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Measuring the impact of prefabrication on construction waste reduction: an empirical study in Shenzhen, China

Zhengdao Li [a*], Geoffrey Qiping Shen [b] and Mustafa Alshawi [c]

[a*] Corresponding author, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Tel: (+852) 34008135, Fax: (+852) 2764 5131. Email: clyde.zhengdao@connect.polyu.hk

[b] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Tel: (+852) 2766 5817, Fax: (+852) 2764 2572. Email: bsqpshen@polyu.edu.hk

[c] Faculty of Business, Law and the Built Environment, Salford University, Salford, United Kingdom. Email: m.a.alshawi@salford.ac.uk

Abstract

Prefabrication has been widely regarded as a sustainable construction method in terms of its impact on environmental protection. One important aspect of this perspective is the influence of prefabrication on construction waste reduction and the subsequent waste handling activities, including waste sorting, reuse, recycle, and disposal. Nevertheless, it would appear that existing research with regard to this topic has failed to take into account its innate dynamic character of the process of construction waste minimization; integrating all essential waste handling activities has never been achieved thus far. This paper proposes a dynamic model for quantitatively evaluating the possible impacts arising from the application of prefabrication technology on construction waste reduction and the subsequent waste handling activities. The resulting model was validated based on an actual building project in Shenzhen, China.

The simulation results of the design scenarios indicate that the policy on providing subsidy for each square meter of the prefabrication adopted in the construction would have more significant effect on promoting the use of prefabrication and improving the performance of construction waste reduction compared to the increase of income tax benefits. The results also show that (1) interaction exists among different management measures, and (2) the combined effect of multiple policies is larger than the simple sum of their individual impacts, indicating the need for comprehensive consideration on the combined effect of these potential polices. This paper demonstrates the potential benefits of using a system dynamics approach in understanding the behavior of real-world processes. The developed model not only serves as a practical tool for assessing the impact of off-site prefabrication on construction waste reduction and the corresponding waste handling activities, but also help provide a valuable reference to policy makers through the comparison of simulation results generated under various scenarios such that the best policy mix can be identified prior to production.

Key words: Waste management; Prefabrication; Material flow; System Dynamics; China

1. Introduction

In recent years, along with China's rapid economic development and the expanding process of urbanization over the past decades, the growth in waste generation, particularly in construction waste, has resulted in a series of environmental problems in urban construction. As a large amount of construction waste is generated from various kinds of construction activities, construction industry is generally regarded as a major culprit of the degradation of environment (Wang et al., 2014). Statistics show that In Hong Kong, more than 2900 tons construction waste was transported to landfills per day in 2007 (HKEPD, 2007), while Mainland China produced 29% of the world's municipal solid waste in 2008, of which nearly 40% is construction waste (Wang et al., 2008). The interest of researchers and practitioners on the impact of construction waste on the environment has increasingly grown, emphasizing on waste management and putting forward various measures with potential to minimize the adverse impacts of construction waste. Such efforts include waste minimization, reuse, recycling, and disposal (Yuan, 2013). Waste minimization is a process that avoids, eliminates, or reduces waste at its source, enabling the reuse/recycling of waste for benign purposes. Thus, waste minimization has been considered as the most desirable method of waste management because of its benefits of eliminating waste disposal and reducing construction costs of waste sorting and transportation (Lu and Yuan 2011).

Prefabrication is a manufacturing process that generally occurs at a specialized facility where various materials are formed as a component of the final installation (Tatum et al., 1987). Various forms of prefabricated construction modules normally applied in the construction industry in Hong Kong can be classified into three categories: (1) semi-prefabricated nonstructural elements, such as windows, ceiling, facades, and partition walls; (2) comprehensive prefabricated units containing structural prefabricated elements, such as columns, beams, floor or roof sheathing, slabs, load-bearing walls, and staircases, most of which are completed in the factory prior to assembly; (3) and modular buildings that are wholly completed offsite as a one-stop system (Tam et al., 2007).

Prefabrication has been commonly considered as a key strategy to effectively promote construction waste minimization (Lu and Yuan 2013; Chiang et al., 2006; Yee and Eng 2001; Aye et al., 2012; Zhang et al., 2011). This consideration is largely a result of its lower dependence on conventional construction technologies, such as cast-in-place concrete, bamboo scaffolding, timber formwork, reinforcement, tiling, and plastering (Tam et al., 2007). Prefabrication reduces the complexity of wet-trade work, thereby contributing to construction waste minimization (Aye et al. 2012; Li et al., 2014). A typical sustainable prefabricated building is the T30 Tower Hotel constructed by The Broad Sustainable Building Co., Ltd., a leading enterprise specializing in factory-made skyscrapers. The On-site construction of the 30-storey tower hotel, along with a helicopter pad, took just 15 days. Various prefabricated components, done during the laying of the foundation, were finished within 40 days. This prefabricated hotel is said to show several benefits that include magnitude 9-earthquake resistance, low construction cost, high thermal efficiency (leading to low maintenance cost), and, especially, only 1% construction waste generation compared with conventional buildings. In line with the sustainable building development program proposed by the Chinese Housing and Urban–Rural Development Ministry in 2012, many property developers, including the Vanke Group, have practiced building industrialization by adopting prefabrication technologies. However, practical experience in the construction industry of Shenzhen indicates that tools for effectively forecasting the possible impact of prefabrication in terms of waste generation and subsequent waste disposal activities are still lacking.

To quantify the impact of prefabrication use on construction waste reduction and subsequent waste handling activities, this paper proposes an evaluation model employing a system dynamics approach incorporated within a Vensim software package. This evaluation model was established to (1) explore interactional and interdependent relationships underlying the identified significant variables within the processes of policy implementation, prefabrication application, and construction waste handling; (2) quantify the merits of applying the prefabrication technology in terms of construction waste reduction and compare the performance with traditional construction methods; and (3) analyze the effects of various management measures on promoting the use of prefabrication technology and its potential contribution to construction waste reduction.

2. Background research

Studies in the past 10 years reveal that researchers have considered the significance of prefabrication technology on construction waste-related issues. For example, Tam et al. (2005) suggests that through prefabrication, construction waste from use of timber formwork could be reduced by 74% to 87% by using steel formworks, and concrete wastage could be reduced by 51% to 60%. A similar study revealed that waste generation can be reduced by up to 100% after the adoption of precast technology, in which up to 84.7% can be saved on wastage reduction (Tam et al., 2007). Recent studies have also contributed various instruments for assessing the impact of adopting prefabrication. Jaillon et al. (2009) compared prefabrication with conventional construction in relation to waste reduction based on a questionnaire survey and case study analysis. The average waste reduction level was found to be approximately 52% when precast construction was used.

Other techniques, such as the environmental management system and the design structure matrix technique, have also been employed to assist designers in visualizing the complex construction design process and analyzing the impact of precast techniques on construction waste reduction on site (Zeng et al., 2005; Baldwin et al., 2009). Chen et al. (2010) developed a decision support model for evaluating the potential merits (including construction waste reduction) of prefabrication use in concrete buildings by employing the multi-attribute utility theory. Moreover, the sustainable construction aspect considerations in the reduction of construction dust, noise, and waste were examined by a comparative case study through an environmental perspective between prefabrication and traditional construction methods (Jaillon and Poon, 2008).

Given their contributions on analyzing the influence of prefabrication adoption on waste reduction, two problems were found in these studies that require further investigation. First, Existing decision support tools only consider the impact of prefabrication adoption from the perspective of waste generation, failing to consider the impact on other significant construction waste management activities, including waste sorting, reuse, recycle, and disposal. Second, most of previous studies have been approached from a static point of view that takes each identified variable as independent subject that are not supposed to affect each other in the process of construction, that is, the interrelationships among different influence factors are ignored to a large extent, thereby failing to consider the impact of feedback loops and complex interactions among policy, prefabrication, and subsequent waste handling activities.

Furthermore, given that the objectives of this paper lie in formulating, simulating, and validating the impacts of prefabrication on construction waste reduction and waste handling activities, the major characteristics of this process should be first given sufficient consideration, namely:

(1) The quantitative assessment of the influence of prefabrication on construction waste management demands a full understanding of the related material flows, covering holistic processes, including prefabricated component application, waste generation, waste sorting,

reuse, recycle, and landfilling. As such, the process is better viewed as a complex system with numerous variables to be considered;

(2) The vast majority of the variables involved in this system tend to be interactional and interdependent, whereas existing studies have treated them as independent variables;

(3) More significantly, from the application of prefabricated components to the generation and disposal of construction waste, the entire process is dynamic, compared with traditional approaches that have adopted a static perspective.

Recent developments in system dynamics theory have integrated the features of conventional management with dynamic feedback regulation, which has been applied extensively in various domains, including the construction process. Shen et al. (2009) formulated a system dynamics model that comprises an integrated environmental-social-economic system for sustainable land use and urban development. Their findings confirm that the methodology can effectively examine the interactions among its five sub-systems. Thus, applying the system dynamics discipline to assess the social performance of construction waste management, Yuan (2012) found that the method is ideal in simplifying various complex interrelationships and feedback loops underlying numerous variables in the systems that were investigated. All of these studies expressly indicate that system dynamics is an appropriate method for better depicting the interrelationships between underlying variables within a complex system from a dynamic point of view. Thus, it would seem that system dynamics can ideally match the major characteristics of material flows and can help fill the knowledge gap in existing research. Thus, the system dynamics approach is applied in this paper to quantify the impact of prefabrication on construction waste management.

3. Research Methodology

System dynamics, introduced by Jay Forrester in the 1960s at the Massachusetts Institute of

Technology, is defined as a computer-aided approach for understanding the behavior of a system with time (Forrester, 1968). System dynamics is now widely applied in various fields, such as social science, agriculture, management, economics, and engineering. It is accepted as a conceptual modeling technique capable of understanding, studying, simulating, and analyzing large-scale complex systems. The conventional methodology applied to system issues tends to depict relationships underlying system variables and comprehend subsequent system behavior from a narrow or isolated perspective. By contrast, large-scale complex systems normally comprise numerous sub-systems. Among these sub-systems are causal relationships that are interactive and interactional: one value-changed variable would have a feedback-based impact on another, eventually influencing the behavior of the whole system. The system dynamics methodology specializes in handling stated characteristics because it can simplify a complex system into operable units through its special analytical tools. These analytical tools include causal-loop diagram and stock-flow diagram, which also contribute in analyzing feedback relationships from a multi-dimensional and dynamic perspective.

Causal-loop diagrams and stock-flow diagrams are two major tools for system dynamics modeling. Causal-loop diagrams serve as the preliminary sketches of causal hypotheses during model formulation and simplified representation of the real-world behavior. Meanwhile, a stock-flow diagram is a computer-based tool visualized for quantitative simulation and anal ysis, which is built based on the causal-loop diagram. . A feedback loop would be determined as positive feedback if it includes an even number of negative causal links and as negative feedback when containing an odd number of negative causal links. Stock-flow diagrams can be represented by four structural elements: stocks (represented by a rectangle) indicate major accumulation within a system; flows (values with block arrow symbol) serve as an instrument that hinder or prompt the flow of information from the stock; converters (symbolized by a lone circle) act as intermediate variables for miscellaneous calculation; and connectors (symbolized as simple arrows) serve as information links that represent the reasons and impacts within the model structure (Yuan et al., 2012).

4. Model formulation

Normally, a five-step procedure as shown in Figure 1 is adopted to develop a system dynamics model, which includes: (1) system description, in which researchers are required to determine the scope of a proposed system, and identifying the major variables associated with the research questions is emphasized; (2) causal-loop diagram and (3) stock-flow diagram, where qualitative analysis is conducted to depict the interrelationships underlying the identified variables before mapping them into causal-loop diagrams, and stock-flow diagrams are subsequently constructed based on the causal-loop diagram and visualized by the Vensim software package for quantitative analysis; (4) model validation, which serves as an essential process for increasing confidence in the proposed model, in which, a series of tests suggested by Coyle (1996) would be run prior to the model implementation; and (5) policy analysis, which mainly comprises a base run simulation and scenario simulations that would be finally conducted to analyze the possible impacts of various devised management strategies after the model has been validated.

Figure 1: Research path for model development

4.1 Identification of key influencing factors

To facilitate the illustration of the prefabrication-adoption-to-waste-disposal process, a definition of the material flow is provided, that is, a flow consisting of a series of material processing activities. The activities mainly include prefabricated component adoption, prefabrication assembly, waste generation, waste sorting, waste reuse and recycle, and waste disposal. Construction materials undergo all of these activities in sequence, with the preceding activity having an impact on the succeeding activity. For instance, the adoption of prefabricated facades would reduce the amount of conventional construction trades, such as concreting, rebar fixing, and plastering, which minimize the generation of waste in concrete, wood, and metal. Naturally, the quantity of on-site waste sorting will decrease along with waste reduction, thereby affecting other relevant waste-handling issues. Thus, modeling the material flow can provide a framework to elucidate the stream direction of building materials and the manner by which prefabrication influences the waste disposal activities as a result of a reduction in the in situ construction trades. Furthermore, the material flow is a cluster of separate material handling activities as well as a complex system where various activities are interdependent and interactive. Thus, system dynamics is adopted as the major methodology of this study. A list of typical variables influencing the material handling activities are presented, as derived from existing literature, site surveys, and related reports. These variables along with the concept model of material flow are shown in Figure 2.

Figure 2: A conceptual framework of the material flow

4.2 Causal-loop diagram

After the identification of variables with the potential of influencing the behavior of the proposed system, qualitative analysis was conducted to identify the underlying interrelationships among these variables based on an extensive literature review and semi-structured interviews with practitioners and professionals. The diagram (Figure 3), which consists of a series of feedback loops that determine the behavior of the whole system by establishing connections among various factors, serves as a visualized conceptual model for presenting the results of the qualitative analysis. The definitions of the key variables and their underlying causal relationships within the diagram are defined as follows:

(1) Prefabrication adoption refers to the application of innovative prefabricated items, such as facades, dry walls, cooking benches, precast slabs, and staircase units, which

are produced, assembled, and pre-finished in off-site factories to replace on-site activities/trades, such as timber formwork, cast-in-situ concrete, painting, scaffolding, and plastering. The interviewees emphasized that the adoption of prefabrication can reduce the quantity of traditional labor-intensive construction trades including concreting, rebar fixing, bricklaying, and plastering. These construction activities normally result in poor workmanship quality and the overwhelming use of multi-layered subcontractors, which both hampers management control and generates excessive waste. Thus, along with the reduction in construction trades, various waste streams (concrete, bricks, mortar, metal, and wood) tend to be minimized.

(2) Inert waste and non-inert waste are the categories used to classify construction waste. Inert construction materials, containing mainly concrete, building blocks, and tiles, are deposited at public filling areas for land reclamation, whereas non-inert waste, comprising mainly wood, plastics, and other organic materials, is disposed at landfills as solid waste (Yuan et al., 2013). The "recycling and reusing" in this paper is narrowly defined within the non-inner waste, referring to the most common activities such as metal waste collection and the reuse of wooden scaffolding discarded. Broadly speaking, the inner construction waste that is crashed and transported to the public landfilling site for the purpose of land reclamation are typically a form of recycling and reusing activity, while this research has classified this kind of recycling activities as public landfilling. Besides, prior to transporting construction waste to public landfilling site, the relatively intact inner materials would be sorted and reused. This research simply boils down these activities involved in the waste management process as public landfilling for simplification purpose.

(3) On-site sorting refers to the separation of construction waste in cases where a mixture of both inert and non-inert construction materials exist (Poon et al., 2001). On-site

sorting separates construction waste according to their categories so that some of the waste can be reused and recycled, whereas the rest can be deposited at public filling areas or landfills.

(4) Reuse and recycle, deposit at public landfill, deposit at landfill, and illegal dumping are the four major methods suggested by the interviewed contractors. These methods are commonly adopted for handling construction waste generated from new residential construction projects in mainland China. These approaches are listed in ascending order according to their adverse impact to the environment from low to high. Among these methods, reuse and recycle is regarded as the best alternative for managing the generated waste because of its minimal influence on the environment in while reducing the cost of waste disposal (Tam, 2009). When reuse and recycle becomes difficult, waste should be disposed at landfills and/or public fills to avoid polluting the environment (Seadon, 2010). Furthermore, the interviewees indicated that uncontrolled and illegal dumping widely occurs in inadequately supervised districts.

(5) Construction waste management performance refers to the overall performance comprising four attributes, namely, recycle and reuse waste, landfilling waste, public landfilling waste, and illegal dumping waste. These attributes cover all the perspectives of the ultimate disposal of construction waste management activities. Among the four attributes, the recycle-and-reuse-waste attribute is positively correlated with the overall performance, that is, the more construction waste is recycled and/or reused, the more contribution it would make toward the overall improvement in performance. Meanwhile, the remaining attributes have negative correlation with the overall performance.

(6) Incentives for promoting prefabrication adoption indicate the combined effect of the

policies of the measures proposed by the government for facilitating the application of prefabrication technologies. Construction is not an environment-friendly activity, and economic benefit is the priority target of various construction participants (Chen et al., 2002; Shen et al., 2010). Economic incentives from the government are necessary to promote the use of prefabrication because compared with conventional building methods, the overall construction cost of prefabrication is still relatively higher (Diao et al., 2009). Developers will not likely spontaneously abandon the pursuit for profits over better environmental benefit, as suggested by the interviewees. In addition, the definitions of incentives in this study are mainly confined to economic incentives, such as tax relaxation and fiscal subsidy. Other environmental or social regulations are out of the scope of this study.

Based on the analyses above, two typical feedback loop clusters are defined within the diagram:

Feedback loop cluster A:

Construction waste management performance → Incentives for promoting prefabrication adoption → Prefabrication adoption → (Rebar fixing, Plastering, Bricklaying, Concreting) → Waste generation → Waste on-site sorting → (Metal waste, Wood waste) → Non-inert waste → (Recycle and reuse waste, Landfilling waste) → Construction waste management performance

Feedback loop cluster B:

Construction waste management performance → Incentives for promoting prefabrication adoption → Prefabrication adoption → (Rebar fixing, Plastering, Bricklaying, Concreting) → Waste generation → Waste on-site sorting → (Concrete waste, Bricks and building blocks waste, Mortar waste) → Inert waste → (Illegal dumping waste, Landfilling waste, Public landfilling waste) → Construction waste management performance

Each feedback loop is a closed loop circuit, within which one variable influences another along the arrow direction in either positive or negative feedback. All of the feedback loops constitute the complete causal-loop diagram, as displayed in Figure 3.

Figure 3: Causal-loop diagram of the effect of prefabrication on construction waste reduction

4.3 Stock-flow diagram

With the interrelationships underlying the identified variables qualitatively defined within the causal-loop diagram, a stock-flow diagram should be constructed to mathematically quantify their impacts by employing the Vensim software. The stock-flow diagram is a more detailed model compared with the causal-loop diagram. A number of auxiliary variables absent in the causal-loop diagram are added to the stock-flow diagram to ensure that the previously defined relationships can be smoothly converted to quantitative expressions. To facilitate understanding, the established model, along with brief definitions of the variables within the model, is presented as shown in the Figure 4 and Table 1.

Figure 4: Stock-flow diagram of the effect of prefabrication on construction waste reduction

Table 1: Depiction of variables used in the model

Data were obtained primarily through two channels. One source involved access to numerous publications, government reports, and webpage information. Construction waste stream (concrete, wood, metal, mortar, and brick) generation indexes are typically extracted from a technical manual issued by the Housing and Construction Bureau of Shenzhen (2011). The other source of data was an on-site survey that was conducted in a practical project located at the junction of Shenzhen and Huizhou. The studied project covers a net area of about 34,000 m^2, consisting of six 34-storey residential buildings with several shops at podiums, a two-storey garage, and an equipment room. The construction area of the project is about 180,000 m^2, with a project duration period of 22 months. An interview questionnaire was designed as a supplementary tool to determine the values of several qualitative variables influencing material flow. Investigators ranked the qualitative variables based on a five-point Likert scale according to the response of the professionals on the importance level of the qualitative variables, where 1 and 0 indicate the most important and the least important variables, respectively.

Variables within the model can be divided into three categories, namely, constant, dependent, and qualitative variables. Each type of variable has corresponding data sources. The values of constant variables, which are expected to remain unchanged throughout the entire simulation period, are assigned by referring to the collected materials, such as the literature (Quantification approach A). The values of dependent variables depend on one or more variables within the model in terms of mathematical functions; their values are quantified by various functions within the Vensim software. This software specializes in describing the interrelations among any two or more variables (Quantification approach B). The values of qualitative variables are quantified based on the following formula (Quantification approach C):

$$I_{ji} = \left(\frac{n_1 * 0 + n_2 * 0.25 + n_3 * 0.5 + n_4 * 0.75 + n_5 * 1}{n_1 + n_2 + n_3 + n_4 + n_5}\right) * 100$$

where I is the value of the qualitative variable, and n_1, n_2, n_3, n_4, and n_5 represent the number of interviewees who rated the qualitative variable as 0, 0.25, 0.5, 0.75, and 1, respectively. The major variables, along with their corresponding quantification approach are shown in Table 2.

Table 2: Quantification method classification

5. Model validation

Prior to conducting the simulation analyses, the model should be tested to verify the extent to which it could reflect the real-world situation. Two types of validation were conducted in this study, one for structural validity and another for behavioral validity. Extreme conditions and behavior sensitivity are generally accepted as the most effective and practical structure test. An extreme condition test examines whether the generated system behavior is consistent with the expected behavior of the real situation under extreme condition. This test is conducted by assigning extreme values to typical variables. Meanwhile, the behavioral sensitivity analysis mainly focuses on identifying the variables to which the system is highly sensitive, and the rationality of the system behavior after adjusting the value of the identified sensitive variables is then examined (Talyan et al., 2007). A typical example related to these sensitivity analyses is presented in Figure 5. Regulation implement supervision (RIS), a qualitative variable, with a score of 100 demonstrating the strongest supervision and 0 indicating the most relaxed supervision, is regarded as one of the most critical variables affecting the illegal dumping rate (IDR) (Poon et al., 2001). For the devised positive (A) and negative (B) scenarios, the RIS value is first increased to twice the base value and then decreased to half of the base value. The Figure 5 shows that IDR is stable at very low levels under scenario A and then sharply increases in scenario B. The simulation result is consistent with the true situation in Shenzhen, as suggested by interviewees. They stated that if governmental supervision for illegal dumping is limited, contractors may not transport the collected waste to the appointed landfill, which is normally located in a remote suburb, thereby saving the cost of transportation and landfilling. Similar tests regarding other significant variables were also conducted, and all of the tests produced favorable effects. This result indicated that the established model can reasonably forecast the outcomes when changes in system behavior occur.

Figure 5: An example of a sensitivity analysis

Historical data comparison analysis was adopted for behavioral validity. The common practice is to check whether the simulation results of certain typical quantitative variables within the model are in agreement with the corresponding historical data. This verification is performed by comparing the error percentage between the historical data and simulation results. Nevertheless, the on-site survey indicated that the contractors are not likely to record the actual generated construction waste, which makes common practice become impossible to assess. Thus, an alternative approach to compensate the lack of historical data was introduced by Housing and Construction Bureau of Shenzhen (2011), named as Base Calculation in this study. This method was adopted for forecasting the outcomes of significant quantitative variables including concrete waste generation (CWGe), wood waste generation (WWGe), metal waste generation (MeWGe), mortar waste generation (MWGe), and brick and building block waste generation (BBBWGe). The results will be adopted as substitute for historical data for comparison with the simulation results based on the tolerance analysis for verifying the credibility of the established model. The matching effect of the model will be considered as preferable if the variable, whose relative error is less than 5%, accounts for 70% or more of the total tested variables, and the average relative error of each variable is less than 10% (Maddala, 1983). Table 3 shows that the relative errors of all of the tested variables are lower than 10%, with an average error of 3.91%. These results demonstrate the satisfactory matching effect of the model and verify the established model could reflect the real-world situation to a large extend. Thus, further simulation can be conducted to analyze the impact of related policy on the use of prefabrication and construction waste reduction.

Table 3: Behavioral validity based on two different calculation methods

6. Policy analysis

6.1 Baseline scenario

After completing the necessary tests for verifying the developed model, a simulation analysis can be further conducted. The simulation period of the established model was set to 22 months, which is consistent with the duration of the studied project. The selected input and output variables of the baseline scenario are presented in Table 4. Subsidy for prefabrication of each square meter (SPESM), income tax benefits (ITB), and unit landfilling charge (ULC) was constant throughout the entire simulation period, which was assigned as 20 Yuan/m2, 15%, and 5.88 Yuan/tons, respectively. Willingness to adopt prefabrication (WAP) is a dependent variable determined by the effect of regulation. This variable is dependent on the above three constant variables, with 0 demonstrating the least willingness and 100 the greatest willingness. The simulation results imply that WAP remained at a relatively low level at the beginning and gradually increased as the project proceeded, reaching a record high of 7.63 in the middle of the project. Afterward, the value decreased until the end of the project. This result was confirmed by the consulted project managers, who stated that conventional methods are more suitable for construction in foundations and basements because these two building elements (constructing at the beginning of the project duration) require non-standard designs that are adaptable to changes related to underground conditions. Prefabricated components and advance forecast are difficult to apply in these two elements, whereas structural frame elements (constructing at the middle of project duration), such as column, beam, bearing wall, and slab, are recommended for prefabrication to improve construction productivity and waste reduction. Based on the model shown in Figure 3, prefabrication adoption rate (PAR) is positively correlated with WAP, that is, more prefabricated components would be adopted when the value of WAP increases. This effect eventually influenced the performance of construction waste reduction and the corresponding waste handling activities. This relationship was confirmed by the simulation results displayed in Table 4, in which CWRe, BBBWRe, MWRe, MeWRe, and WWRe are approximately 214.47, 30.38, 22.58, 45.91, and 77.41 tons, respectively (Note that due to the limited length, the table only presents the final-month stock results in terms of total value, that is, the sums of flow value of the selected output variables represent the final month stock value of CWRe, BBBWRe, MWRe, MeWRe, WWRe, and etc). Furthermore, the simulation results indicated a significant reduction in construction waste after adopting prefabrication: (1) the on-site sorting process saved 277.23 tons of construction waste; (2) 121.77 tons were prevented from disposition in landfill; (3) 120.34 tons were prevented from disposition in public landfill; and (4) a reduction of 40.11 tons of illegal dumping waste was achieved. Such a reduction in construction waste would be helpful in decreasing construction cost by reducing the number of workers for sorting waste as well as saving landfill charge and transportation cost. The reduction also contributes to the alleviation of the environmental problem.

Figure 6a, 6b and Table 4 show that CWRe, BBBWRe, and MWRe were mainly concentrated in the middle of the project, whereas a higher amount of WWRe was recorded at the early stage. The possible explanations for these results include the following: (1) the studied project proposes to adopt a portion of metal formwork to replace conventional bamboo scaffolding, resulting in a reduction in wood waste at the beginning of the project; and (2) rebar fixing and wet trade would be avoided by an early installation of semi-precast external facades and prefabricated staircase units into the structural frame during its construction stage, thereby decreasing the generation of concrete, bricks, mortar, and metal waste. Furthermore, the value of recycle and reuse waste reduction (RRWRe) is reflected by the model as negative, with an amount of 46.03 tons of waste saved from the reuse and recycle at the end of the project duration. This finding indicates an increase in collected recycle-and-reuse waste rather than reduction, in agreement with the previous studies conducted by Poon et al. (2001), who suggested waste reuse and recycle would be much easier when prefabricated components are used because they lead to convenient disassembly.

Figure 6a and 6b: Baseline Scenario of construction waste reduction and handling

Table 4: Simulation results of the Baseline Scenario on a monthly basis

6.2 Scenario analysis

Recognizing the benefits of adopting prefabrication technology, many district governments have proposed various policy options to promote the application of prefabricated component in the building industry. Among these policies, economic incentives are commonly considered as necessary. This supposition is attributed to the probable high cost of construction if prefabricated components are adopted for construction in a large area when prefabrication has not been industrialized in a large-scale. Therefore, the scenario analysis in this study mainly focuses on economic policy. Moreover, given that exhaustively illustrating all possible policies with respect to prefabrication applications is impractical, two widely accepted typical policies were selected for simulation. By implementing the two policies individually and in combination with each other, various possible scenarios were generated for analysis.

Policy scenario A (PSA) – subsidy for prefabrication of each square meter (SPESM): This scenario is a single-policy scenario, aiming at examining the influence of changing SPESM on WAP and total construction waste reduction (TCWR) in the building project.

Table 5: Simulation results of the Policy scenario A

To analyze the various possible situations, two operational subsidy policies aside from the baseline policy for promoting prefabrication adoption were assumed as 40 and 60 Yuan/m2. These two policies were defined, respectively, as sub-scenarios PSA-1 and PSA-2. Table 5 shows that the increase in subsidy for the construction area that adopted prefabrication significantly contributed to the improved willingness of the participants to use prefabrication technology, thus enhancing the performance of construction waste reduction. This condition is manifested by the average values of WAP and TCWR, which respectively increased from 5.56 and 17.76 tons under the baseline scenario to 7.43 and 27.9 tons in run PSA-1 and to

8.91 and 63.13 tons in run PSA-2. These values generated an improvement of 60.25% for WAP and 255.46% for TCWR over this simulation period. The simulation results clearly showed the large and significant effects that can be obtained through the adoption of prefabrication as promoted by improving the subsidy toward its use.

Policy scenario B (PSB) –income tax benefits (ITB): This scenario, which is similar to A, is also a single-policy scenario that is devised to verify the effect of the increase in ITB on WAP and TCWR in the building project.

Table 6: Simulation results of the Policy scenario B

To examine the impact of the increase in ITB on WAP, two devised sub-scenarios were simulated under this scenario for comparison with the base run, namely PSB-1 and PSB-2, which have assumed values of 15% and 30%, respectively. Unexpectedly, the simulation results indicated that even the rise in ITB toward construction corporations could increase to a certain extent the willingness to adopt prefabrication, as presented in Table 6. The expected effect is more moderate, which verified the increase in WAP and TCWR from 5.56 and 17.76 tons of the baseline scenario to 6.08 and 19.54 tons in the run PSB-1 and to 6.08 and 19.72 in the last run with the largest ITB, indicating non-significant enhancements of 9.35% (WAP) and 11.04% (TCWR) over this scenario simulation compared with PSA. Therefore, according to the dual factors theory raised by Herzberg (2005), the ITB policy can only be treated as a maintenance factor rather than incentive measures for the promotion of prefabrication adoption.

Policy scenario C (PSC) - Multiple policies combined: this scenario is a multi-policy scenario designed to simulate the influence of the concurrent changes in SPESM and ITB on WAP and the performance of TCWR.

Table 7: Simulation results of the Policy scenario C

As mentioned in the previous section, factors within a system are not isolated. These factors are interactive and influence each other in a certain manner. To verify such interrelationships and to evaluate the combined effect of the integrated policies, two alternative management measures were implemented concurrently in this scenario. PSA-2 and PSB-2, which were identified by the above simulations as the most effective in promoting the use of prefabrication and enhancing the performance of construction waste reduction, were included. The simulation results are exhibited in Table 7.

The results show an obvious increase in WAP and TCWR when the two most effective management measures were adopted simultaneously. Particularly, the average improvement in WAP reached up to 82.44% until the end of the project duration, 14.31% larger than the simple sum of PSA-2 and PSB-2 of 69.13% (recorded at 59.91% and 9.22%, respectively) over the same period. Thus, TCWR had a better performance of 111.39 compared with the simple sum. The results demonstrate that (1) interaction exists among different management measures, and (2) the integrated impact of multiple policies on the promotion of prefabrication adoption is greater than the simple sum of the two measures. These findings are also confirmed by the results of construction waste reduction shown in Table 7. The most plausible reason that may account for this phenomenon is that the system is an organic whole running in a highly iterative manner such that one verified factor within the system may result in another enhancement in a blown-up feedback loop, leading to amplified effectiveness. A deeper understanding of this "systemic" behavior can provide a valuable perspective to policy makers, in which the combined effect of possible various management measures should be fully considered to achieve the expected performance (Shin et al. 2008). Furthermore, this result can only be obtained when a systems dynamic method of analysis, or a similar approach, is applied to the data. The Vensim software allows for this type of analysis to be applied in a relatively easy manner.

7. Conclusion

With the expectation of improving construction productivity and alleviating the adverse environmental impacts brought by various construction wastes, a number of developers have pioneered the adoption of prefabrication. However, practical experience in the construction industry of Shenzhen indicates the lack of straightforward methods for measuring the different impact on construction waste reduction and subsequent waste handling activities between cast in-situ and prefabrication construction method. This study, therefore, proposes a model that can facilitate the quantification of the impact of adopting prefabrication on construction waste reduction by holistically considering the dynamics and interdependences of the variables underlying the processes of prefabricated construction. Major variables in relation to the material flow were first identified. Then, a causal-loop diagram was developed to depict the potential interrelationships underlying the identified variables prior to the establishment of the quantitative model. The resulting model was validated using data obtained from a construction project in Shenzhen, China.

The simulation results demonstrate that the policy of increasing the subsidy for the construction process to adopt prefabrication have the largest influence on promoting the adoption of prefabrication, whereas income tax benefits tend to have more moderate impacts on the promotion of prefabrication adoption and construction waste reduction. Moreover, the simulation results also show that the combined impact of the two selected policies (STESM and ITB) is larger than the simple sum of the impact of each single policy. Given the limited length, only three policy scenarios are simulated and analyzed through the comparison with the results of the base scenario. Nevertheless, based on the established model, similar simulations can be conducted and analyzed under scenarios comprising other designed policies.

This paper demonstrates the potential benefits of using a system dynamics approach in understanding the behavior of real-world processes in two dimensions. First, the causal-loop diagram depicting the interrelationships among key variables within the material flow can not only enrich the research in the management of prefabricated construction, but also facilitate deepening project stakeholders' understanding on the influence of the prefabrication and related policies on construction waste reduction and subsequent handling activities. Meanwhile, the application of the stock-flow model to the prefabrication of the construction process shows significant and tangible savings in costs and reduction in wastage, which can be achieved compared with the conventional methods of construction. The proposed model serves as a practical tool for quantitatively assessing the impact of off-site prefabrication on construction waste reduction and corresponding waste handling activities. Moreover, this model provides a valuable reference for policy makers through the comparison of simulation results generated under various scenarios, thereby identifying the best policy mix prior to production.

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Figure 1

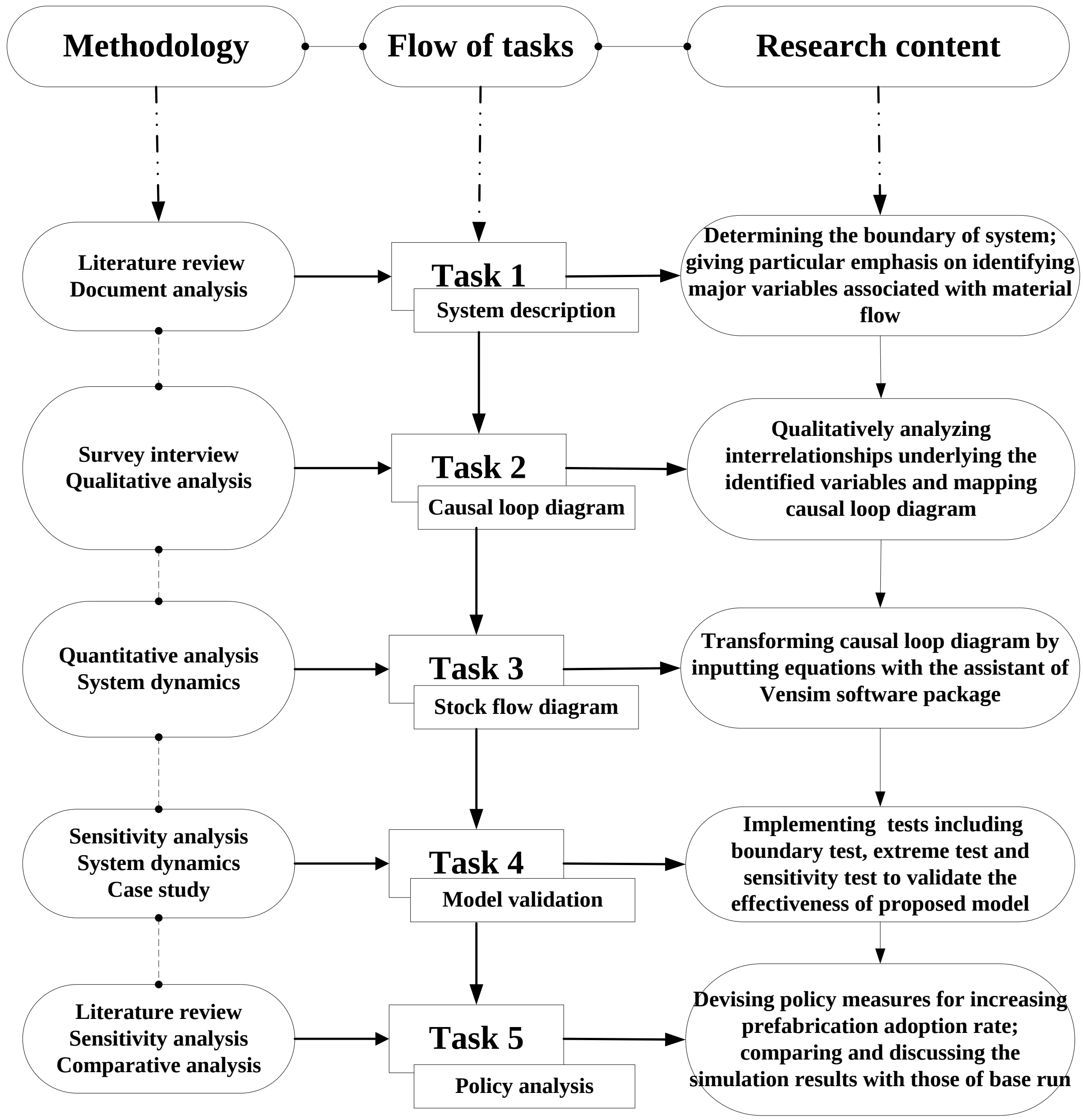

Figure 1: Research path for model development

Figure 2

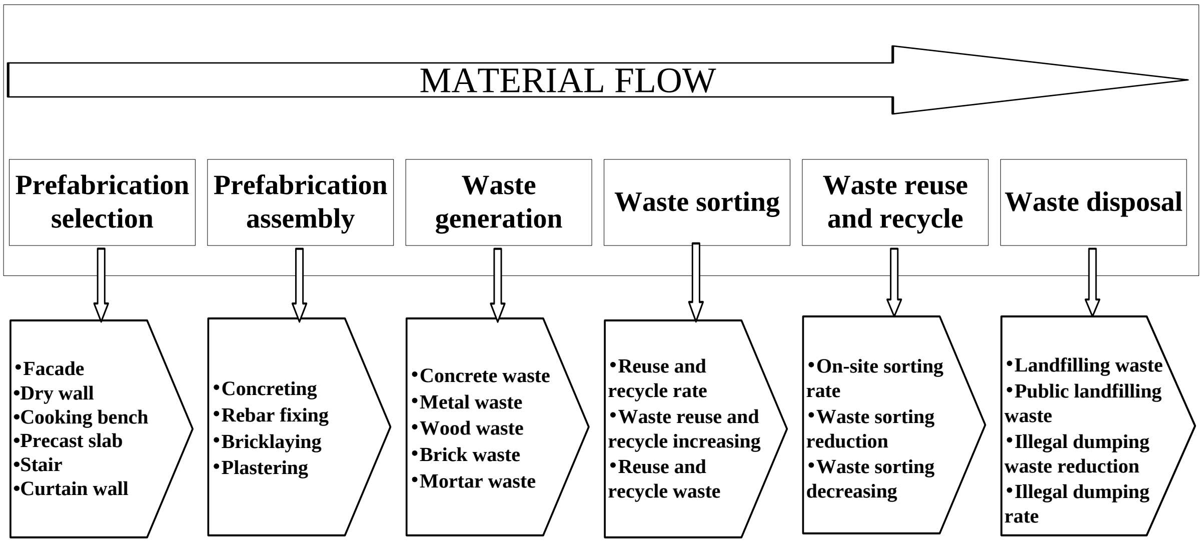

Figure 2: A conceptual framework of the material flow

Figure 3

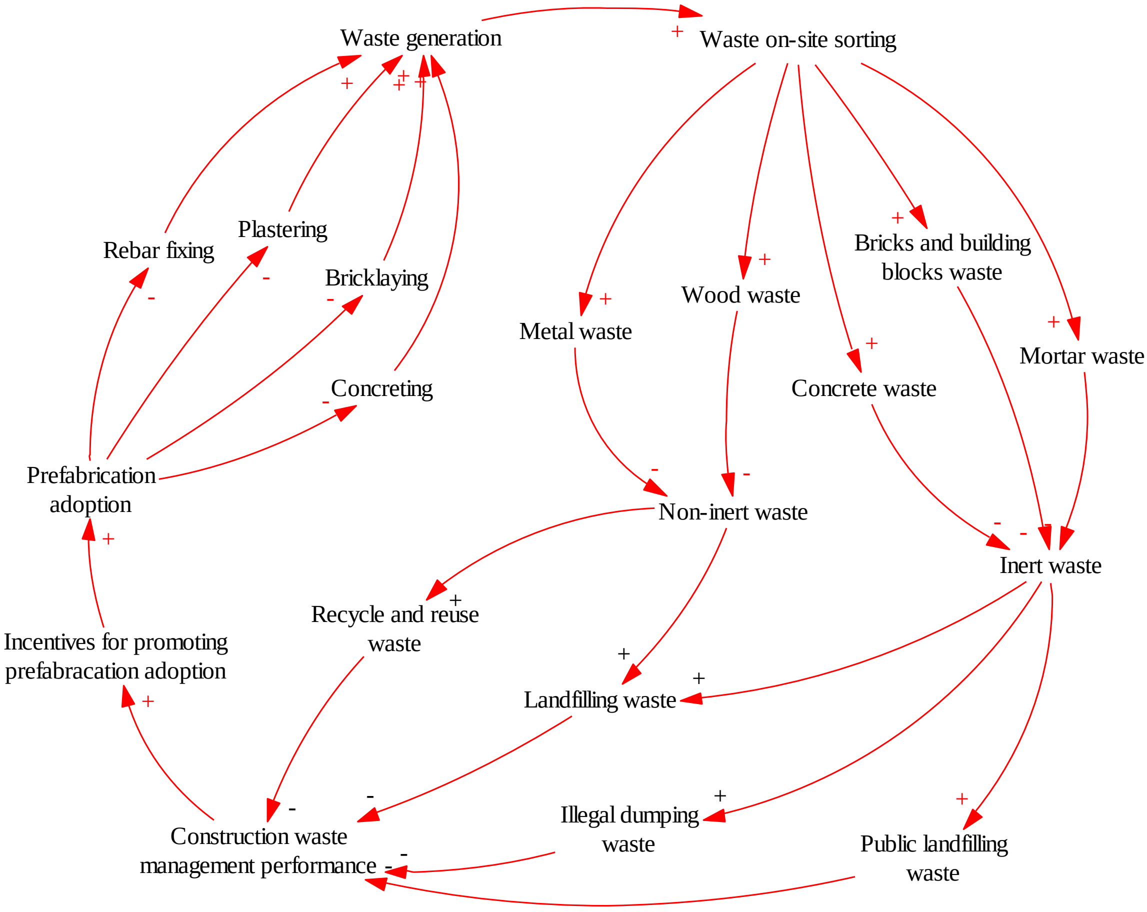

Figure 3: Causal-loop diagram of the effect of prefabrication on construction reduction

Figure 4

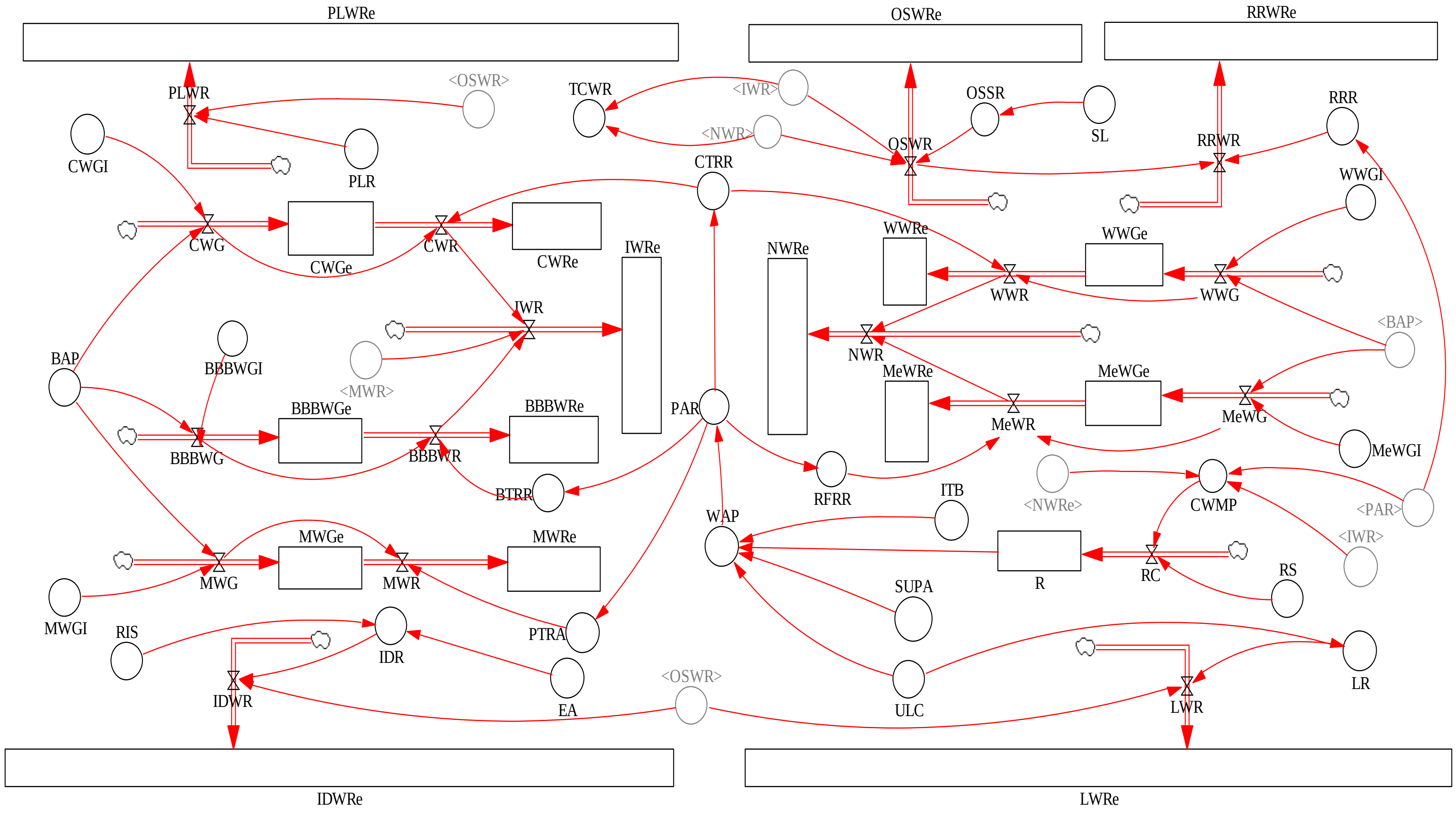

Figure 4: Stock-flow diagram of the effect of prefabrication on construction reduction

Figure 5

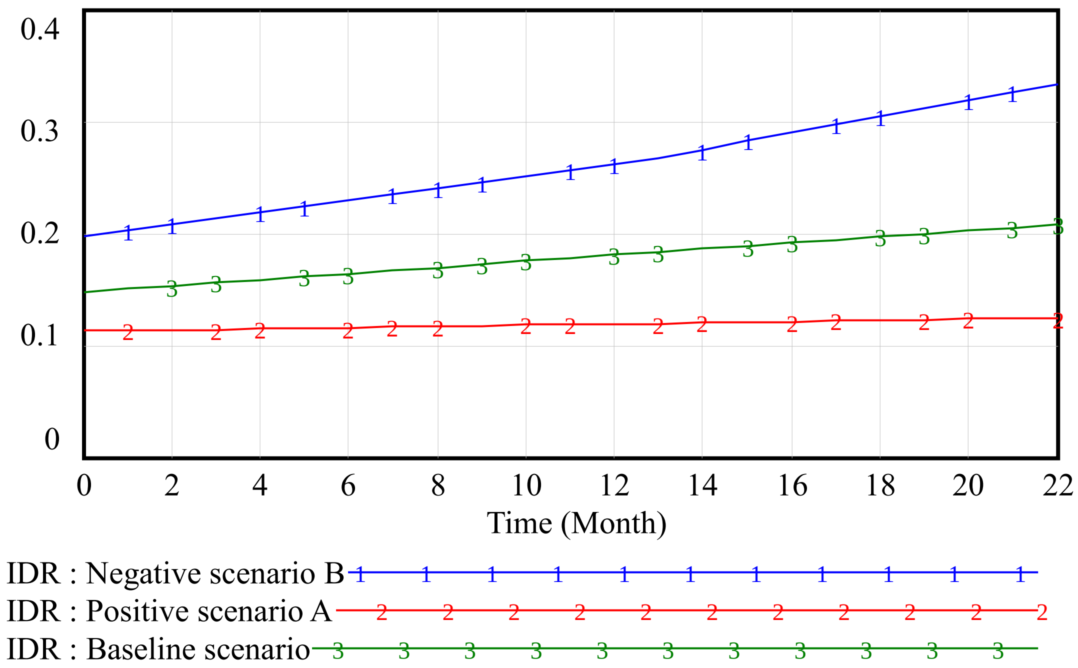

Figure 5: An example of a sensitivity analysis

Figure 6

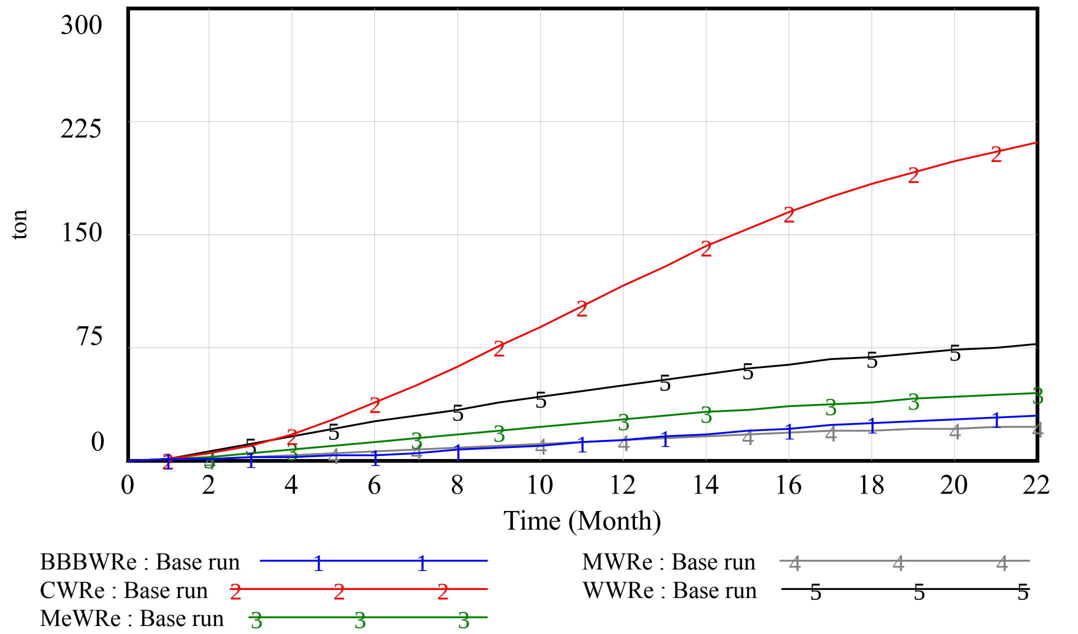

Figure 6a: Baseline Scenario of construction waste reduction and handling

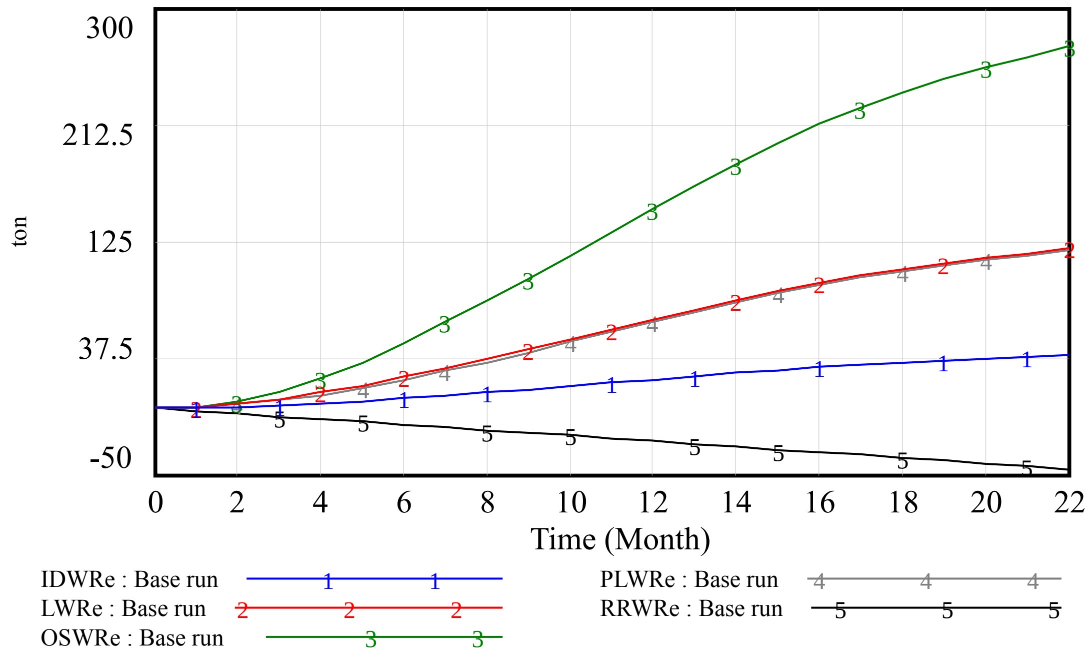

Figure 6b: Baseline Scenario of construction waste reduction and handling

Table 1: Depiction of variables used in the model

No.	Acronym	Variable definition	Variable type	Input/output variable	Unit

1	BBBWG	Brick and building block waste generating	Flow	Output	tons/month
2	BBBWGe	Brick and building block waste generation	Stock	Output	tons
3	BBBWGI	Brick and building block waste generation index	Convertor	Input	tons/m2
4	BBBWRe	Brick and building block waste reduction	Stock	Output	tons
5	BBBWR	Brick and building block waste reducing	Flow	Output	tons/month
6	BTRR	Bricklaying trade reduction rate	Convertor	Input	1
7	BAP	Building area of the project	Convertor	Input	m2
8	CWG	Concrete waste generating	Flow	Output	tons/month
9	CWGe	Concrete waste generation	Stock	Output	tons
10	CWGI	Concrete waste generation index	Convertor	Input	tons/m2
11	CWRe	Concrete waste reduction	Stock	Output	tons
12	CWR	Concrete waste reducing	Flow	Output	tons/month
13	CTRR	Concreting trade reduction rate	Convertor	Input	1
14	CWMP	Construction waste management performance	Convertor	Input	1
15	EA	Environmental awareness	Convertor	Input	1
16	IDR	Illegal dumping rate	Convertor	Input	1
17	IDWRe	Illegal dumping waste reduction	Stock	Output	tons
18	IDWR	Illegal dumping waste reducing	Flow	Output	tons/month
19	ITB	Income tax benefit	Convertor	Input	%
20	IWR	Inert waste reducing	Flow	Output	tons/month
21	IWR	Inert waste reduction	Stock	Output	tons
22	LR	Landfilling rate	Convertor	Input	1
23	LWRe	Landfilling waste reduction	Stock	Output	tons
24	LWR	Landfilling waste reducing	Flow	Output	tons/month
25	MeWGe	Metal waste generating	Flow	Output	tons/month
26	MeWG	Metal waste generation	Stock	Output	tons
27	MeWGI	Metal waste generation index	Convertor	Input	1
28	MeWR	Metal waste reducing	Flow	Output	tons/month
29	MeWRe	Metal waste reduction	Stock	Output	tons
30	MWGe	Mortar waste generating	Flow	Output	tons/month
31	MWG	Mortar waste generation	Stock	Output	tons
32	MWR	Mortar waste reducing	Flow	Output	tons/month
33	MWRe	Mortar waste reduction	Stock	Output	tons
34	MWGI	Mortar waste generation index	Convertor	Input	tons/m2
35	NWR	Non-inert waste reduction	Stock	Output	tons
36	OSSR	On-site sorting rate	Convertor	Input	1
37	OSWR	On-site sorting waste reducing	Flow	Output	tons/month
38	OSWRe	On-site sorting waste reduction	Stock	Output	tons
39	PTRR	Plastering trade reduction rate	Convertor	Input	1
40	PAR	Prefabrication adoption rate	Convertor	Input	1
41	PLR	Public Landfilling rate	Convertor	Input	1
42	PLWRe	Public landfilling waste reduction	Stock	Output	tons
43	PLWR	Public landfilling waste reducing	Flow	Output	tons/month
44	RFRR	Rebar fixing reduction rate	Convertor	Input	1
45	RRR	Recycle and reuse rate	Convertor	Input	1
46	RRWRe	Recycle and reuse waste reduction	Stock	Output	tons

47	RRWR	Recycle and reuse waste reducing	Flow	Output	tons/month
48	R	Regulation	Convertor	Output	1
49	RC	Regulation changing	Flow	Output	1
50	RIS	Regulation implement supervision	Convertor	Input	1
51	RS	Regulation strengthening	Convertor	Input	1
52	SL	Space limitation	Convertor	Input	1
53	SPESM	Subsidy for prefabrication of each square meter	Convertor	Input	Yuan/m2
54	TCWR	Total construction waste reducing	Convertor	Output	tons/month
55	ULC	Unit landfill charge	Convertor	Input	Yuan/tons
56	WAP	Willingness to adopt prefabrication	Convertor	Input	1
57	WWG	Wood waste generating	Flow	Output	tons/month
58	WWGe	Wood waste generation	Stock	Output	tons
59	WWGI	Wood waste generation index	Convertor	Input	tons/m2
60	WWR	Wood waste reducing	Flow	Output	tons/month
61	WWRe	Wood waste reduction	Stock	Output	tons

Table 2: Quantification method classification

Quantification method	Variables	Category
Approach A	BBBWGI, CWGI, MeWGI, MWGI, WWGI, ULC, SPESM, ITB, BAP	Constant
Approach B	BTRR,IDR,LR,OSSR,RFRR,CTRR,RFRR,WAP	Dependent
Approach C	EA,RIS,RS,SL	Qualitative

Table3: Behavioral validity based on two different calculation methods

Selected variables	CWGe	MWGe	BBBWGe	WWGe	MeWGe
Simulation results	3241.32	229.173	304.021	1398.12	713.21
Base calculation	3403.1	236.579	327.571	1419.48	727.936
Relative error	4.99%	3.23%	7.75%	1.53%	2.06%

Table 4: Simulation results of the Baseline Scenario on a monthly basis

Duration (months)	Selected input variables			Selected output variables									
	SPESM	TB	WAP	CWR	BWR	MWR	MeWR	WWR	OSWR	PLWR	LWR	RRWR	LWR
1	20	15%	1.90	3.18	0.43	0.57	2.20	5.18	4.54	1.88	2.55	−2.05	0.63
2	20	15%	3.08	5.27	0.58	0.93	2.28	5.12	7.24	3.05	3.60	−2.05	1.02
3	20	15%	4.18	7.36	0.73	1.11	2.36	5.05	9.76	4.14	4.57	−2.05	1.38
4	20	15%	5.24	9.45	0.79	1.29	2.48	4.97	12.19	5.19	5.50	−2.05	1.73
5	20	15%	6.19	11.45	0.84	1.34	2.59	4.50	14.33	6.13	6.30	−2.06	2.04
6	20	15%	6.62	11.94	1.25	1.35	2.60	4.27	15.26	6.55	6.64	−2.06	2.18
7	20	15%	6.96	12.44	1.48	1.37	2.59	4.17	16.01	6.88	6.93	−2.07	2.29
8	20	15%	7.29	12.94	1.69	1.38	2.56	4.06	16.75	7.20	7.20	−2.07	2.40
9	20	15%	7.61	13.43	1.87	1.38	2.49	3.95	17.42	7.51	7.45	−2.07	2.50
10	20	15%	7.63	13.47	1.87	1.37	2.42	3.84	17.43	7.52	7.44	−2.08	2.51
11	20	15%	7.58	13.35	1.88	1.36	2.36	3.80	17.28	7.46	7.37	−2.08	2.49
12	20	15%	7.54	13.24	1.88	1.34	2.19	3.76	17.13	7.41	7.30	−2.08	2.47
13	20	15%	7.50	13.11	1.86	1.33	2.02	3.72	16.94	7.34	7.21	−2.09	2.45
14	20	15%	6.91	12.01	1.82	1.19	1.87	3.54	15.55	6.76	6.66	−2.10	2.25
15	20	15%	6.31	10.91	1.77	1.02	1.85	3.15	14.13	6.17	6.08	−2.11	2.06
16	20	15%	5.70	9.81	1.71	0.86	1.83	2.76	12.70	5.57	5.50	−2.12	1.86
17	20	15%	5.06	8.71	1.58	0.69	1.81	2.37	11.20	4.94	4.90	−2.12	1.65
18	20	15%	4.38	7.41	1.46	0.61	1.73	2.18	9.59	4.27	4.26	−2.13	1.42
19	20	15%	4.09	6.95	1.34	0.58	1.60	2.01	8.91	3.99	3.98	−2.14	1.33
20	20	15%	3.82	6.48	1.26	0.54	1.48	1.84	8.27	3.73	3.71	−2.14	1.24
21	20	15%	3.54	6.01	1.19	0.51	1.36	1.66	7.62	3.46	3.44	−2.15	1.15
22	20	15%	3.27	5.54	1.11	0.47	1.24	1.49	6.98	3.20	3.17	−2.16	1.07
Total				214.47	30.38	22.58	45.91	77.41	277.23	120.34	121.77	-46.03	40.11
				Unit: tons									

Table 5: Simulation results of the Policy Scenario A

Months	PSA-1				PSA-2			
	WAP	Variation	TCWR (tons)	Variation	WAP	Variation	TCWR (tons)	Variation
1	2.20	16.00%	17.27	49.47%	2.47	0.30	30.84	78.62%
2	3.61	17.40%	21.10	48.89%	4.09	0.33	39.14	85.50%
3	5.23	25.10%	25.65	54.42%	6.16	0.47	57.29	123.34%
4	6.25	19.40%	27.88	46.95%	7.16	0.37	54.46	95.33%
5	7.01	13.20%	28.80	38.99%	7.74	0.25	47.48	64.86%
6	8.36	26.30%	32.07	49.76%	9.91	0.50	73.52	129.24%
7	8.50	22.20%	31.70	43.84%	9.88	0.42	66.29	109.09%
8	8.70	19.30%	31.48	39.09%	9.96	0.36	61.33	94.84%
9	10.43	37.10%	35.71	54.42%	12.94	0.70	100.81	182.31%
10	10.56	38.40%	36.44	58.59%	13.17	0.73	105.20	188.70%
11	10.59	39.70%	37.02	62.76%	12.82	0.69	103.51	179.60%
12	10.13	34.40%	35.99	60.53%	12.05	0.60	91.99	155.63%
13	10.60	41.40%	37.53	70.23%	12.90	0.72	81.87	118.14%
14	9.89	43.20%	35.72	74.88%	12.10	0.75	79.76	123.28%
15	9.05	43.40%	33.30	77.99%	11.07	0.76	74.54	123.85%
16	8.22	44.10%	29.67	74.79%	10.08	0.77	67.00	125.84%
17	7.23	42.70%	25.72	69.55%	8.83	0.74	57.07	121.85%
18	6.27	43.20%	22.25	66.15%	7.67	0.75	49.67	123.28%
19	5.88	43.90%	20.33	62.95%	7.21	0.76	45.79	125.27%
20	5.50	44.10%	18.47	59.27%	6.74	0.77	41.72	125.84%
21	4.80	35.40%	15.76	46.95%	5.73	0.62	31.68	101.02%
22	4.41	34.70%	14.02	42.39%	5.25	0.60	27.91	99.02%
Sum	163.42	724.60%	613.87	1252.85%	195.91	12.96	1388.86	2674.45%
Average	7.43	32.94%	27.90	56.95%	8.91	0.59	63.13	121.57%

Table 6: Simulation results of the Policy Scenario B

Months	PSB-1				PSB-2			
	WAP	Variation	TCWR (tons)	Variation	WAP	Variation	TCWR (tons)	Variation
1	1.97	4.01%	12.07	4.49%	1.98	4.05%	12.12	4.94%
2	3.21	4.44%	14.87	4.98%	3.22	4.49%	14.95	5.47%
3	4.44	6.38%	17.80	7.14%	4.45	6.45%	17.92	7.86%
4	5.51	5.12%	20.06	5.73%	5.51	5.17%	20.17	6.31%
5	6.42	3.74%	21.59	4.19%	6.43	3.79%	21.67	4.61%
6	7.08	6.96%	23.09	7.80%	7.08	7.06%	23.25	8.58%
7	7.38	6.09%	23.54	6.82%	7.39	6.15%	23.69	7.50%
8	7.70	5.50%	24.02	6.15%	7.70	5.58%	24.16	6.77%
9	8.36	9.83%	25.67	11.01%	8.37	9.99%	25.93	12.11%
10	8.41	10.24%	25.61	11.47%	8.42	10.35%	25.88	12.62%
11	8.39	10.65%	25.46	11.93%	8.41	10.83%	25.73	13.12%
12	8.25	9.49%	24.80	10.63%	8.27	9.66%	25.04	11.69%
13	8.34	11.23%	24.82	12.58%	8.35	11.35%	25.10	13.84%
14	7.72	11.76%	23.12	13.17%	7.74	11.98%	23.39	14.49%
15	7.06	11.91%	21.20	13.34%	7.07	12.15%	21.45	14.67%
16	6.40	12.18%	19.29	13.64%	6.40	12.30%	19.52	15.00%
17	5.67	11.94%	17.20	13.38%	5.68	12.19%	17.40	14.71%
18	4.91	12.16%	15.21	13.62%	4.92	12.43%	15.40	14.98%
19	4.60	12.43%	14.21	13.92%	4.60	12.55%	14.38	15.31%
20	4.30	12.58%	13.23	14.08%	4.31	12.86%	13.40	15.49%
21	3.92	10.61%	12.00	11.88%	3.93	10.86%	12.12	13.07%
22	3.62	10.54%	11.01	11.81%	3.62	10.65%	11.13	12.99%
Sum	133.65	199.79%	429.88	223.76%	133.83	202.89%	433.80	246.14%
Average	6.08	9.08%	19.54	10.17%	6.08	9.22%	19.72	11.19%

Table 7: Simulation results of the Policy Scenario C

Months	PSC (PSA-2,PSB-2)			
	WAP	Variation	TCWR (tons)	Variation
1	2.69	41.49%	31.69	83.56%
2	4.47	45.23%	40.29	90.98%
3	6.90	65.21%	59.31	131.20%
4	7.89	50.62%	56.21	101.64%
5	8.34	34.77%	48.80	69.48%
6	11.16	68.69%	76.27	137.82%
7	11.01	58.21%	68.66	116.59%
8	11.01	50.89%	63.46	101.61%
9	14.98	96.93%	105.14	194.42%
10	15.28	100.33%	109.80	201.32%
11	14.92	96.69%	108.36	192.73%
12	13.88	84.12%	96.20	167.32%
13	15.06	100.89%	87.07	131.98%
14	14.19	105.45%	84.94	137.77%
15	13.00	106.07%	79.42	138.52%
16	11.84	107.73%	71.45	140.84%
17	10.37	104.65%	60.85	136.56%
18	9.02	105.99%	53.01	138.26%
19	8.49	107.61%	48.91	140.58%
20	7.95	108.41%	44.58	141.34%
21	6.65	87.68%	33.74	114.09%
22	6.09	85.94%	29.73	112.01%
Sum	225.19	1813.62%	1457.89	2920.59%