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A System Dynamics Model for Construction Waste Resource Recovery Management in China

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Abstract

Construction waste resource recovery management (CWRRM)is a key focuswithinacademia and industry, as it is directly related to the effectiveness ofconstruction waste management (CWM) activities, and to a great extent,affects the sustainable development of green buildings and the environment. How to provide incentivesand generate the enthusiasm of stakeholders in waste management is especially critical. This paper usesthe system dynamics (SD) method to study the CWRR problem, through the analysis of the relationship between various influences factorsfor contractors to resourcefully dispose CW,we firstly establish a model for CW resourceful disposal in three stages of construction,use VENSIM software for simulation,and apply the model in a construction project in Chengdu, China. The results showed thatthe most effective measures to increase the amount of waste resource recovery (WRR)are to improve the market demand in renewable materials,to improve the construction enterprises' consciousness in setting up green images, and to improve the recycling market development level.SD applied to study the problem of CWRR, can better reflect the complex relationships between various factors in the system,and can be used toprovide guidance and reference for the establishment of CWRRM measures.

Key words: System dynamics; Construction waste resource recovery management; Construction stages

1.Introduction

The construction industry is one of the largest solid waste producers worldwide, with the increasing of construction activities, producing large amount of CW every year. Compared to the amount of CW every country produces each year, the recycling ratio is small, especially in developing countries. Project decision-makers tend to put more emphasis on cost, time, quality and safety, etc, traditional construction targets, while ignoring the effect that the large amount of waste generated in the construction process has on environmental sustainability.

Along with the growing of China's urban population and the quickening of urbanization, waste generated by urban construction activities is also growing. According to statistics, China's urban CW generation has reached 30% to 40% of the total municipal solid waste at present. In 2014, China produced almost 1 billion tonneof CW, with a recovery rate of only 5%, this wasting a lot of land resources, and also greatly affect the sustainability of the urban environment (NDRC, 2014). In China, CW recycling technology has no barriers; lack effective process patterns, incentive policies, and a good market environment become the main bottleneck of CWRR. How to realize CWRR has become a critical focus of people's attention. It should be pointed out thatCWRRin this paper included waste recycling and reuse, onsite and off-site.

At present, Yuan (2012) indicatedthat CWM research is still in its infancy. In terms of static study of CWM system, Yuan and Shen (2013) analyzed eight major international journal publications from 2000 to 2009, and summarized the latest research trends inCWM. Lu and Yuan (2010)put forward the key factors for CWM, then, they established a CWM research framework, and pointed out important directions for research in the future(Lu and Yuan, 2011). Lu et al., (2015) used valid CWMdata sets from Hong Kong, to establish a series of reliable waste generation rates. Liet al., (2016) established a quantitative estimation model for CW, to improve the accuracy of CW quantitative estimation at the project level.

The dynamics study of CWM system needs to consider the interaction relationship between the variables in the system (Hao et al., 2010; Yuan et al., 2011). Based on the economic benefits perspective, Yuan et al., (2011) established a system dynamics model for CW cost-benefit analysis.Yuan and Wang (2014) determined a scientific and reasonable CW disposal charging fee. Based on the environmental benefits perspective, Gui et al., (2012) establisheda system dynamics model to evaluate CWM environmental benefits.Ding et al., (2016) set up a CW reduction management model based on the theory of planned behavior, to simulate the environmental benefits of CW reduction management. Based on the social benefits perspective, Yuan (2012) established an evaluation model for the social benefits ofCWMusing the system dynamics method. Wang et al., (2015) set up a quantitative evaluation model for different management strategies and policy implications of CW reduction at the design stage.Some scholars in China have begun to study CWM with the SD method, but overall, still in its infancy(Wang and Yuan, 2008; Wang and Yuan, 2009; Wang et al., 2012; Yuan and Wang, 2013; Liu et al., 2014).

Recently, CW reduction and recycling have been the focuses of the scholars. Waste reduction research takes scholars' attentions.Yuan et al., (2012) assessed CW reduction strategies in different situations with the SD method. Li et al., (2015) investigated designers' attitudes and behavior inCW minimization, and determined the influence factors in the design process. Research inWRR is relatively less, Tam (2008) summarized three benefits of recycling: (1) Recycling reduces the demand for new resources; (2) Recycling reduces energy consumption in transportation and production; (3) Recycling realizes reasonable waste utilization. Mohamed and Shimaa (2014) evaluated CWM methods in the impact of both the economy and environment, and encouraged contractor recycling waste. Also, some scholars studied the economic feasibility of waste recycling centers(Zhao et al., 2011; Srour et al., 2013). However, research on WRRis relatively superficial, and has not put forward specific strategies to promote WRR. Based on above research, this paper expands the concept of recycling to the resource recovery level, and puts forward specific strategies aiming at promoting WRR.

In recent years, the "reduction, recycle and reuse" (3R) strategies is being implemented globally. In China, the effect of the strategy is at a basic stage. The most important factor is the lack of effective management and incentive measures. At present, Liu et al., (2014) stated that economic measuresforCWMinvolve fines, but the effect is not ideal, and waste management consciousness in construction enterprises has not improved. Due to the lack of related management and incentive measures, maturation of the waste recycling market is low, and is short of the consciousness that construction enterprises need to set up green images. Not only that, because of people's strange psychology of the CW concept, customer trust level is extremely low, Liu and Huang (2014) indicated. So, in conducting CWRR disposal, system analysis andchoosingthe right strategies is of great significance.

How to determine the CWRR strategies andmake management decisions, forboth construction enterprises and governments is a very important question.Past studies involved CW quantitative research mostly using the method of experience value estimation, rarely referred toCWM staging studies. But due to the various stages of construction processesinvolvedifferent working aspects and building materials properties, general quantitative analysis can't truthfully reflect the generation and disposal situations of CW. Based on the discussion above, this paper uses the system dynamics method to develop aCWRR disposal model, taking a construction project in Chengdu, China as an example, The construction processes are innovatively divided into three stages:foundation engineering, main body engineering, and decoration engineering. This validates the rationality and validity of the model, using VENSIM software for simulation analysis, and provides guidance and reference for construction projects in taking WRR management measures at different construction stages.

2.System dynamics approach

2.1 System dynamics and its application

The model proposed in this study is constructed in line with theprinciple of system dynamics (SD), which is a method originated by JayForrester in the 1960s to deal with large-scale systems of highcomplexities. It is based on feedback control theory, by means of computer simulation technology, and is mainly used for research on the relationship between complex systems structures, functions and dynamic behavior. CWM itself is a complex system,involving different stakeholders (such as owners, contractors, engineers, waste managers, etc.) and many links(such as generation, landfill, recycling, etc.).Because of this, the application of SDcan solve related problems with good rationality. In recent years, SD applied research in the field of CWMhas also been increasing.

2.2 SD model on the VENSIM software

There are two ways to representSD models, the causal loop diagram andthe stock-flow diagram. These two kinds of representation are embodied in the different stages of modeling. A causal loop diagram is used to represent the main information in a real system, which can be seen as a conceptual model;and a stock-flow diagram is on the basis of the causal loop diagram, using computer simulation software. In a sense, the causal loop diagram andthe stock-flow diagram are actually different manifestations of the real system.The main difference is thatstock-flow diagram is a detailed version of the conceptual model, forquantitative simulation and analysis. Liu et al., (2014) mentioned thatskilled modeling can be directly establishedina stock-flow diagram of the software environment, but the causal loop diagram is more suitable for a clearer understanding of the influence mechanism of the model.

In this study, the stock-flow diagram is established by VENSIM software, specially designed for SD modeling. Based on the above, there are four steps for establishingthe SD model, as shown in table 1.

Table 1 Modeldeveloped steps

Process	Comment	Tool
System description	Describe the interactional relationshipbetween variables in the system	Causal loop diagram
Build model	Turn the causal loop diagram into the stock-flow diagram, and define variables	Stock-flow diagram(VENSIM)
Model validation	Using historical data to verify the correctness of the SD model	(VENSIM)
System analysis	Model simulation and policy Suggestions	(VENSIM)

3. MODEL DEVELOPMENT

The development of the SD model usually follows a few steps, includingsystem description (causal loop diagram), Stock-flow diagram, model validation and system analysis. This paperfollows the same steps to establish the model for CW resourceful disposal in three stages of construction.

3.1. SYSTEM DESCRIPTION

The SD model established in this paperinvolves two ways forCWdisposal, which arewaste landfill and WRR;three stages of project construction, which arefoundation, main body and decoration. The model clearly describes two waste flows after CW generation, activities and behavior of CW through each stageconstitutes the complete CWdisposal feedback loop. After this, the model introduces the economic benefitsindexes of the two disposal ways, which are the economic benefit of WRR andthe economic benefit of waste landfilling,encouraging contractors toundertakeWRR disposal.Parameters used in this model are from field research studies and a large number of publishedstudies.

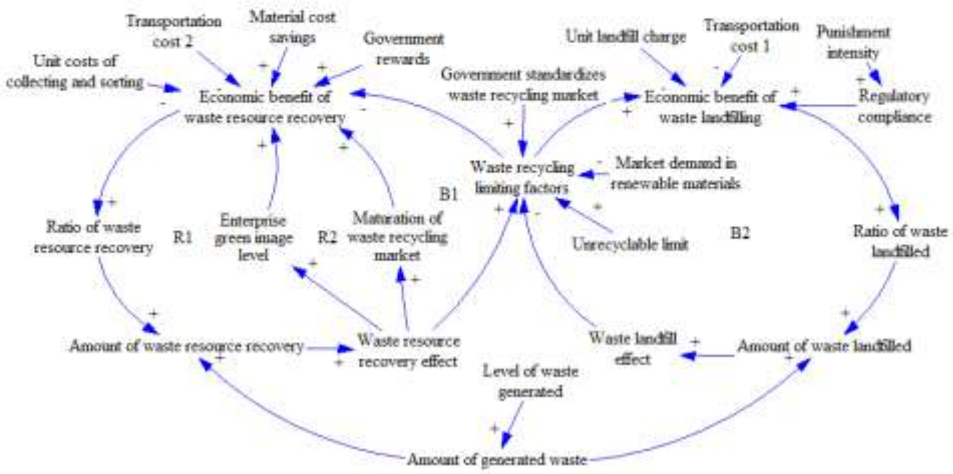

Figure 1. The causal loop diagram

3.2.CAUSAL LOOP DIAGRAM

A causal loop diagram describes the internal relations between each element in the SD model, based on a large number of publishedstudies, establishing a causal loop diagram as shown in Fig. 1. The figure includes 2 positive feedback loops (i.e. R1 and R2) and 2 negative feedback loops (i.e.B1and B2), also including variables that do not participate in a feedback loop, which pose causal chainswith other variables, as seen in the figure. It is noted that a change in any variablewithin the positive feedback loops will eventually affect itself in a positive way. On the contrary,Yuan and Wang (2013)referred that a change in any variable within the negative feedback loops will affect itself in a negative way.

In the positive feedback loop R1, as shown in Fig. 1, anincrease in the amount of WRR will increase the WRR effect, whichleads to animprovementin the enterprise green image level.It will then improvethe economic benefit of WRR, the largereconomic benefitimprovingthe ratio of WRR. In the end,a higherratio of WRR will stimulatemanagers to conductWRR disposal.

By replacing the variable "maturation of waste recycling market" with the variable"enterprise green image level" in the feedback loop R1, a new feedbackloop R2 can be developed. The causal relationships among loopR2 are similar to those in loop R1.

Feedback loop B1 has similar but opposite causal relationships as the feedbackloop R1, while the difference is replacing the variable "waste recycling limiting factors" with the variable"enterprise green image level".Then, the largerWRR effect will cause morewaste recycling limiting factors, which to some extentminimizethe economic benefit of WRR.Eventually,a lower economic benefit of WRR willlead to a smaller amount of WRR.

The feedback loop B2 is also negative. In this causal loop, anincrease in the amount of waste landfilledwill contribute toa larger waste landfill effect. As a consequence, contributing to fewer waste recycling limiting factors, it will causea reduction in the economic benefit of waste landfilling.Lowereconomic benefitleads to alower ratio of waste landfilled. Finally, lower ratio of waste landfilledwill affect a smaller amount ofwaste landfilled.

Some of the key factors'meanings in the causal loop diagram are explainedas following.

- Amount of generated waste: There are two main sources, one is generated by the construction process, and another is generated during demolition. This paper only discusses the CW, as shown in Fig. 2. Assuming no illegal dumping, all waste generated is collected.There are two possible waste flows after collection, one flow is transported to the waste landfill site, another is conducted waste classification, transporting recyclable waste to the waste recycling center, and unrecyclable waste to the waste landfill site.
- Amount of WRR: Refers to the amount of waste recycled and reused onsite and transported to the recycling center by contractors during the construction.
- Amount of waste landfilled: Refers to the amount of waste transported to the waste landfill site.
- Waste recycling limiting factors: These include the unrecyclable limit,the government standardized waste recycling market and the market demand in renewable materials,weights 0.3, 0.2, and 0.5, respectively.
- Maturation of waste recycling market:Mainly refers to the development level of the CW recycling market, with the value 1 expressingthe present recycling market development situation.

- Enterprise green image level: Mainly refers to construction enterprises'consciousness in establishing green images, with the value 1 expressingthe averagegreen image consciousness of enterprisesat present.
- Economic benefit of WRR: Refers to the economic benefits broughtby contractorsconduct WRRdisposal. The costs of collecting and sorting, andtransportation reducethe economic benefits, whereas the material cost savings and the government rewards increase the economic benefits.
- Economic benefit of waste landfilling: Refers to the economic benefits brought by contractorsconduct waste landfilldisposal.Landfill chargeandtransportation costsreduce the economic benefits, whereas the regulatory compliance increasesthe economic benefits.

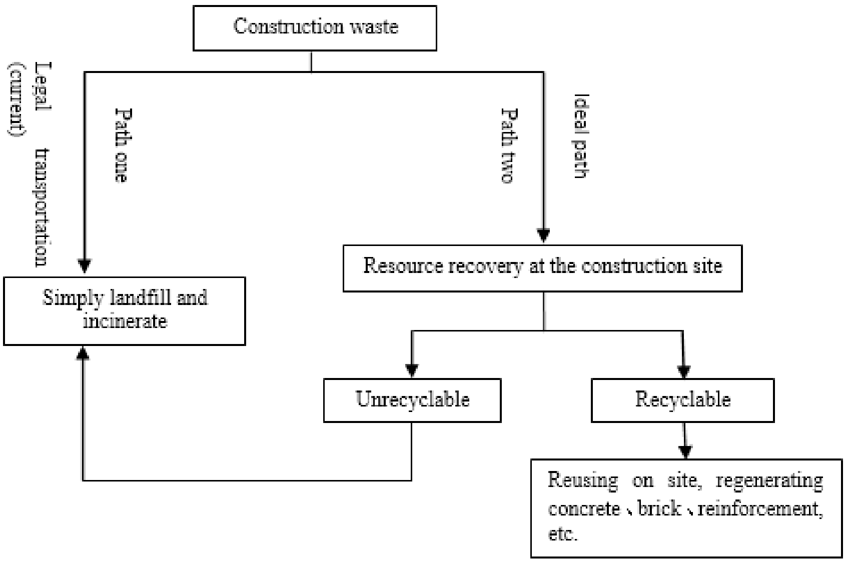

Figure 2. Construction waste disposal pattern

3.3. STOCK-FLOW DIAGRAM

According to the causal loop diagram constructedin Fig. 1,equations can be further used to describe the logical relationships between the system variables, clearing the quantitative relationships between the system variables and control processes, and describingthe feedback and dynamic law ofthe system. Astock-flow diagram for CW resourceful disposal in three stages of constructionis shown in Fig.3,and the equations are given in Appendix A.

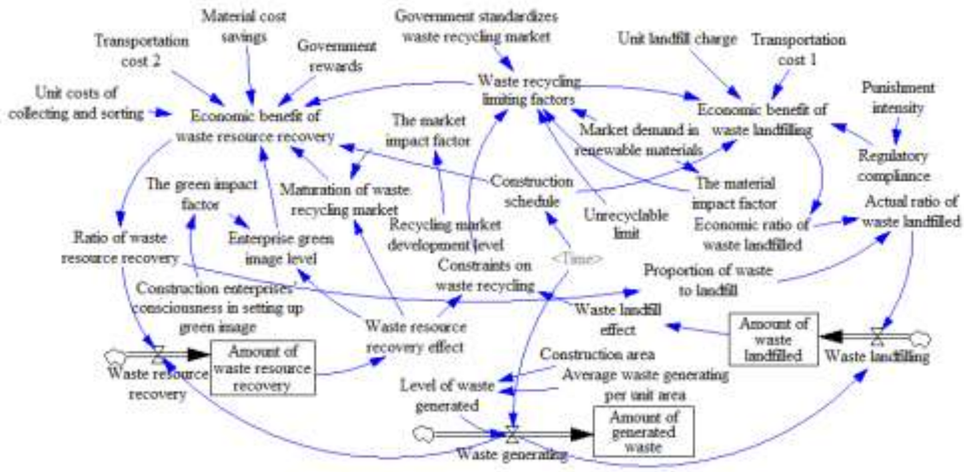

Figure 2. The stock-flow diagram

When analyzinga system, we usually consider four variables, namelystock, flow, auxiliary and parameters. Stocks describe the state of the system at any given moment; flows are used to show the stocks'change speed;auxiliaries make the complex decision function easy to understand;parameters are various reference numbers in the system, remaining the same in a run.

In this paper, the names ofthe variables and their types are shown in table 2.

Table 2 Determination of the variable properties

Variable name	Variable type	Variable name	Variable type
Amount of generated waste	Stock	Government standardizes waste recycling market	Parameter
Waste generating	Flow	Unrecyclable limit	Parameter
Level of waste generated	Auxiliary	Market demand in renewable materials	Parameter
Amount of waste resource recovery	Stock	Amount of waste landfilled	Stock
Waste resource recovery	Flow	Waste landfilling	Flow
Ratio of waste resource recovery	Auxiliary	Actual ratio of waste landfilled	Auxiliary
Economic benefit of waste resource recovery	Auxiliary	Economic benefit of waste landfilling	Auxiliary
Unit costs of collecting and sorting	Parameter	Unit landfill charge	Parameter
Transportation cost 2	Parameter	Transportation cost 1	Parameter
Material cost savings	Parameter	Regulatory compliance	Auxiliary
Government rewards	Parameter	Punishment intensity	Parameter
Enterprise green image level	Auxiliary	Waste landfill effect	Auxiliary
Maturation of waste recycling market	Auxiliary	Constraints on waste recycling	Auxiliary

Construction enterprises' consciousness in setting up green image	Parameter	Waste resource recovery effect	Auxiliary
Recycling market development level	Parameter	Economic ratio of waste landfilled	Auxiliary
Construction schedule	Auxiliary	Proportion of waste to landfill	Auxiliary
Waste recycling limiting factors	Auxiliary	The market impact factor	Auxiliary
The green impact factor	Auxiliary	The material impact factor	Auxiliary
Construction area	Parameter	Average waste generating per unit area	Parameter

4. MODEL SIMULATION AND RESULTS ANALYSIS

4.1 QUANTIFICATION OF VARIABLES

The development of above SD model is based on relations wherethe factors influence each other of the system. To simulate the model developed and carry out quantitativeanalysis, the WRR practices in the constructionindustry of ChengduCity, southwest China, is investigated.The selected case is a new commercial integrated project, located in the high-tech zone of Chengdu, with total construction area 134441.00m2, total project duration 24 months, including 5 months of foundation engineering, 10 months of main bodyengineering, and 9 months of decoration engineering.The initial value and methods to determine the variables are shown in table 3.

Data is collected by all kinds of irregular field investigations, using questionnaires and carrying out a series of formal and informal interviews, meetings and face to face communication with a number of stakeholders who participate in CWM (including project managers, site managers, on-site technical engineers, supervision engineers, etc.). Allstakeholders selected have 6 years working experience inCWM, andhave a deep understandingof waste management practices.

Table 3 Quantitative variable values

Variable name	Initial	Further information
Unit costs of collecting and sorting	30yuan/tonne	Yuan et al., (2011)
Transportation cost 2	50yuan/tonne	Yuan and Wang(2014)
Material cost savings	5yuan/tonne	Yuan et al., (2011)
Government rewards	0yuan/tonne	Current waste recycling subsidy standards in Chengdu
Construction enterprises' consciousness in setting up green image	1	Construction enterprises' consciousness basic value of setting up green image during construction
Recycling market development level	1	Basic value ofCW recycling market development level
Government standardizes waste recycling market	1	Government make policy to standardize waste recycling market

Unrecyclable limit	1	Existing unrecyclable (must landfill) CW
Market demand in renewable materials	1	Building materials market demand basic value of recycling waste for renewable
Unit landfill charge	1.33yuan/tonne	Current waste landfill charge standards in Chengdu
Transportation cost 1	25yuan/tonne	Yuan and Wang(2014)
Punishment intensity	1	Penalties for illegal dumping behavior
Construction area	134441m2	Case project information
Average waste generating per unit area	47.6/1000	Yuan et al., (2012)

4.2. MODEL TESTING AND VALIDATION

After determining all variables and functions of the model, it is critical tocheck the validity through a set of tests, to ensure its reliability and applicability, and at the same time in order to ensure that the model is an accurate abstraction of real world systems.SD model tests mainly include mechanical error tests(check the model for spelling errors and logic connection errors), dimension consistency test (check all variable dimensions in the equation), model validation test, and extreme conditions test.After testing, the parameter "government rewards", as an example to illustrate the model validation test.

Current CWRR rewards in Chengdu is 0 yuan/tonne, in order to test the modelbehavior effectwhen the "government rewards" changes,if is assumed that there are other three feesscenarios (5 yuan/tonne, 10 yuan/tonne and 15 yuan/tonne, respectively),to simulate the above four scenarios, then to inspect the change ofWRR amount and waste landfilled amount. Simulation resultsin Fig. 4show that compared tothe base scenario (government rewards of 0 yuan/tonne), when the government rewards up to 5 yuan/tonne, 10 yuan/tonne, and 15 yuan/tonne, respectively, theWRR amount appears significantly increasing, and the waste landfilled amount decreasing significantly. Thus, when the other parameters in the model are the same, as the government rewards increasing,the WRR amount will be more and the waste landfilledamount will be less. This is mainly because the economic benefit of WRRis rising, and the economic benefit of waste landfilling is declining, in line with the actual situation.

To sum up, the model in this paper, through the model validation, can reasonably reflect actual situation, and can be used in the simulation analysis.

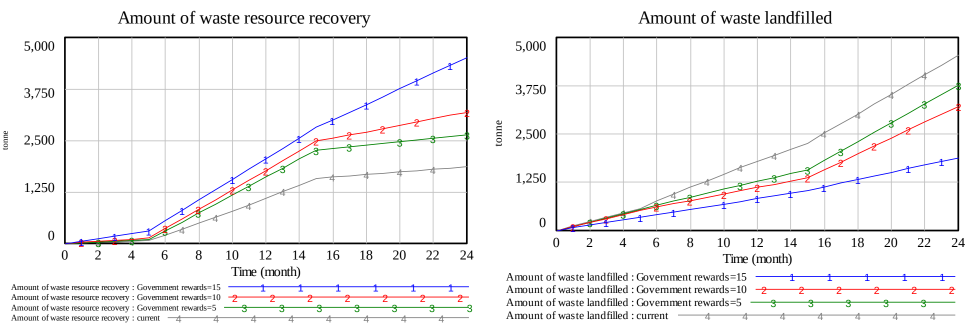

Figure 4. The model validation results (government rewards)

4.3 RESULTS OF THE BASE RUN

In the case study, the model is simulated in a total period of 24 months, which is corresponding to the construction duration ofthe project as indicated previously. The baserunsimulation results reflect the status quo of the project CWM,the key variables values areas follow, recycling market development level=1;construction enterprises' consciousness in setting up green image=1;the limiting value ofmarket demand in renewable material=1. The baserun simulation results are shown in table 4. Table 4 shows thatthe project generated 6399.39 tonneof waste in all during construction,including 639.939 tonne of the foundation engineering, 3199.691 tonne of the main bodyengineering, and 2559.76 tonne of the decoration engineering. Conducted WRR disposal 1858.87tonnetotally, including 65.0272 tonne of the foundation engineering, 1515.6928tonne of the main bodyengineering, and 278.15tonne of the decoration engineering. Waste landfilled 4540.52tonne in total, covered 574.912 tonne of the foundation engineering, 1683.998tonne of the main bodyengineering, and 2281.61tonne of the decoration engineering.

It can be seen from the results thatWRRrate of the foundation engineering is low, mainly due to the engineering involvinga small amount of recyclable building materials;the main bodyengineering's WRR rate is relatively high, mainly because building materials such as reinforcement, formwork and woodcan bewidelyrecycled;the WRRrate of the decoration engineering is also low, as only some metal components can be recycled.

Table 4 The baserun simulation results

Month	Amount of generated waste(tonne)	Amount of waste resource recovery(tonne)	Amount of waste landfilled(tonne)
0	0	0	0
1	127.988	12.9908	114.997
2	255.976	25.9889	229.987
3	383.964	38.9943	344.969
4	511.951	52.0071	459.944
5	639.939	65.0272	574.912
6	959.909	202.222	757.687
7	1279.88	342.438	937.44
8	1599.85	485.739	1114.11
9	1919.82	632.189	1287.63
10	2239.79	781.853	1457.93
11	2559.76	934.798	1624.96
12	2879.73	1091.09	1788.64
13	3199.7	1250.79	1948.9
14	3519.66	1413.98	2105.68
15	3839.63	1580.72	2258.91
16	4124.05	1611.47	2512.58
17	4408.47	1642.26	2766.21
18	4692.89	1673.08	3019.8
19	4977.3	1703.95	3273.36
20	5261.72	1734.85	3526.87
21	5546.14	1765.8	3780.34

22	5830.56	1796.78	4033.78
23	6114.97	1827.8	4287.17
24	6399.39	1858.87	4540.52

4.4 RESULTS OF THE POLICY SCENARIOS

In order to encourage contractorsinCWRR,raise the level of CWM;formulate rational and effective measures,by finding the key variables includingthe enterprise green image level,the maturation of waste recycling market and the waste recycling limiting factors. Through the changes of the key variables,studythe influence degree of the amount of WRR and waste landfilled,to make scientific and effective waste management measures, to improve the economic benefit of WRR,and then to promote increasing of the amount of WRR. As a result, three policy scenarios are developed accordingly, which are:

- Scenario 1 (S1): this scenario is concerned with how changes in the enterprise green image level (EGIL) affect the amount of WRR and waste landfilled;
- Scenario 2 (S2): this scenario is designed to simulate howchanges in the maturation of the waste recycling market (MWRM) influencethe amount of WRR and waste landfilled; and
- Scenario 3 (S3): this scenario aims at examining how the effect ofchanging the waste recycling limiting factors (WRLF) influencethe amount of WRR and waste landfilled.

Table 5 Input variable values of three scenarios

Scenario	Run	Values of variables
scenario1(S1)	Run1(S1-1)	Base run: Construction enterprises' consciousness in setting up green image (CECGI)=1
	Run2(S1-2)	In this simulation, take effective measures to increase the value of CECGI, then, increase the value of economic benefit of WRR. So, CECGI=Key variable values in base run*(1+0.1)
	Run3(S1-3)	CECGI=Key variable values in base run*(1+0.2)
	Run4(S1-4)	CECGI=Key variable values in base run*(1+0.3)
scenario2(S2)	Run1(S2-1)	Base run: Recycling market development level (RMDL)=1
	Run2(S2-2)	In this simulation, take effective measures to increase the value of RMDL, then, to increase the value of economic benefit of WRR. So, RMDL=Key variable values in base run*(1+0.1)
	Run3(S2-3)	RMDL=Key variable values in base run*(1+0.2)
	Run4(S2-4)	RMDL=Key variable values in base run*(1+0.3)
scenario3(S3)	Run1(S3-1)	Base run: The limiting value of market demand in renewable material (LMDRM)=1; The weighted value of waste recycling limiting factors (WWRLF)=1
	Run2(S3-2)	In this simulation, take effective measures to increase the value of MDRM, and to reduce the value of WRLF, then, to increase the value of economic benefit of WRR. So, LMDRM=Key variable values in base run-0.1; WWRLF=Key variable

		values in base run-0.05
	Run3(S3-3)	LMDRM=Key variable values in base run-0.2; WWRLF=Key variable values in base run-0.1
	Run4(S3-4)	LMDRM=Key variable values in base run-0.3; WWRLF=Key variable values in base run-0.15

The input variable values ofthe three scenarios are shown in table 5. It is clear that S1, S2 and S3 are all single-policy scenarios. In a single-policy scenario, only one managementmeasure is taken while other variables remain unchanged, as they are in the model validation.

As shown in the model (see Fig. 3), the amount of WRR and waste landfilled in the three stages of construction are determined by their economic benefit, the economic benefits affected by the three variables, the EGIL, the MWRM and the WRLF.Therefore, S1 is carried out by improving the value of EGIL, S2 by increasing the MWRM value, and S3 by decreasing the value of WRLF. Through the policy scenarios simulations,different construction stages are discussed,and determinedthe effective measures to raise the economical benefit of WRR. The simulation results of the three scenarios are shown in Fig. 5-7.

Scenario 1 is used to testthe impact of the value changes of CECGI when relevant measures are adopted. Inthis scenario, the model is simulated under four situations, amongwhich one is the base run and the other three are designed to testhow different levels of the measure could contribute tothe amount of WRR and waste landfilled (see Table 5). Based on the simulation resultsin Fig. 5, it is seen that after adoption of the green imagemeasure, the amount of WRR value has increased from1858.87tonne in the base run to2407.9 tonne in thefourth run (increased by 29.5%); the amount of waste landfilled value has decreased from 4540.52 tonne in the base run to 3991.5 tonne in thefourth run (decreased by 12.1%), demonstrating that the levelof WRR can be improved by adopting measures to encourageconstruction enterprises to set up green image.

Scenario 2 is to test the impact of the RMDL value changes when measures are implementedin thecurrent market. In this scenario, the model is alsosimulated under four situations, in which one is the base run and the other three are designed to simulate how different levelsof the marketdevelopment measure could contribute to the amount of WRR and waste landfilled(see Table 5). According to the simulation resultsin Fig.6, it is seen that the value of the WRR amount changed significantly,from1858.87tonne in the base run to2239.79 tonne in the fourth run (increased by20.5%);the value of waste landfilled decreased from 4540.52 tonne in the base run to 4159.6 tonne in the fourth run (decreased by 8.4%), indicating that adoption of measures for promotingmarketdevelopment can lead to improvement in thelevel of WRR in the studied project.

In scenario 3, measures are taken to improve the market demand in renewable materials to test the impact of the WWRLF changes.In this scenario, the model is alsosimulated under four situations, one is the base run and the other three are designed to simulate how different levelsof the market demand measure could contribute to the amount of WRR and waste landfilled(see Table 5).Simulation results in Fig.7 demonstrate that the value of WRR amount can be increased from1858.87tonne in the base run to2988.18 tonne (increased by 60.8%); the value of waste landfilled amount can be decreased from 4540.52 tonne in the base run to 3411.21 tonne (decreased by 24.9%) after adoptingthe relevant measures mentioned above.

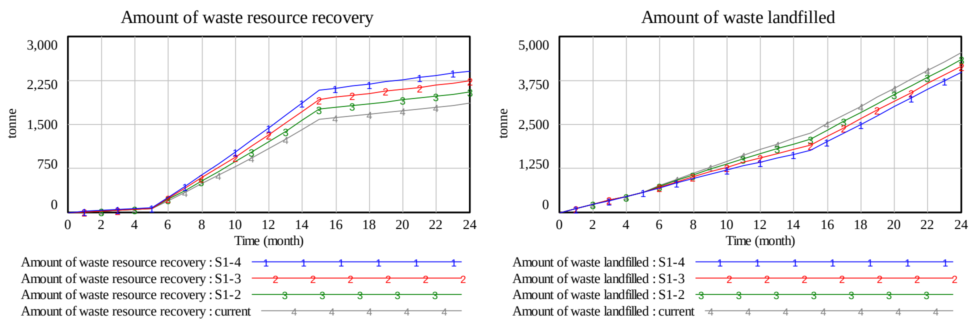

Figure 5. Scenario 1 simulation results (enterprise green image level)

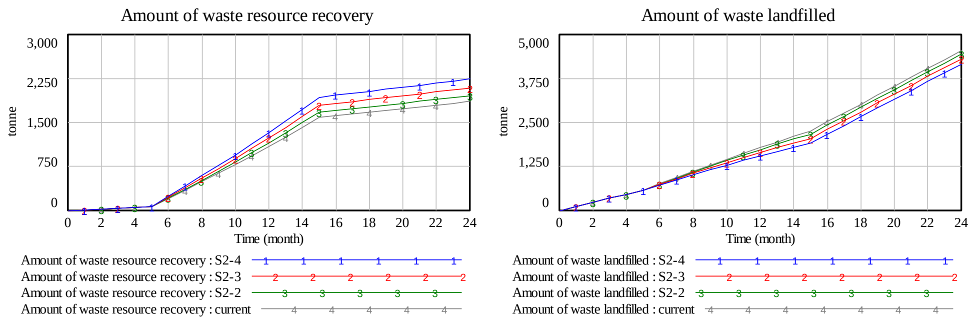

Figure 6. Scenario 2 simulation results (maturation of waste recycling market)

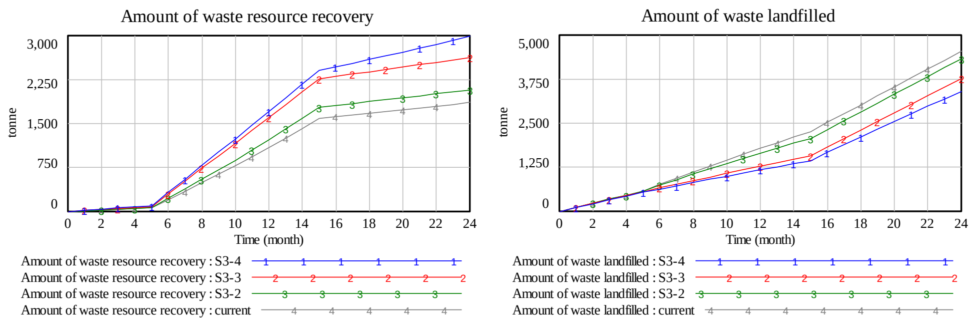

Figure 7. Scenario 3 simulation results (waste recycling limiting factors)

By comparing the simulation results of the scenarios(i.e. S1, S2 and S3), it is observed that:

1.The most effective measures to increase the amount of CWRR is to improve the market demand in renewable materials;the second is to promoteconstruction enterprises in setting up green images; the last isto adopt measures for promoting the marketdevelopment.Compared with the first two measures the last has no significant effect and its growth rate is slower.

2. As shown inFig. 5-7, (a) because of the building materials limitation in the foundation engineering stage, the effect of taking measures to improve the level of WRR is not obvious; (b)the period of main bodyengineering stage is long, construction materials have large consumption, so taking measures to raise the level of WRR effect is very significant; (c)consumption of the variousbuilding materials in the decoration engineering stage is relatively large, but very little is recyclable waste, so the effect of taking measures to raise

the level of WRRis generally much less.Therefore, construction enterprises should focus WRR on the main bodyengineering stage, and WRRin decoration engineering stage should also be considered.

5. DISCUSSIONAND CONCLUSIONS

CWRRM has always been a focuswithinacademia and industry, as it is directly related to the effectiveness of CWM activities, and to a great extent,affects sustainable development in green buildings and the environment. How to incentive the enthusiasm of stakeholders in waste management is especially critical. So far, although some researchershave discussed the CWRR problem,but the results cannot quantitatively reflect the dynamic changesof CWRRat different construction stages. Therefore, this paper has established a model for CW resourceful disposal in three stages of construction,SD method was used,and it can well reflect the dynamic change of CWRR at different stages of the construction.

Through the model validation and empirical simulation, the main conclusions are as follows:

1. Most CW generated in the case study is still conduct landfill disposal as the main disposal way. While making use of the strategies to improve the economic benefit of WRR, resourceful waste is also increasing, but the proportion is low.

2. By improving the market demand in renewable materials,the amount of WRR can be increased, and reducing the amount of waste landfilled. In fact, the production technical maturity of recycled materials is very high, and the quality of recycled materials can meet the requirements of most construction projects. Compared with natural building materials, their environmental protection index is high; theirenergy preservation and heat insulation effect is also good. Therefore, recycled materials can be quality certified, to do a goodpropagandajob, and to encourage the greater use of recycled materials in the field of construction projects.

3. Improving the construction enterprises' consciousness in setting up green images,can increase the amount of WRR, and reduce the amount of waste landfilled. Construction enterprises choose a green development strategy, not only to meet the requirement of the external environment, butto enhance their own competitiveness, and the inevitable requirement of improvedsustainable development.Government could consider establishing an evaluation index system forconstruction enterprises green images,visualizing and reifyingthe green mission and green responsibility of construction enterprises, indicatingenterprisesthe operationalgreen strategy targets, at the same time providing green criteria for the government and the public to oversee construction enterprises' development.

4. Improving the recycling market development level,can increase the amount of WRR, and reduce the amount of waste landfilled. Subsidiesareamong the most effective incentives.Government can introduce CWRR subsidy policies, giving reasonable rewardsto projects forWRRdisposal; cutting taxes for companies whichundertakeWRRdisposal; project financingcan also introduce corresponding policy support.Promoting the development and improving the maturation level of the waste recycling market would be a positive approach.

This paper develops the model for CW resourceful disposal in three stages of construction,can well describes the main interaction of the factors in the study system studied. The results of the empirical research provide useful information for CWRR.The influence of multi-policy scenariosto the amount of WRRand waste landfilled can be studied,to determine the optimal portfolio strategy.The model can also be applied to other similar construction projects,to scientifically evaluate the effect of WRRmanagement measures.

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APPENDIX A.

Amount of generated waste(t+1)=Amount of generated waste(t)+Waste generating(t+1)

INIT Amount of generated waste=0tonne

Waste generating=IF THEN ELSE(Time<=4,(Level of waste generated*0.1)/5,IF THEN ELSE(Time>4:AND:Time<=14,(Level of waste generated*0.5)/10,(Level of waste generated*0.4)/9))

Level of waste generated=Construction area*Average waste generating per unit area

Amount of waste resource recovery(t+1)=Amount of waste resource recovery(t)+Waste resource recovery(t+1)

INIT Amount of waste resource recovery=0tonne

Waste resource recovery=Ratio of waste resource recovery*Waste generating

Ratio of waste resource recovery=WITH LOOKUP(Economic benefit of waste resource recovery)

([(-90,0)-(85,10)],(-90,0.01),(-85,0.1),(-80,0.13),(-75,0.15),(-70,0.3),(-65,0.66),(-60, 0.71),(-55,0.78),(-50,0.8))

Economic benefit of waste resource recovery=((((-Unit costs of collecting and sorting-Transportation cost 2+Material cost savings+Government rewards)/Enterprise green image level)/Maturation of waste recycling market)*Waste recycling limiting factors)*Construction schedule

Amount of waste landfilled(t+1)=Amount of waste landfilled(t)+Waste landfilling(t+1)

INIT Amount of waste landfilled=0tonne

Waste landfilling=Actual ratio of waste landfilled*Waste generating

Economic ratio of waste landfilled=WITH LOOKUP(Economic benefit of waste landfilling)

([(-200,0)-(140,10)],(-140,0.21),(-120,0.22),(-100,0.23),(-80,0.24),(-60,0.48),(-40,0.7),(-15,0.81),(-5,0.91))

Economic benefit of waste landfilling=(((-Unit landfill charge-Transportation cost 1)*Regulatory compliance)/Waste recycling limiting factors)/Construction schedule

Waste resource recovery effect=WITH LOOKUP(Amount of waste resource recovery)

([(0,0)-(10000,10)],(0,1),(1000,1.01),(2000,1.02),(4000,1.05),(8000,1.1))

Waste landfill effect=WITH LOOKUP(Amount of waste landfilled)

([(0,0)-(7000,10)],(0,1),(7000,1.01))

Constraints on waste recycling=Waste resource recovery effect*0.5+Waste landfill effect*0.5

Waste recycling limiting factors=(Unrecyclable limit*0.3+Market demand in renewable materials*0.5+Government standardizes waste recycling market*0.2)*Constraints on waste recycling*The material impact factor

Enterprise green image level=Waste resource recovery effect*The green impact factor

Maturation of waste recycling market=Waste resource recovery effect*The market impact factor

The material impact factor=WITH LOOKUP(Market demand in renewable materials)

([(0,0)-(10,10)],(0.7,1.039),(0.8,1.04),(0.9,1.041),(1,1))

The green impact factor=WITH LOOKUP(Construction enterprises' consciousness in setting up green image)

([(0,0)-(10,10)],(1,1),(1.1,1.01),(1.2,1.02),(1.3,1.03))

The market impact factor=WITH LOOKUP(Recycling market development level)

([(0,0)-(10,10)],(1,1),(1.1,1.005),(1.2,1.012),(1.3,1.02))

Construction schedule=IF THEN ELSE(Time<=4,1.13,IF THEN ELSE(Time>4:AND:Time<=14,0.91,1.14))

Proportion of waste to landfill=1-Ratio of waste resource recovery

Actual ratio of waste landfilled=IF THEN ELSE(Economic ratio of waste landfilled=Proportion of waste to landfill,Economic ratio of waste landfilled,Proportion of waste to landfill)