarly, the curve of density function of the amount of GHG, NO_x, SO₂, CO and PM emission shown in the **Fig. 12** are generated by R when the simulation time step is 575, which illustrates the distribution of the total amount of GHG, NO_x, SO₂, CO and PM emission of 1000 times simulation at the end.

The ranking of the harmful gas emissions is GHG, CO, NO_x, SO₂ and PM with a decreasing order. The amount of GHG generated in DWM is the largest which has a serious negative impact on the environment. The reason for these harmful gas emissions is the use of different machinery during the landfill and transportation. Therefore, reducing the waste landfill and transportation is vital to the improvement of the environmental performance. On the other hand, the use of clean energy should also be encouraged.

(a)

(b)

Fig. 13. The three dimension diagram of triple indicators

In order to further visually analyze the environmental impact of DWM, the three dimension diagram of triple indicators is drawn in Matlab. For example, the ratio of Green Manager, total actual DW generation, total construction materials saving, the occupation of landfill space and total GHG emission were used as the X-axis, Y-axis or Z-axis as shown in **Fig. 13**. It can be seen that with the increase of green manager ratio, the total actual DW generation is gradually reduced (see **Fig. 13** (a)) and the total amount of construction materials saving is growing (see **Fig. 13** (b)). The total landfill space occupation and the total GHG emission are decreasing with the increasing ratio of green manager. It can be concluded that the change of demolition managers' and design managers' attitude to the demolition method and design concept has a significant effect on the environmental impact of DWM. Therefore, efforts and regulations should be made to promote deconstruction technology and DfD concept as an

alternative for the conventional demolition method and design concept.

3.4. Calibration-Validation

3.4.1. Model validation

The main task of validation is to show that the model is suitable for the targeting domain and useful for the understanding of the problem in this study. This study does not claim that the model can accurately predict such a transition or actions taken by demolition or design companies. Yet the model can help to identify patterns emerging from stakeholders' interaction and attitude change in future DWM. Thus the model offers novel insights about the adaptive and dynamics of the DWMS. In this paper, the model validation includes two main efforts: the first is to provide a transparent model developed in an open process, and the second is to use expert opinions to validate the model. When it comes to expert validation, it was done in all stages of the model development so that the model accurately represents essential aspects of the real-world system and provides useful insights.

3.5. Model utilization and application

3.5.1. Model use

The model presented can be used for decision support, meaning that different scenarios can be tested in a simulation. Then the best solution can be implemented in the real world. For instance, the model developed for the environmental impact assessment of DWM can be used by government in DWM policy making. It can also be utilized by project stakeholders (e.g. design or demolition company) from the construction industry since the model provides a new method to evaluate the environmental impact of DWM in a project level.

The model can also be applied in a regional level if the data about the regional demolition projects can be obtained. In particular, the simulation model served to illustrate how various interactions and decisions by stakeholders in the DWMS might affect opportunities for waste reuse and recovery thereby the environment. For instance, with the increasing ratio of green deconstruction manager, the waste reusing and recycling show an upward trend while the waste landfill, illegal dumping and transportation decline. As a result, the negative environmental impact could be reduced. In general, this study will be an important step towards the development of decision support tools which can be used by different stakeholders.

4. Discussion

The simulation results showed that government should pay more attention to the DWM in the future because of its huge quantity and great damage to the environment, especially in the phase of landfill and transportation. The simulation results also demonstrate the significance of stakeholders' interaction and attitude such as demolition manager and design manager as well as the application of green deconstruction technology. Therefore, efforts should be made to improve and further enhance the effectiveness of DWM. First of all, policies should be formulated to focus on raising stakeholders' awareness of DWM, promoting knowledge and communication among stakeholders with regard to environment and waste management concepts and practices, especially demolition or design manager. The vocational training and education schemes should cover the application of deconstruction technology, knowledge about the source reduction and design concepts in a hope to create a culture change (Ajayi, 2016; Knoeri et al., 2011b; Wang, 2008). Furthermore, DfD at the design stage to avoid demolition should be encouraged while deconstruction technology should be utilized and prioritized over the conventional

demolition method at the end of buildings' life. For instance, integrating building information modeling (BIM) with deconstructability assessment score to examine the deconstruction scheme can be considered by designers in the design stage (Akinade, 2015; Saghafi, 2011; Tingley and Davison, 2012). Meanwhile, reasonable compensation incentive and punishment scheme can be established to encourage managers to adopt green deconstruction method and design concept, and motivate practitioners to promote green DWM practices in various ways such as encouragement of innovative construction approaches for ease of future deconstruction (Tam and Tam, 2008). Finally, the locations of waste landfill site and recycling plants should be arranged reasonably so as to shorten the transport distance (Coelho and de Brito, 2013; E. Dosal, 2013; Feo and Gisi, 2014) while a standardized C&D waste transportation is necessary to improve the coordination among different transport management departments (Economopoulou et al., 2013; Zhang, 2012).

DW zero emissions and green DWM will be the future of the construction industry because of their positive impacts on the economy, environment and society. To achieve this goal, efforts should be made to promote publicity and education by governments or other stakeholders (Lu and Yuan, 2010), improve the implementation of pay-as-you-throw policy (Yuan and Wang, 2014) and DWM level, refine legislations and regulations (Saez et al., 2013; Wang et al., 2010) so that designers and demolition workers could improve their awareness of DWM. Thus all stakeholders are motivated to carry out green DWM in order to reduce the amount of DW, improve the level of source reduction, reusing and recycling, and increase the economic, environmental and social benefits.

5. Conclusions

Building construction and demolition waste (C&D waste) is drawing more and more attention worldwide in terms of economic, environmental and social concerns. This paper has described the application of ABM as a promising bottom-up approach to evaluate the environmental impacts of DWM activities by taking into account the difference between conventional and green DWM, the attitude and interaction of the heterogeneous stakeholders of DWMS from the perspective of CAS. The empirical research presented in this paper has shown that the developed model can be used to support the DW decision-makers. Particularly, the DWMS is a decentralized, complex and adaptive system with many heterogeneous agents with different objectives and procedure for decision-making, and physical components interacting through different flows such as waste, information and monetary. Hence, the collective decisions made by these autonomous agents at various levels of the system results in the overall system behavior. Therefore, the dynamic model integrates all major variables affecting the environmental impact of DWM and is capable of studying behaviors of these heterogeneous actors from a CAS perspective. These assessments cover the different pollutant emissions resulting from disposal in landfills, emissions avoided by reusing and recycling as well as the impact of transportation and illegal dumping. In this way, the environmental impact assessment of DWM is better investigated.

The construction industry has shown commitment to environment protection by extending the fundamental objectives of project management to cover environmental management (Zhang et al., 2015). Since DW is a major problem for the urban development and construction sustainability, it is urgent to research how to effectively implement DWM. Therefore, this paper proposed an agent based model as an effective instrument to measure and assess the environmental impact of DWM. Meanwhile, the major variables that affect the effective implementation of DWM were identified and different scenarios were simulated to explore the environmental impact of DWM. The simulation results indicate that the improvement on the level of green DWM has the strongest positive effect on the general DWM. For

example, if the green deconstruction method and the deconstruction oriented design are widely adopted by architects and engineers, the negative environmental impacts generated by DW can be reduced by at least 50%. The simulation results provide policy makers and other stakeholders with insights about reducing demolition waste and negative impacts on the environment as well as comparing different dynamic outcomes under various green levels of DWM.

Future research should focus on the following two aspects: Firstly, integrate the big data of buildings with geographic information systems (GIS) to take advantage of the huge building information and the physical simulation space so that the model could be more consistent with the real world (Feo and Gisi, 2014; Lu et al., 2016). Moreover, further research may include landfill site selection and transportation routes optimization (Coelho and de Brito, 2013). Secondly, improve agents' decision rules in the model. For example, agents could be designed with more intelligent learning capabilities by introducing game theory, genetic algorithms, neural networks etc. (Komly et al., 2012).

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