A model for assessing the economic performance of construction waste reduction

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Abstract: Although a plethora of research has been conducted to investigate the economic performance of construction waste (CW) management, the vast majority of studies have concentrated on the economic feasibility of CW recycling, while ignoring the economic performance of CW reduction strategies and measures. Moreover, previous studies mostly focused on one specific waste stage for waste reduction, failing to envisage dynamic interactions among various factors inherent in different waste management stages including waste generation, on-site reduction, and waste disposal, which inevitably affects the effectiveness of implementing those management strategies. To address these research gaps, this study developed a system dynamics model to investigate the economic performance of CW reduction. The model is constructed based on the interrelationships of major factors affecting the economic performance of CW reduction and comprises three subsystems covering waste generation and disposal, waste reduction, and economic performance assessment. Data from a residential building project were used for model validation and simulation. The findings reveal four strategies to effectively promote the economic performance of CW reduction, including: enhancing waste sorting, reducing illegal dumping behaviors, promoting government's financial subsidy on waste recycling, and raising waste landfilling charge. Furthermore, model simulations

inform that combining different waste reduction strategies could result in better outcomes than a single measure regarding CW reduction. This study is significant in revealing the interrelationships of factors affecting the economic performance of CW reduction. Meanwhile, the results are helpful for designing policies to improve CW reduction practice.

Keywords: construction waste; waste reduction; economic performance; system dynamics.

1. Introduction

With the acceleration of urbanization and rapid development of the construction industry over the last decade, a substantial amount of construction waste (CW) has been generated from construction, renovation and demolition activities. The challenge of CW is faced by all economies worldwide, whether developing or developed (Yuan et al., 2012, Wang et al., 2014, 2015). It has been reported that the amount of CW in China reached 1.5 billion tons in 2014, with most of the waste disposed of through landfilling and illegal dumping (Jia et al., 2017, Huang et al., 2018). Disposing of CW through landfill increases the depletion of land resources, and illegally dumped waste seriously pollutes soil, water and air thereby threatening the surroundings. How to minimize CW and solve the existent *garbage siege* phenomenon has become an urgent and challenging issue around the world.

To respond to the challenge, increasing research efforts have been devoted to CW management strategies and measures, ranging from waste reduction, treatment, and recycle through to final disposal (Yuan et al., 2012). Among all of those CW management strategies, waste reduction is generally given the highest priority because it is a vital step in preventing CW generation. Many studies have been thus conducted to reduce CW at different stages of construction projects, such as improving designers' awareness and adopting prefabricated building components at the design stage (Baldwin, et al., 2009; Tam et al., 2007), implementing on-site sorting and enhancing contractors' CW management behavior at the construction stage (Wang et al., 2010; Wu et al., 2017), launching a CW disposal-charging scheme and designing an appropriate waste disposal charge at the disposal stage (Hao et al., 2008; Yuan and Wang, 2014).

Among the studies, how to promote CW reduction through effective economic measures and strategies has been one of the central concerns. Mahpour and Mortaheb (2018) provided a rationale for this, claiming that economic incentives are more conducive to driving CW reduction, compared with other waste management strategies. A review of relevant literature has told that although some attempts have been made over the past few years for investigating the economic performance of CW management activities (see Begum et al., 2006; Duran et al., 2006; Tam, 2008; Zhao et al., 2010; Coelho and Brito, 2013a, 2013b; Wijayasundara et al., 2016; Neto et al., 2017), several research gaps are distinct.

Firstly, previous studies mainly focused on investigating the economic feasibility of CW recycling (that is, to examine whether CW recycling activities are economically feasible or not), while ignoring the economic performance of CW reduction strategies and measures. However, CW reduction strategies are the first-priority in line with the classical 3R principles in circle economy (i.e. reduction, reuse, recycling) because CW waste can be largely avoided through waste reduction strategies and measures (Ghisellini et al., 2018; Huang et al., 2018). Secondly, previous studies mostly concentrated on one specific waste stage for waste reduction, failing to investigate various factors inherent in different waste management stages including waste generation stage, on-site reduction and management stage, and waste disposal stage. This inevitably affects effects of management strategies for reducing CW because reducing CW from a system and lifecycle perspective has been regarded as very essential for revealing system complexity and enhancing effectiveness of management strategies and measures (Marzouk & Azab, 2014; Dahlbo et al., 2015; Jalaei et al., 2019). As Yuan and Wang (2014) found, a policy of waste disposal charge, which belongs to the waste disposal stage, would influence the effectiveness of CW on-site waste reduction strategies through impacting attitudes and behaviors of major project stakeholders (such as contractors') toward CW reduction. Thirdly, CW reduction is a system of prominently dynamic characteristics. Prior studies do not well envisage the dynamic interactions inherent in various factors of the system. Although similar efforts have been made in assessing the environmental performance of CW reduction (Ding et al., 2018), there is a lack of research in examining the economic performance of CW reduction. These research limitations largely account for the limited effectiveness of current CW reduction strategies and measures.

To address the above research gaps, this study aims to investigate the economic performance of CW reduction by considering the dynamic interrelationships of major factors influencing CW reduction. The study was carried out based on a system dynamics (SD) approach. The novelty of this study mainly lies in two aspects: the first is to reveal interactive relationships among major factors affecting CW reduction in different waste management stages, which is fulfilled by identifying the main factors influencing the economic performance of CW reduction and further examining the interactive relationships among the factors; the second is to evaluate the dynamic effects of various management strategies on the economic performance of CW reduction, which is achieved by designing and simulating various scenarios using a developed SD simulation model. The interrelationships among the identified factors associated with CW reduction could deepen major stakeholders' understanding of how to promote CW reduction. Meanwhile, the proposed model would enable decision-makers to examine the effects of a particular management strategy and measure before implementing it in practice so that the management strategies and measures for maximizing the economic performance of CW reduction can be identified.

The rest of this paper is organized as follows. Section 2 reviews related literature and research methods employed. Section 3 develops a SD model for analyzing the economic performance of CW reduction. Section 4 quantifies the variables in the model. Section 5 validates the proposed model, followed by model simulation and scenario analysis. Section 7 discusses the results and presents policy implications and finally we conclude this paper.

2. Literature review

2.1 Economic performance of CW management

Economic performance has been critical in promoting CW management strategies and measures because cost is the first priority when project stakeholders consider whether to adopt CW management strategies or not (Jia et al., 2017; Silva et al., 2017; Liu et al., 2019). In this regard, several studies have been carried out to investigate factors affecting the economic performance of CW management from waste generation through to waste disposal, though from different perspectives (Yuan et al., 2011；Yuan et al., 2014). However, as afore-mentioned, most existent studies tend to focusing on investigating the economic feasibility of CW recycling or waste recycling plants. For example, a benefit–cost analysis was conducted by Begum et al. (2006) for investigating the economic feasibility of recycled and reused CW through the employment of mathematical equations. A model was proposed by Duran et al. (2006) for assessing the economic viability of CW recycling under different governmental policies. Tam (2008) considered the economic benefits of recycling concrete waste through a comparative study on costs and benefits between the current practice and the proposed concrete recycling method. Also, significant efforts were made to investigate economic benefits of recycling plants through investment analysis such as payback period and internal rate of return (Coelho and Brito, 2013a, 2013b; Neto et al., 2017).

For the economic performance of CW reduction, prior studies mostly identified factors from a static point of view, such as factors affecting project design including factors affecting designers' perceptions, attitudes and behaviors (Li et al., 2015; Wang et al., 2015; Wang et al., 2019), factors affecting on-site waste management (Gangolells et al., 2014; Ajayi et al., 2017), incentives for encouraging waste reduction (Wu et al., 2017; Bakshan et al., 2017; Mak et al., 2019) and factors affecting waste dumping and disposal (Lu et al., 2015; Yang et al., 2017; D'Amato et al., 2018; Li et al., 2018; Seror et al., 2018). Given factors in different waste management stages can be interrelated, it is essential to consider such factor interrelationships for better revealing the behavior of the real CW reduction system. In addition, effects of a management strategy or measure on CW reduction can be changing and dynamic; consequently, a dynamics perspective for understanding such effects is desired. The current literature fails to address the above considerations.

2.2 System dynamics (SD) method

The SD approach is currently prevalent in studies concentrating on economic, social, environmental and managerial systems of great complexity, covering a wide range of disciplines, such as energy management (Qudral-Ullah and Seong, 2010; Mutingiab et al., 2017), project management (Wang and Yuan, 2017), and supply chain management (Rebsa et al., 2019). In the discipline of CW management, the method has also been adopted for evaluating the social performance of CW management (Yuan, 2012), promoting CW minimization at project design (Wang et al., 2015), developing an optimal waste disposal charge for stimulating CW minimization (Yuan and Wang, 2014), and assessing the environmental benefits of CW reduction (Ding et al., 2016; 2018). The studies by Ding et al. (2016, 2018) have proven that SD is capable of dealing with the dynamic interrelationships among factors affecting the environmental performance of CW reduction. All the above studies indicate that CW management is a complex system containing multiple interconnected stages including waste generation, collection, sorting, recycling, and final disposal. As the SD method is also capable of dealing with the complexity of the CW management system and interactions among major factors in the studied system. With similar endeavors as Ding et al. (2016, 2018), we highlight the significance of the economic performance of CW reduction and thus attempt to investigate effects of management strategies on the economic performance of CW reduction, expecting to maximize the effectiveness of CW reduction strategies.

3. Model development

Based on a review of related literature, this paper divides the economic performance (cost-benefit) assessment model of CW reduction into three sub-systems, which are: waste generation and disposal subsystem, CW management subsystem, and economic benefit assessment subsystem. The three subsystems interact with each other, thus forming a holistic system. The overall structure of the proposed model is shown in Figure 1.

Please insert Figure 1 here.

Several factors influence the economic performance of CW reduction, but generally they can be divided into direct factors and indirect factors. The former may include the total cost of CW reduction (such as cost of CW collecting, sorting, reuse, recycling, landfilling and dumping), and the total benefit of CW reduction (such as purchasing cost saving and revenue from selling recycled materials and products). Therefore, the direct factors affecting CW management include collection percentage, sorting percentage, recycling percentage, reusing percentage, and landfilling percentage. The indirect factors affecting CW management include efforts to reduce waste, completeness of regulations, strength of supervision, and maturity of recycling market (Wu et al., 2010; Yuan et al., 2012; Yuan and Wang, 2014). Given that these factors are closely interlinked and their relationships are very complex, a systematic approach such as system dynamics is applied to deal with their interrelationships and complexity.

3.1 Waste generation and disposal subsystem

In the waste generation and disposal subsystem, the whole process of waste generation, collection, sorting, reusing and recycling to the final landfilling is involved. The normal process of CW generation to final disposal in China is as follows. Firstly, CW is generated and collected at construction sites where the amount of CW generation is directly affected by the constructed floor area. After collecting the waste, two treatment methods for the collected CW can be applied. One is illegal treatment; that is, some contractors may illegally dump CW to unauthorized areas in order to prevent waste treatment costs. The other is waste sorting at the construction site (normally referred to as on-site sorting), during which recyclable building materials such as metal and wood will be sold to waste recycling companies for further processing, while the non-recyclable waste will be sent to landfills. The causal loop diagram for the waste generation and disposal subsystem is shown in Figure2.The symbol + indicates that the increase (decrease) in the arrow-tail variable inherent in the loop can increase (decrease) the result to the arrowhead. It can be seen that there are four negative feedback loops in this subsystem. Taking loop B1 (waste generating → waste collecting → illegal dumping → waste management effect → waste generating) as an example, when the waste generation increases, the waste that can be collected will increase. Thus, the contractor may illegally dump more waste in order to reduce its costs for waste disposal, which seriously pollutes the environment. In this regard, relevant personnel are in need to strengthen CW reduction and management. This is expected to improve the waste management effect, and consequently to promote the reduction of waste generation. In loop B1, because the amount of generated waste increases and will decrease itself after a cycle of feedbacks as explained above, it is defined as a negative feedback loop. Following similar rules, all four feedback loops can be explained accordingly.

Please insert Figure 2 here.

According to the causal-loop diagrams in the waste generation and disposal subsystem, all the key variables affecting waste generation and disposal and the causal relationships among the variables are identified. Then the *Vensim* software package is applied to convert the causal-loop diagram in the subsystem into a stock-flow diagram (see Figure 3) to enable quantitative simulation and analysis. All the key variables and the type of the variables in this subsystem are tabulated in Appendix Ⅰ. The equations depicting the interrelations among these variables are provided in Appendix Ⅱ.

Please insert Figure 3 here.

3.2 CW management subsystem

CW management would be affected by both internal and external environment. For example, internal factors can be related to the general management of the projects and the organization, such as on-site management, participants' awareness and behavior toward CW reduction (Ajayiet al., 2016; Jin et al., 2017; Bakshanet al., 2017), while external environment concerns the effects of external stakeholders and environment on waste management, such as completeness of regulations, degree of government supervision, and maturity of the waste recycling market (Yuan and Wang, 2014; Jin et al., 2017; Huang et al., 2018). Based on a literature review (such as Yuan and Wang, 2014; Ajayiet al., 2016; Jin et al., 2017; Bakshanet al., 2017; Jin et al., 2017; Huang et al., 2018), major factors affecting CW management were identified and their relationships developed to formulate the causal-loop diagram of the CW management subsystem (see Figure 4).

Please insert Figure 4 here.

It can be seen from Figure 4 that there are five negative feedback loops (i.e. B1, B2, B3, B4, B5) in the CW management subsystem. In the negative feedback loop B1 (waste generating → waste collecting →waste sorting → waste landfilling → completeness of regulations → efforts to reduce waste→ waste management effect → waste generating), along with the increase in the amount of waste generation, the amount of waste to be landfilled will increase. Subsequently, more landfilled waste will drive the completeness of CW management regulations. The more complete the regulations, the more effort will be needed for waste reduction. Consequently, the amount of CW is reduced in relation to waste reduction efforts. Loop B3 (waste generating → waste collecting →waste sorting → waste recycling→ maturity of recycling market → cost of recycling → efforts to reduce waste→ waste management effect → waste generating) mainly considers the impact of maturity of the recycling market on CW management. Some of the interrelationships in loop B3 are similar to loop B1. In this loop, the increase in the amount of waste generation will promote waste collecting and sorting; recycled waste will then increase. Subsequently, the increased waste will increase the maturity of the recycling market, thus reducing the cost of waste recycling. Considering the cost reduction, the construction management staff will be more willing to reduce the waste. Given the improvement of CW management, the waste management effect will be promoted, and the amount of generated waste will be reduced. Loop B4 (waste generating → waste collecting →waste sorting → waste landfilling → strength of supervision → probability of illegal dumping being discovered→ cost of illegal dumping→ efforts to reduce waste→ waste management effect → waste generating) describes the impact of government supervision on CW management. As the amount of illegally dumped waste increases, the government will raise the corresponding degree of supervision, and the probability of illegal waste dumping behavior. Government fines will increase the cost of illegal waste dumping behavior, which drives construction managers to take more active CW management measures. Ultimately, this will reduce the amount of generated waste.

Similarly, according to the causal-loop diagram in the CW management subsystem, a stock-flow diagram is developed and shown in Figure5. All the key variables and the type of the variables in this subsystem are tabulated in Appendix Ⅰ. The equations depicting the interrelations among the variables are provided in Appendix Ⅱ.

Please insert Figure 5 here.

3.3 Economic-benefit assessment subsystem

Assessment of the economic-benefit of CW management aims to evaluate various costs and benefits in waste management activities. It would be useful to systematically analyze the cost-benefit effects of CW management under various management strategies and measures. The causal-loop diagram for this subsystem is shown in Figure 6.

Please insert Figure 6 here.

It is seen that there are five positive feedback loops and three negative feedback loops in the subsystem. Taking the positive feedback loop R1 (waste generating → waste collecting → cost of collecting→ total cost of managing waste→ net benefits of managing waste → waste management effect → waste generating) as an example of the five positive feedback loops. As the amount of waste generation increases, the waste that can be collected also increases, which increases the waste collection cost. Then, the increased cost contributes to the total cost of waste management and continues to decrease the net benefits of waste management. Eventually, the reduction in net benefits will have a negative effect on the waste management effect, and the reduced waste management effect will lead to more waste generation. Further, taking the negative feedback loop B1 (waste generating → waste collecting →waste sorting → waste recycling → purchasing cost saving → total cost of managing waste→ net benefits of managing waste → waste management effect → waste generating) as an example of the five negative feedback loops. With an increase in CW generation, collection and sorting, there will be more recyclable waste, thus saving the procurement cost of new materials and increasing net benefits of waste management. Correspondingly, the waste management effect will be promoted and thus reduce CW generation.

Based on the causal-loop diagrams, the stock-flow diagram for the waste economic-benefit assessment subsystem is developed and shown in Figure 7. All the key variables and the type of the variables in this subsystem are tabulated in Appendix Ⅰ. The equations depicting the interrelations among the variables are provided in Appendix Ⅱ.

Please insert Figure 7 here.

3.4 Cost-benefit assessment model of CW reduction

The three subsystems (i.e. waste generation and disposal subsystem, CW management subsystem, and economic benefit assessment subsystem) interact with each other through common variables, thus forming a holistic system for assessing the economic performance of CW reduction. For example, the CW management subsystem could influence the waste generation and disposal subsystem in following ways. The implementation of different CW reduction measures during the construction phase will affect CW through making efforts to reduce waste, which would consequently influence CW generation in the waste generation and disposal subsystem. Similarly, the CW management subsystem could influence the economic benefit assessment subsystem. For example, “government supervision” would affect corresponding costs in waste management activities, and subsequently influence the economic benefit in the economic benefit assessment subsystem. Furthermore, the economic benefit assessment subsystem would also influence the waste generation and disposal subsystem. When it is possible to obtain revenue through CW management, the contractor will be more proactive in conducting waste management activities, which results in decreased waste generation. Integrating the interrelationship and mutual influences among the three subsystems, a holistic flow diagram with the three subsystems is obtained (Figure 8).

Please insert Figure 8 here.

4. Variables and data

Our study selected a residential building project in Chengdu, the capital of southwestern China's Sichuan province, for real-world case analysis. The total planned construction area is about 357,450 square meters, and the total investment was estimated to be 1.5 billion. The construction period of the project was planned to be 32 months (from March 2016 to October 2018). The planned average monthly construction area was 11,170 square meters.

To carry out further quantitative analysis with the model, it is essential to quantify the variables as well as variable relationships in the model. This was achieved through a comprehensive review of relevant literature and reports, analyzing the specific functions of system dynamics, and conducting a project survey with expert interviews.

Some parameters can be determined by review of literature and reports. Existing literature and reports were obtained by referring to documents such as literature from research database, government reports, statistical yearbooks, and related authoritative websites and documents. Through the literature review (similar as Yuan et al., 2011;

Wang and Yuan, 2014; Ding et al., 2016), some parameters in the waste economic-benefit assessment subsystem were obtained (see Table 1).

Please insert Table 1 here.

To handle the complicated relationships between variables, the *Vensim* software package provides a set of commonly used functions such as Table functions, delay functions and logic functions. For some variables (such as dependent variables) that cannot be expressed in analytic expressions of general elementary functions, Table functions can be utilized to define their relationships. A dependent variable can be determined by describing its interrelationship with other independent variables. Specifically, the interrelationship can be illustrated by a graph, which can be realized by “AS Graph” option in *Vensim*. As an example of Table function, the interrelationship between “efforts to reduce waste” and “completeness of regulations” is presented in Figure 9. It should be noted that although it is presented as a table function, the relationship between the two variables has to be determined based on outcomes from expert interviews. Similarly, variables such as completeness of regulations, waste reduction effects, and maturity of the recycling market can also be described by following such a rule.

Please insert Figure 9 here.

Some parameters need to be determined by expert interviews. Those data were collected from eight interviewees participating in the project, including 1 project manager, 2 construction supervisors, 3 construction site managers, and 2 construction site technical engineers. They were selected because of their eminent experience in participating in CW management. Variable values were obtained through site interviews and are shown in Table 2.

Please insert Table 2 here.

5. Model validation

Prior to conducting quantitative simulation and analysis, it is essential to assure the validity of SD model through a series of model tests. According to Sterman (2000), main tests include: 1) boundary-adequacy test, 2) structure assessment test, 3) dimension consistency test, 4) extreme condition test, and 5) sensitivity analysis.

The boundary-adequacy test is to determine whether the variables and feedback loops set by the model are sufficient to describe the research problem and whether the intended research objectives can be achieved. In this study, the screening of each parameter in the model has undergone a rigorous literature review and multiple expert interviews to assure that variables are streamlined and comprehensive for abstracting the research problem.

The structure assessment test ensures that the constructed SD model is logical and consistent with the actual feedback system. By referring to the causal-loop diagrams in Figures 2, 4 and 6 that are based on a comprehensive literature review and waste management practices, the test was validated. Hence, the developed SD model was able to meet the requirements of the structure assessment test.

The dimension consistency test verifies that the equation relationships in the model are theoretically correct, and checks whether the units at the left and right ends of the dynamic equation have been determined in the model. Clicking "Units check" in the *Vensim* software performs this test. It is found that all the equations in the proposed model passed the dimension consistency test.

The extreme condition test is to verify that the model is realistic and credible in extreme conditions. The main test method for extreme condition testing is to adjust the values of some parameters to extreme values and observe whether the simulated results are in line with the actual situation. Taking the illegal dumping percentage in the model as an example, the normal value of it is between 0 and 1. According to the above analysis, the illegal dumping percentage (IDP) in the SD model established in this paper is 0.12. In order to test whether the model can pass the extreme condition test, this study assigned the value 0, 0.12, 0.5, and 1 respectively to observe the amount of waste landfilled (ALW), and the results are shown in Figure 10. When the value is 0 (line 1), it means that there is no illegally dumped waste, and the amount of waste landfill reaches the maximum value; when the variable is assigned the value 1 (line 4),it means all collected waste at the construction site has been illegally dumped and there is no landfilled waste, which is consistent with curve 4; when the IDP is 0.12 (line 2) and 0.5 (line 3), as the IDP increases, the ALW will decrease and the value of ALW is between the maximum and the minimum. The tests show IDP is in line with the actual situation under extreme condition, indicating the variable passes the extreme condition test. The extreme conditions tests of other variables follow similar procedures and rules and all are successfully verified.

Please insert Figure 10 and Figure 11 here.

The sensitivity analysis includes two main contents. The first is to test whether the model is affected by small changes in individual parameters. The second is to change parameter values within a reasonable range and observe the behavior change of the model. Taking the impact of the *sorting percentage* (SP) on *total benefits of managing waste* (TBMW) as an example, the value of SP is assigned as 0, 0.5, 0.6, 0.7, and 0.8, respectively. The results in Figure 11 indicate that the larger the SP, the more TBMW, and there is a significant change of TBMW even when the SP is small. Particularly, the TBMW is zero when SP is 0%, which is in line with the actual situation of CW management. In the same vein, other major influencing variables are tested and have passed the sensitivity test.

In summary, the SD model proposed for economic-benefit assessment of CW reduction has passed five validity tests, and can be used for simulation and scenario analysis.

6. Simulation and scenario analysis

6.1. Scenario design

In this section, different scenarios are conceived and simulated by using the proposed model. The overall purpose of designing different scenarios for simulation is to assess impacts of various management measures and strategies (options) on the cost-benefit of CW reduction. Generally, the CW system can be influenced by various factors (i.e. management measures or strategies), and effects of different factors on the system behavior can be reinforced or balanced, which is evident in line with the system dynamics principles (Yuan, 2012). In this regard, two types of scenarios are designed and simulated. One is the single-factor scenario involving four scenarios (i.e. Scenario I, Scenario Ⅱ, Scenario Ⅲ and Scenario Ⅳ), which is used to test single-factor influence on the system behavior (i.e. the economic performance of CW reduction). The other is a multivariate scenario (Scenario Ⅴ), which combines the four factors involved in the single-factor scenarios and mainly targets for explaining the reinforced or balanced effects resulted from combined factors. The above practice of designing scenarios enables a comparison between effects of single-factor analysis and multi-factor analysis.

The literature generally shows extensive research investigating CW management strategies and measures from the perspective of contractors and the government. It also reveals some major factors affecting CW management, including sorting percentage (SP), illegal dumping percentage (IDP), financial subsidy on recycling (FSR), and unit landfilling charge fee (ULCF). The economic benefit of these CW management measures are investigated in Scenario Ⅰ, Scenario Ⅱ, Scenario Ⅲ and IV respectively in the single-factor scenario analysis, while the combination of the four CW management measures forms the base for developing the multi-factor scenario (Scenario V). Specific aim of simulating each scenario is illustrated as follows.

Scenario Ⅰ: This scenario is concerned with how changes in SP of contractors would affect the economic benefit of CW reduction;

Scenario Ⅱ: This scenario is concerned with how changes in IDP of contractors would affect the economic benefit of CW reduction;

Scenario Ⅲ: This scenario is used to reveal how changes in FSR of the government would affect the economic benefit of CW reduction;

Scenario Ⅳ: This scenario concerns how changes in ULCF of the government would affect the economic benefit of CW reduction; and

Scenario V: This is a multi-factor scenario focusing on how changes of SP and IDP of contractors, and FSR and ULCF of the government simultaneously would affect the economic benefit of CW reduction.

6.2. Single-factor scenario analysis

Scenario Ⅰ simulates and analyzes the impact of SP on the NBMW (net benefits of managing waste) and the TWMS (total waste materials saved). Previous studies indicate that on-site sorting activities at construction sites can effectively reduce the amount of waste to be landfilled and promote reuse and recycling (Wang and Yuan, 2010). Thus, the change of SP can directly impact waste recycling percentage and reuse percentage, which in turn affects the total amount of generated waste and the total cost of waste management. According to afore-mentioned expert interviews, the value of SP is 0.68, which is regarded as scenario (Ⅰ-1). When the value of SP is 0.85, it is defined as scenario (Ⅰ-2), and the value 0.95 is defined as scenario (I-3) for the analysis. The results of the impact of SP on the NBMW are shown in Figure 12. To have a better quantitative understanding of the results, Table 3 presents the quantitative impacts of changes in the SP on the NBMW. It can be seen that as the SP increases, the NBMW that can be obtained from waste management will also increase. Particularly, when SP is 95%, the NBMW of waste management can be turned into a positive value in the ninth month. Therefore, during the construction process, the contractor can obtain more net income by increasing the sorting percentage. Additionally, as Figure 13 shows, when SP increases from 0.68 to 0.95, 952 tons of waste can be saved, indicating that the increase of SP is effective in saving wasted building materials.

Please insert Figure 12 and Figure 13 here.

Please insert Table 3 here.

Scenario II concerns the impact of IDP (illegal dumping percentage) on the NBMW. It is widely acknowledged that illegal dumping of waste not only seriously pollutes the environment, but also results in high illegal dumping costs. Scenario II analyzes the impact of IDP by reducing the value of IDP.A predetermined value of 0.12 was set as scenario (Ⅱ-1) and the IDP reduced by 30% for scenario (Ⅱ-2) and by 50% for scenario (Ⅱ-3) for the purposes of scenario analysis. The simulation results and quantitative analysis results are shown in Figure 14 and Table 4 respectively. Apart from reducing environmental pollution to improve environmental benefits, the results show that reducing IDP can increase the NBMW, which is probably due to the benefits from operations such as recycling and reuse.

Please insert Figure 14 here.

Please insert Table 4 here.

Scenario Ⅲ investigates the impact of FSR (financial subsidy on recycling) on the NBMW from the perspective of the government. As a policy incentive, FSR can promote the on-site sorting and recycling of waste, and strengthen the contractor's waste reduction management, thus reducing waste generation. The initial value of FSR is zero (Ⅲ-1), and FSR is assigned the value of 10(Ⅲ-2), 20(Ⅲ-3), 30(Ⅲ-4), 50(Ⅲ-5), respectively. The simulation results and quantitative analysis results are shown in Figure 15 and Table 5, respectively. It can be seen from the results that the NBMW is increasing as FSR increases from 0 to 50 (yuan/ton). Moreover, when FSR increases to 30, the net income from CW management can be converted to a positive value in the seventh month.

Please insert Figure 15 here.

Please insert Table 5 here.

Scenario Ⅳ investigates the impact of ULCF (unit landfilling charge fee) on the NBMW and amount of waste landfilled (AWL). The value of ULCF was initially set as 50yuan/ton, which is regard as scenario (Ⅱ-1). Assuming the value of ULCF raises to 60 (Ⅳ- 2), 70 (Ⅳ-3), 80 (Ⅳ-4) and 90 (Ⅳ-5), the simulation results and quantitative analysis results are provided in Figure 16 and Table 6 respectively. According to the results, when the landfill cost changes from 50 to 90, the NBMW of waste management increases. The major reason for this is that when the cost of waste landfill increases, the contractor will enhance on-site sorting activities in order to reduce the waste disposal costs, thus obtaining greater profits. The influence of ULCF on AWL is shown in Figure 17 from which it can be seen that AWL decreases as ULCF increases. However, curve 4 and curve 5 almost coincides with each other, which is due to the existence of a certain function between ULCF and landfilling percentage. Specifically, when ULCF reaches 80 yuan/ton, the landfilling percentage will not be altered significantly with the increase of the ULCF. This indicates that from the perspective of CW reduction, the ULCF should not surpass 80 yuan/ton.

Please insert Figure 16 and Figure 17 here.

Please insert Table 6 here.

6.3. Multivariate analysis scenario

The previous section adjusted the different values of the four parameters of SP, IDP, FSR and ULCF, to analyze their impacts on the economic benefits of CW management. However, in the practical situation, the situation is of great complexity and those variables might impact the results simultaneously. Thus, the results of the multivariate scenario might very different from that of a single-factor scenario. Therefore, this section will combine the analysis results of the previous sections to conduct a multivariate scenario (Scenario V) analysis. The values of the variables in scenario V are shown in Table 7. The simulation results and quantitative analysis results of NBMW are shown in Figure 18 and Table 8.

Please insert Figure 18 here.

Please insert Table 7 here.

Please insert Table 8 here.

By comparing the results of the multivariate scenario with those of the single-factor scenarios, it can be seen that the values of NBMW obtained by the multivariate scenario are significantly better than those single-factor scenarios. Figure 16 shows that the value of NBMW under scenario V-1 can be converted to positive in the eighth month of the construction duration. However, the value of NBMW under scenario V-1 and scenario V-2 could turn into positive in the seventh month. A plausible explanation is that the effect of promoting economic benefits under the change of single management measures is limited, while the interaction of various management measures could strengthen the effects and lead to better outcomes of economic benefits from CW management.

7. Discussions

The afore-presented model and simulations proved that the proposed SD model is able to well reveal the interrelationships of major factors affecting the economic performance of CW reduction. The four factors used for scenario design and model simulations can be representative in management strategies and measures because two factors (i.e. sorting percentage, illegal dumping percentage) are related to the project contractor, and the other two (i.e. financial subsidy on recycling, unit landfilling charge fee) are related to the local government. It is generally agreed that both stakeholder are critical in developing CW reduction strategies and measures, although the strategies and measures might be at different levels.

The results indicate that a higher sorting percentage and a lower illegal dumping percentage both could enhance the net benefits of CW reduction. Obviously, both of the percentages are dependent on on-site waste sorting activities. Actually, the significance of on-site sorting has been discussed in previous studies (such as Wang and Yuan, 2010; Ding et al., 2016). For instance, Wang and Yuan (2010) indicated that on-site sorting activities in construction projects can effectively reduce the amount of waste to be landfilled. Ding et al. (2016) revealed the advantage of on-site sorting in achieving better environmental performance. Our research findings complement their studies by emphasizing the significance of on-site soring in reaping higher economic benefits. The results are informative to contractors because contractors could take the initiative to improve its economic performance of CW reduction through enhanced on-site sorting practice and reduced illegal dumping percentage.

The results reveal that the impact of “financial subsidy on recycling” on the net benefits of CW reduction is more significant than impacts of other single measures.

This tells that for encouraging contractors' CW reduction, an effective strategy for the governmental is to provide financial subsidy for waste recycling activities. Also, it is found that the unit landfilling charge fee should be in an appropriate range; otherwise a too low fee is not conductive to increasing the net benefits of CW reduction whilst a too high fee is not beneficial to reducing the percentage of landfilled waste. Thus, this informs that the local government has to work out a reasoble landfilling charge fee to maximize its effectiveness in CW reduction.

By comparing results from different model simulations, it is found that compared with a single policy, adopting combined management strategies and measures simultaneously could lead to better outcomes regarding the economic benefits of CW reduction. This finding echoes with prior findings from Wang et al. (2015) and Ding et al. (2018), claiming that multiple waste reduction strategies could be more effective in achieving better environmental benefits. This result is quite informative for the local government when seeking to develop policies for improving the net benefits of CW reduction based on different policy combinations.

8. Conclusions

This study offers an insight into the dynamics and interrelationships of major variables affecting the cost-benefits of CW reduction. A model comprising seventeen feedback loops is developed based on the principles of system dynamics, and tests conducted to ensure that the model is structurally and behaviorally valid and reliable.

The simulation results of the case study indicate that CW in the studied project could be reduced significantly through higher waste landfill charges. The findings also show that both investment in waste management and major stakeholders' compliance with waste management regulations, have an impact on CW reduction. It should be noted that although this study only compared four policy scenarios with the results of the base scenario, the model could also be used to simulate and discuss similar scenarios comprising other policies.

The causal-loop diagrams are useful for depicting the feedback relationships underlying major variables involved in assessing the cost-benefits of CW management. The simulation results reveal that the contractor's improvement in CW reduction measures and the government's development of economic incentives can enhance the economic benefits of CW management. Specifically, 1) when the contractor increases the waste sorting percentage from an initial 68% to 95%, the net income of waste management increases continuously thereby saving 952 tons of waste; 2) when the illegal waste dumping percentage is reduced by 50%, the net income of waste management increases by 127,000 yuan; 3) when the government provides a financial subsidy for waste recycling, the net income of waste management increases significantly; 4) when the government raises unit landfilling charge fees, the net income of waste management will increase, and landfilling percentage will not be altered significantly when the unit landfilling charge fee amounts to 80 yuan per ton. Results of scenario analyses indicate that compared to single waste reduction measures, combining different waste reduction measures can effectively improve the waste management effect and increase the net income of managing waste.

The contributions of this are fourfold. Firstly, the causal-loop diagram delineating the interconnected relationships among major variables could enrich research on assessment of economic benefits of CW reduction. Secondly, the established model in the stock-flow diagram serves as an experimental platform for dynamically simulating the effects of different management measures on the economic benefits of CW management over time. Thirdly, the model could trigger further investigations and debates on applying system dynamics to CW management. Finally, the results of the project case study provide insights into the measures that could play a role in promoting economic benefits of CW management for the project.

Acknowledgement

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Appendix Ⅰ. List of three subsystem variables

Numb	Descriptions	Abbreviatio	Unit	Variable
	Waste generation and disposal subsystem			
1	Constructed floor area	CFA	ton	Constant
2	Waste generating rate	WGR	\	Constant
3	Waste generating	WG	ton/Month	Flow
4	Amount of generated waste	AGW	ton	Stock
5	Waste Collecting	WC	ton/Month	Flow
6	Collecting percentage	CP	\	Constant
7	Amount of collected waste	ACW	ton	Stock
8	Illegal dumping percentage	IDP	\	Constant
9	Illegal dumping	ID	ton/Month	Flow
10	Amount of illegal dumped	AIDW	ton	Stock
11	Sorting percentage	SP	\	Constant
12	Waste sorting	WS	ton/Month	Flow
13	Amount of sorted waste	ASW	ton	Stock
14	Recycling percentage	RLP	\	Constant
15	Waste recycling	WRL	ton/Month	Flow
16	Amount of recycled waste	ARLW	ton	Stock
17	Reusing percentage	RSP	\	Constant
18	Waste reusing	WRS	ton/Month	Flow
19	Amount of reused waste	ARSW	ton	Stock
20	Landfilling percentage	LP	\	Constant
21	Waste landfilling	WL	ton/Month	Flow
22	Amount of waste landfilled	AWL	ton	Stock
23	Materials saved by recycle	MSRL	ton/Month	Flow
24	Materials saved by reuse	MSRS	ton/Month	Flow
25	Total waste materials saved	TWMS	ton	Stock
	CW management subsystem			
26	Impact of efforts to reduce	IERWR	\	Auxiliary
27	Completeness of regulations	CR	\	Auxiliary
28	Strength of supervision	SS	\	Auxiliary
29	Probability of illegal dumping	PIDBD	\	Auxiliary
30	Cost of illegal dumping	CID	yuan	Auxiliary
31	penalty	P	yuan	Constant
32	Maturity of recycling market	MRM	\	Auxiliary
33	Waste generating rate	WGR	\	Auxiliary
34	Efforts to reduce waste	ERW	\	Auxiliary
35	Illegal dumping percentage	IDP	\	Auxiliary
36	Landfilling percentage	LP	\	Auxiliary

37	Impact of landfilling charge	IICFDP	\	Auxiliary
38	Unit landfilling charge fee	ULCF	yuan/ton	Constant
39	Financial subsidy on recycling	FSR	yuan/ton	Constant
40	Unit cost of transportation	UCT	yuan/ton	Constant
	Economic - benefit assessment subsystem			
41	Unit cost of collecting	UCC	yuan/ton	Constant
42	Unit cost of sorting	UCCS	yuan/ton	Constant
43	Unit cost of reusing	UCRS	yuan/ton	Constant
44	Unit cost of recycling	UCRL	yuan/ton	Constant
45	Unit cost of material	UCMP	yuan/ton	Constant
46	Cost of collecting	CC	yuan	Auxiliary
47	Cost of sorting	CS	yuan	Auxiliary
48	Cost of reusing	CRS	yuan	Auxiliary
49	Cost of illegal dumping	CID	yuan	Auxiliary
50	Cost of recycling	CRL	yuan	Auxiliary
51	Cost of landfilling	CL	yuan	Auxiliary
52	Total cost of managing waste	TCMW	yuan	Auxiliary
53	Total benefits of managing	TBMW	yuan	Auxiliary
54	Net benefits of managing	NBMW	yuan	Auxiliary
55	purchasing cost saving	PCS	yuan	Auxiliary
56	Revenue from selling wasted	RSWM	yuan/ton	Constant
57	Revenue from recycling	RR	yuan	Constant
58	Waste management effect	WME	\	Auxiliary

Appendix Ⅱ. Equations of the model

INITIAL TIME = 0
FINAL TIME = 32
TIME STEP = 1（Month）

Waste generation and disposal subsystem

（1）$WG = CFA \times WGR$

（2）ARSW = INTEG (WRS - MSRS,0)

（3）ASW = INTEG (WS - WL - WRL - WRS,0)

（4）$WRS = ASW \times RSP$

（5）ARLW = INTEG (WRL - MSRL,0)

（6）ACW = INTEG (WC - WS - ID,0)

（7）$WS = ACW \times SP$

（8）$WRL = ASW \times RLP$

（9）$WC = AGW \times CP$

（10）AGW = INTEG (WG - WC,0)

（11）TWMS = INTEG (MSRS + MSRL,0)

（12）$WL = ASW \times LP$

（13）AIDW = INTEG (ID,0)

（14）$ID = ACW \times IDP$

（15）AWL = INTEG (WL,0)

CW management subsystem& Economic - benefit assessment subsystem

（16）$WGR = 0.037 \times (1- IERWR)$

（17）IERWR = WITH LOOKUP(ERW, (([(0,0) - (1,1)], (0.1,0.15), (0.2,0.2), (0.3,0.25), (0.4,0.28), (0.5,0.3), (0.6,0.35), (0.7,0.4), (0.8,0.45), (0.9,0.48)))

（18）ERW = WITH LOOKUP(CR, ([(0,0)-(1,1)],(0,0),(0.05,0.0921053), (0.1,0.184211), (0.15,0.29386), (0.2,0.399123), (0.25,0.45614), (0.3,0.561404), (0.35,0.6232), (0.4,0.6713), (0.45,0.730263), (0.5,0.789474), (0.55,0.835526), (0.6,0.881579), (0.65,0.907895), (0.7,0.921053), (0.75,0.953947), (0.8,0.967105), (0.85,0.973684), (0.9,0.980263), (0.95,0.980263)))

（19）CR = WITH LOOKUP(Time , ([(0,0) - (32,1)], (0,0.2), (6,0.25), (12,0.45), (18,0.5), (25,0.55), (32,0.6)))

（20）MRM = WITH LOOKUP(ERW, ([(0,0) - (1,1)], (0.16,0.15), (0.3,0.25), (0.4,0.4), (0.5,0.6), (0.6,0.7), (0.7,0.75), (0.8,0.8), (0.9,0.85)))

（21）$CRL = (UCRL - FSR)\times ARLW$

（22）SS = WITH LOOKUP(Time, ([(0,0) - (32,1)], (0,0.2), (6,0.25), (12,0.65), (18,0.75), (25,0.8), (32,0.85)))

（23）PIDBD = WITH LOOKUP(SS, ([(0,0) - (1,1)], (0,0), (0.1,0.012), (0.2,0.027), (0.3,0.05), (0.4,0.093), (0.5,0.137), (0.6,0.204), (0.7,0.258), (0.8,0.326), (0.9,0.409), (1,0.497)))

（24）$CID = AIDW\times UCT + PIDBD\times P$

（25）IICFDP = WITH LOOKUP(ULCF, ([(0,0) -(1,0.1)], (0.1,0.015), (0.2,0.02), (0.3,0.025), (0.4,0.028), (0.5,0.03), (0.6,0.035), (0.7,0.04), (0.8,0.045)))

（26）$NBMW = TBMW - TCMW$

（27）$CL = AWL\times (ULCF + UCT)$

（28）$RR = ARLW\times (RSWM + FSR)$

（29）$CRL =(UCRL + UCT)* ARLW$

（30）$TCMW = CRS + CS + CRL + CL + CC + CID$

（31）$CRS = ARSW\times (UCRS + UCT)$

（32）$PCS = ARSW\times UCMP$

（33）$CS = ASW\times UCCS$

（34）$CC = ACW\times UCC$

（35）$TBMW = RR\times PC$

Figure

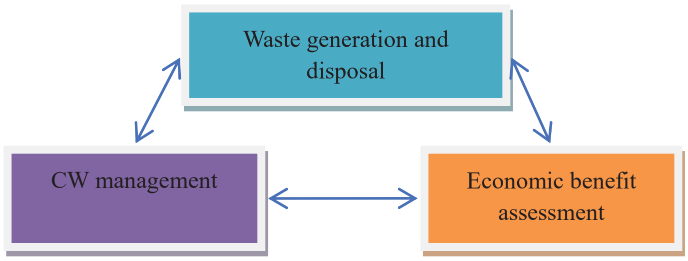

Figure 1. Overall structure of the cost-benefit assessment model

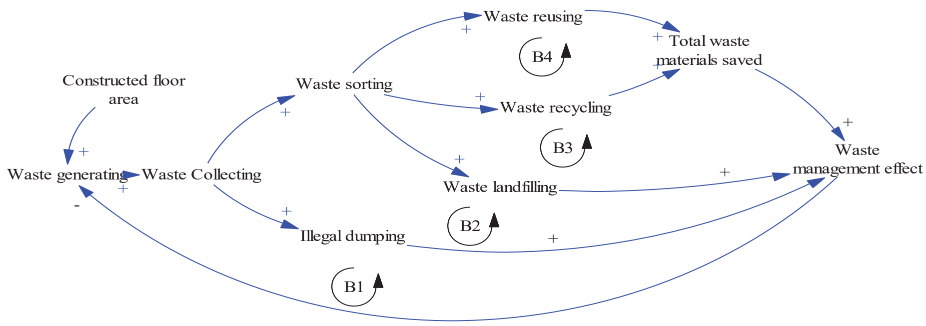

Figure 2. Causal-loop diagram of the waste generation and disposal subsystem

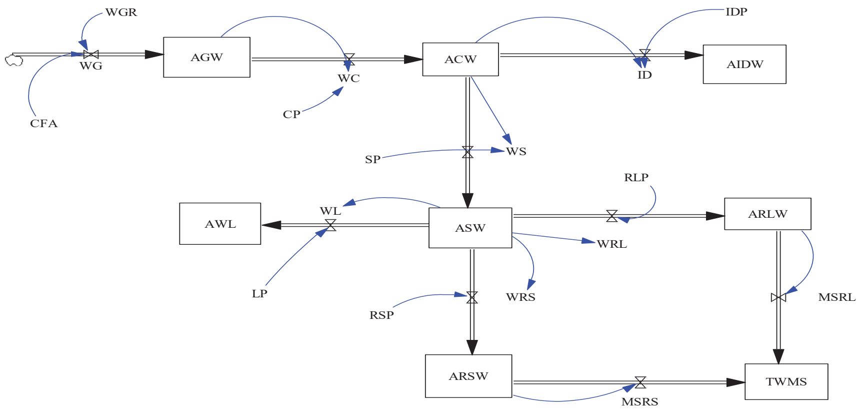

Figure 3. Stock-flow diagram of the waste generation and disposal subsystem

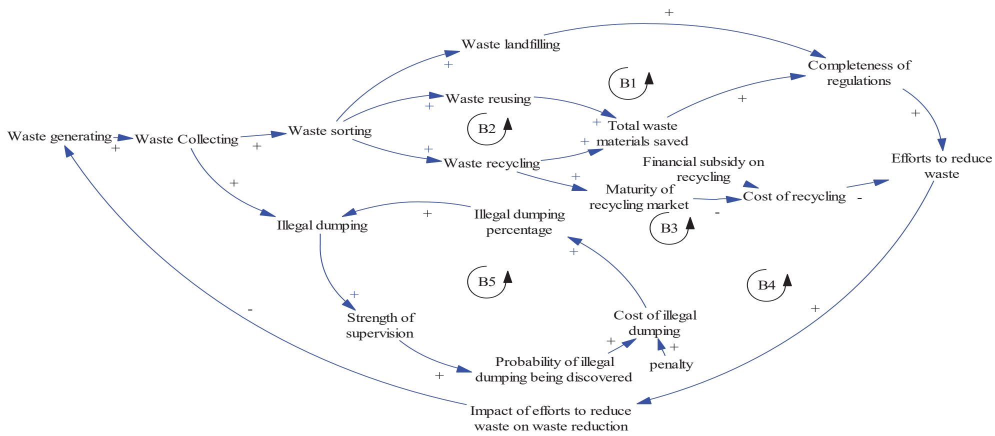

Figure 4. Causal-loop diagram of the CW management subsystem

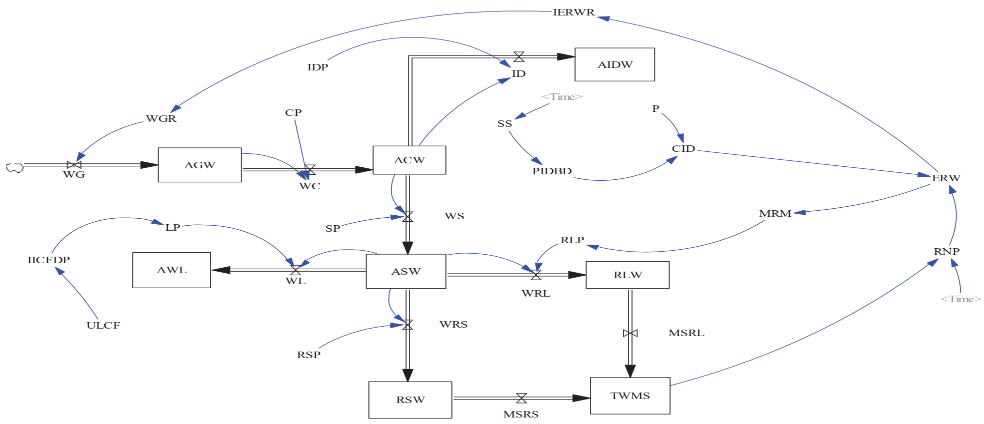

Figure 5. Stock-flow diagram of CW management subsystem

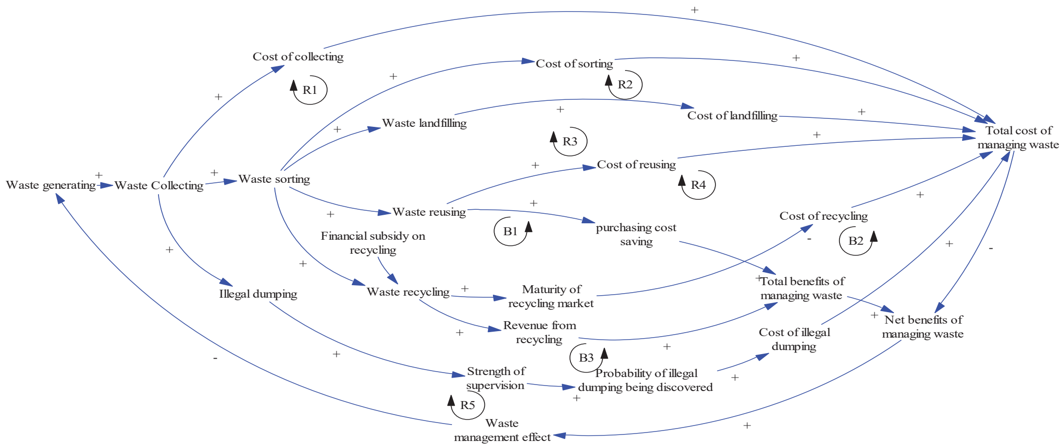

Figure 6. Causal-loop diagram of the economic-benefit assessment subsystem

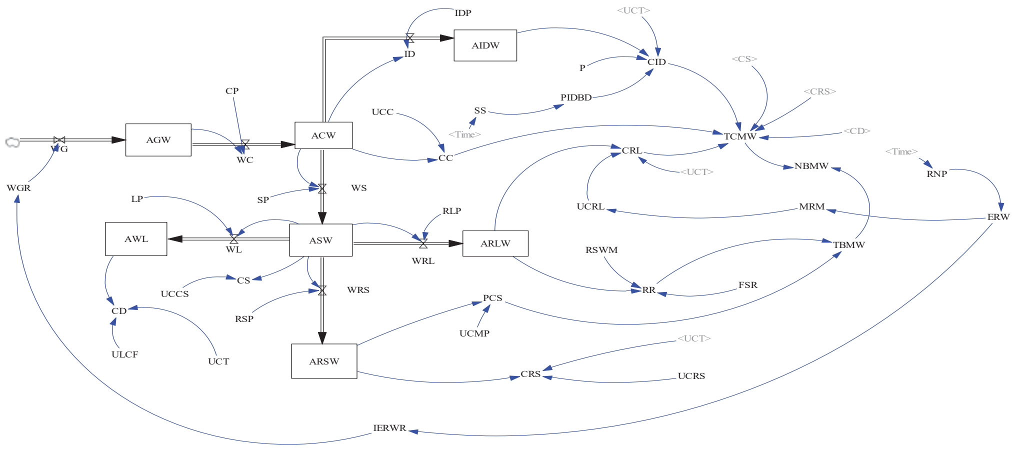

Figure 7. Stock-flow diagram of the economic-benefit assessment subsystem

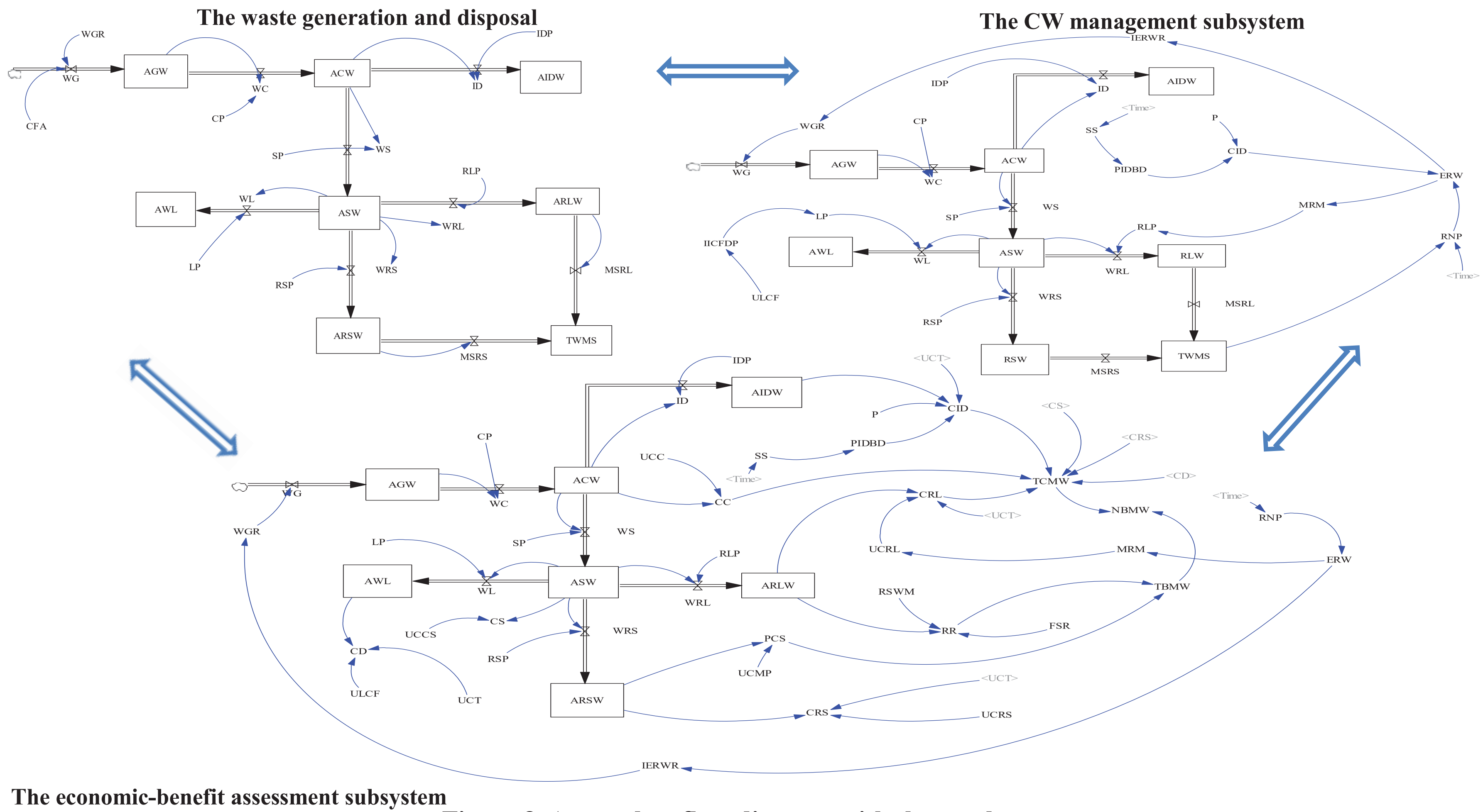

Figure 8. A complete flow diagram with three subsystems

Figure 9. Example of *Vensim* Table function

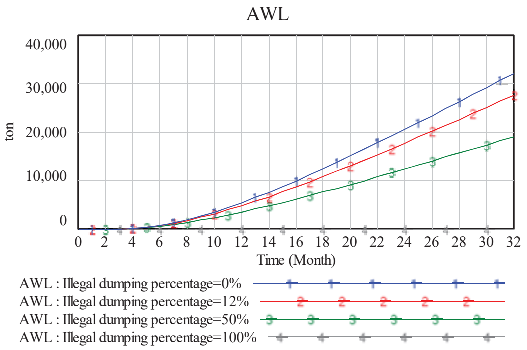

Figure 10. Example of extreme condition testing

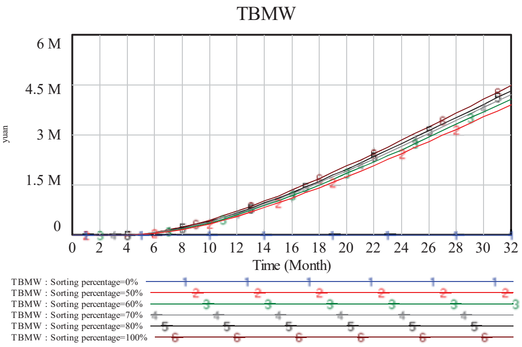

Figure 11.Example of sensitivity analysis

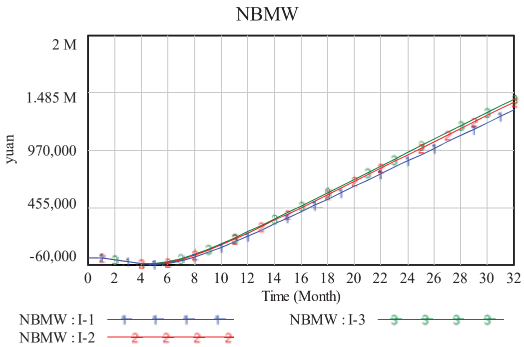

Figure 12. NBMW in scenario I

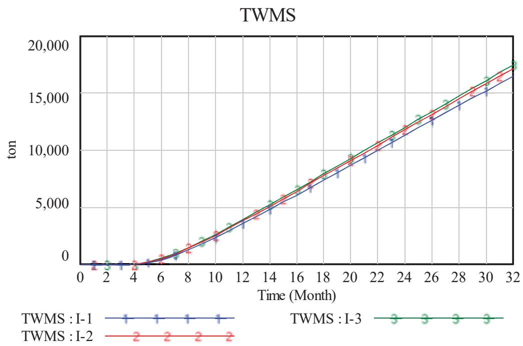

Figure13. The TWMS in scenario I

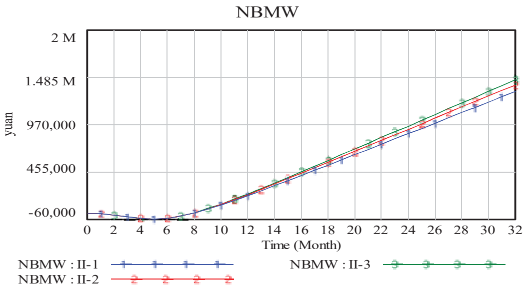

Figure 14. NBMW in the single-factor scenario II

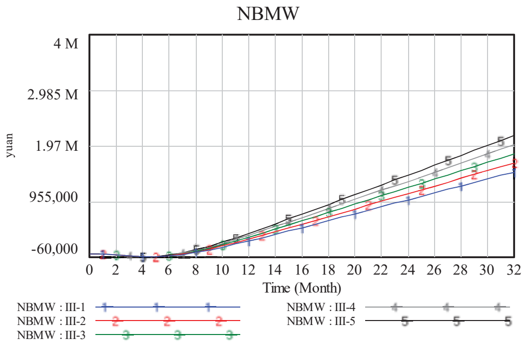

Figure 15. NBMW in scenario III

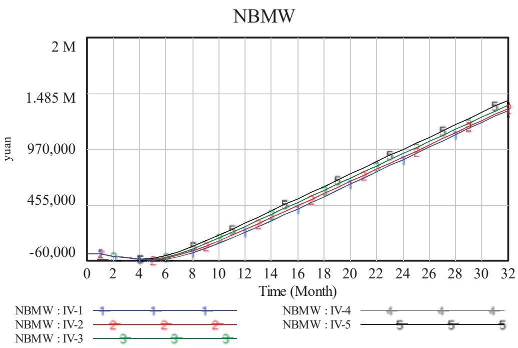

Figure 16. NBMW in scenario IV

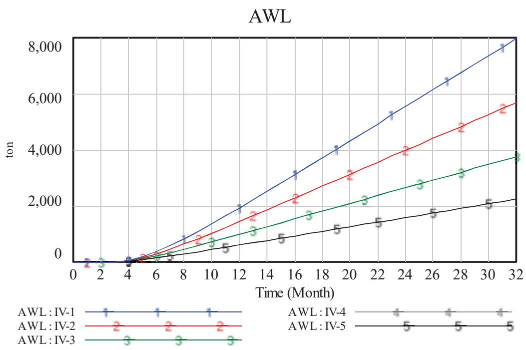

Figure17. AWL in scenario IV

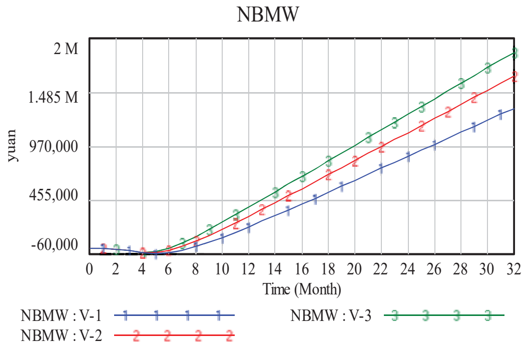

Figure 18. NBMW in the multivariate scenario V

Table

Table 1. Main parameters determined by review of literature and reports (M1)

Variables	Value	Unit	Sources
Unit cost of collecting	15	yuan/ton	Ding et al., 2016
Unit cost of material purchasing	60	yuan/ton	Ding et al., 2016
Unit cost of recycling	20	yuan/ton	Yuan et al., 2011
Unit cost of sorting	20	yuan/ton	Ding et al., 2016
Unit cost of reusing	15	yuan/ton	Yuan et al., 2011
Unit cost of transportation	25	yuan/ton	Yuan et al., 2011
Unit landfilling charge fee	50	yuan/ton	Wang and Yuan, 2014
Revenue from selling wasted	20	yuan/ton	Ding et al., 2016
penalty	3000	yuan/once	Wang and Yuan, 2014
Waste generating rate	0.037	tom/m^2	Ding et al., 2016

Table 2. Main parameter values determined by expert interviews (M3)

Variables	Value	Unit
Collecting percentage	0.85	\
Sorting percentage	0.68	\
Recycling and reusing	0.28	\
Landfilling percentage	0.44	\
Illegal dumping percentage	0.12	\
Constructed floor area	11170	m^2/month

Table 3. Quantitative results in the single-factor scenario I

Scenario I	Scenario I-1	Scenario I-2	Scenario I-3
Values of SP	0.68	0.85	0.95
NBMW（yuan）	1330000	1399000	1430000
Improvement	\	5.2%	7.5%

Table 4. Quantitative results in the single-factor scenario II

Scenario Ⅱ	Scenario Ⅱ-1	Scenario Ⅱ-2	Scenario Ⅱ-3
Values of IDP	0.12	0.084	0.06
NBMW（yuan）	1330000	1404000	1457000
Improvement	\	5.6%	9.5%

Table 5. Quantitative results in the single-factor scenario III

Scenario Ⅲ	Scenario Ⅲ-1	Scenario Ⅲ-2	Scenario Ⅲ-3	Scenario Ⅲ-4	Scenario Ⅲ-5
Values of FSR（yuan）	0	10	20	30	50
NBMW（yuan）	1.33M	1.495M	1.661M	1.826M	2.157M
Improvement	\	9.7%	24.9%	37.3%	62.2%

Table 6. Quantitative results in the single-factor scenario IV

Scenario Ⅳ	Scenario Ⅳ-1	Scenario Ⅳ-2	Scenario Ⅳ-3	Scenario Ⅳ-4	Scenario Ⅳ5
Values of ULCF	50	60	70	80	90
NBMW（yuan）	1.33M	1.346M	1.376M	1.421M	1.511M
Improvement	\	1.2%	3.5%	6.8%	16.6%

Table 7. Values of the variables in scenario V

Scenario V	SP	IDP	FSR	ULCF
Scenario V-1	0.68	0.12	0	50
Scenario V-2	0.85	0.084	10	60
Scenario V-3	0.95	0.06	20	70

Table 8. Quantitative results in the multivariate scenario V

Scenario Ⅴ	Scenario Ⅴ-1	Scenario Ⅴ-2	Scenario Ⅴ-3
NBMW（yuan）	1330000	1636000	1866000
Improvement	\	23%	40.3%