Reducing Construction Waste through Prefabrication at the Design Stage: A Simulation Approach

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Keywords: prefabrication, construction waste reduction, system dynamics.

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Abstract

Since up to 40% of China’s waste is solid waste, the environmental consequences of construction waste (CW) in China are staggering. Reducing CW in a project is an important part of sustainable development and the best way to reduce CW is to design-out the waste. This not only reduces CW during the construction phase of a project, but also improves project safety and quality. This paper proposes a system dynamics simulation model for quantitatively assessing the potential of prefabrication as a method to reduce CW at the design stage. The simulation results show that: (1) Application of prefabrication exerts a considerable influence on construction waste by reducing rework due to design changes; (2) Use of prefabrication at the design stage has the greatest impact on concrete waste reduction; and (3) Increasing investment in designers’ professional training with respect to prefabrication, and strengthening prefabrication policies are two efficient strategies for reducing CW at the design stage. The proposed model will provide designers and policy makers with insights into how the application of prefabrication at the design stage can reduce CW, and allow them to dynamically compare different outcomes under various strategy and policy scenarios.

1. Introduction

Construction waste (CW), referring to the solid waste generated during the process of construction, reconstruction, decoration and demolition in a construction project, has resulted in serious adverse environmental and consequent socio-economic impacts worldwide. Therefore, rational strategies to manage CW are equally necessary for both developed and developing economies [1]. The circular economy is governed by 'reduce, reuse, and recycling' (3Rs), which are the fundamental rules for managing CW [2]. Actual reduction, which not only minimizes waste generation but also reduces the cost for waste sorting, transportation, harmless treatment and disposal [3], is regarded as the most efficient strategy in CW management.

Faced with a rapidly increasing amount of CW, prefabrication is commonly considered as a powerful strategy for CW reduction because of is obvious environmental and socio-economics benefits [4-5]. A plethora of research has been conducted to determine how to apply this advanced construction technology to minimize CW. Jaillon et. al (2009) [6] compared prefabrication with traditional on-site construction through questionnaire survey and case study, finding that an approximate 52% waste reduction can be achieved if prefabrication is adopted. Lu et. al (2013) [7] focused on the production and transportation of prefabricated components and found that prefabrication in a factory environment is more beneficial to waste reduction compared with traditional cast in-situ construction. Wang et. al (2014 and 2015) [9-10] demonstrated that adoption of prefabricated components at the design stage is helpful to minimize the generation of CW. Finch et. al (2019) [11] found that applying computer-aided manufacturing technology to fabricate advanced assemblies can realize a 67% reduction in the time required to recover construction materials for recycling. Although these and other similar studies have provided strong evidence to show that prefabrication generates less CW than traditional construction, they did not systematically and dynamically evaluate the potential for prefabrication to reduce waste at each stage of the whole life cycle of the construction project.

To address this research gap, the study on which this paper is based established a dynamic model for the adoption of prefabrication at the design stage and evaluated the potential impact of this approach on CW reduction at project level. Firstly, the key factors affecting the implementation of prefabrication and its potential for CW reduction at the design stage were identified through a literature review and interviews. Secondly, a system dynamics (SD) simulation model was developed to show how interaction among prefabrication factors at the design stage affects overall CW reduction for a project. Finally, to fully explore the potential effect of prefabrication on CW reduction, different prefabrication measures were analyzed under various scenarios by inputting data collected from residential projects into the SD model. The research results provide a reference for decision-makers, which is significant for promoting the use of prefabrication at the design stage to realize sustainable construction. It also allows for evaluation of the potential effects of prefabrication on CW reduction throughout the whole life cycle of a project.

2. System dynamics approach

System dynamics (SD), introduced by Forrester [11] in the 1960s at Massachusetts

Institute of Technology, is a conceptual modeling technique capable of understanding, studying, simulating, and analyzing complex systems, which is currently widely applied in such fields as social science, engineering, economics and management [12-15]. There are normally five steps to addressing problems with an SD approach: 1) System analysis; 2) Structure analysis—qualitative analysis; 3) Building a specification model—quantitative analysis; 4) Model validation and evaluation; and 5) Model simulation and scenario analysis [16]. The causal loop diagram and the stock-flow diagram are two main tools used in qualitative and quantitative analysis respectively. The processes of SD model building and simulation can be conveniently conducted using in Vensim software package [18].

Hao et. al (2007) [18] first applied SD to CW management in Hong Kong, since when it has been widely adopted in the discipline of CW. Yuan (2012) [19] adopted an SD approach for the assessment of the social performance of CW management. Yuan and Wang (2014) [20] developed an SD model to optimize waste disposal charges for stimulating CW minimization. Ding et al. (2018) [21] applied the SD approach to evaluate the environmental benefits of CW reduction at both the design and construction stages. All the aforementioned studies indicate that a SD approach is suitable for simulating the complexity of a CW management system involving many stakeholders and components.

3. Model development

The process of developing a SD model of the contribution of prefabrication to CW reduction is shown in Figure 1. To determine the system boundaries, all the major factors affecting the implementation of prefabrication and CW reduction at the design stage were identified based on the Theory of Planed Behavior (TPB). The qualitative model was thereafter developed by using a causal-loop diagram.

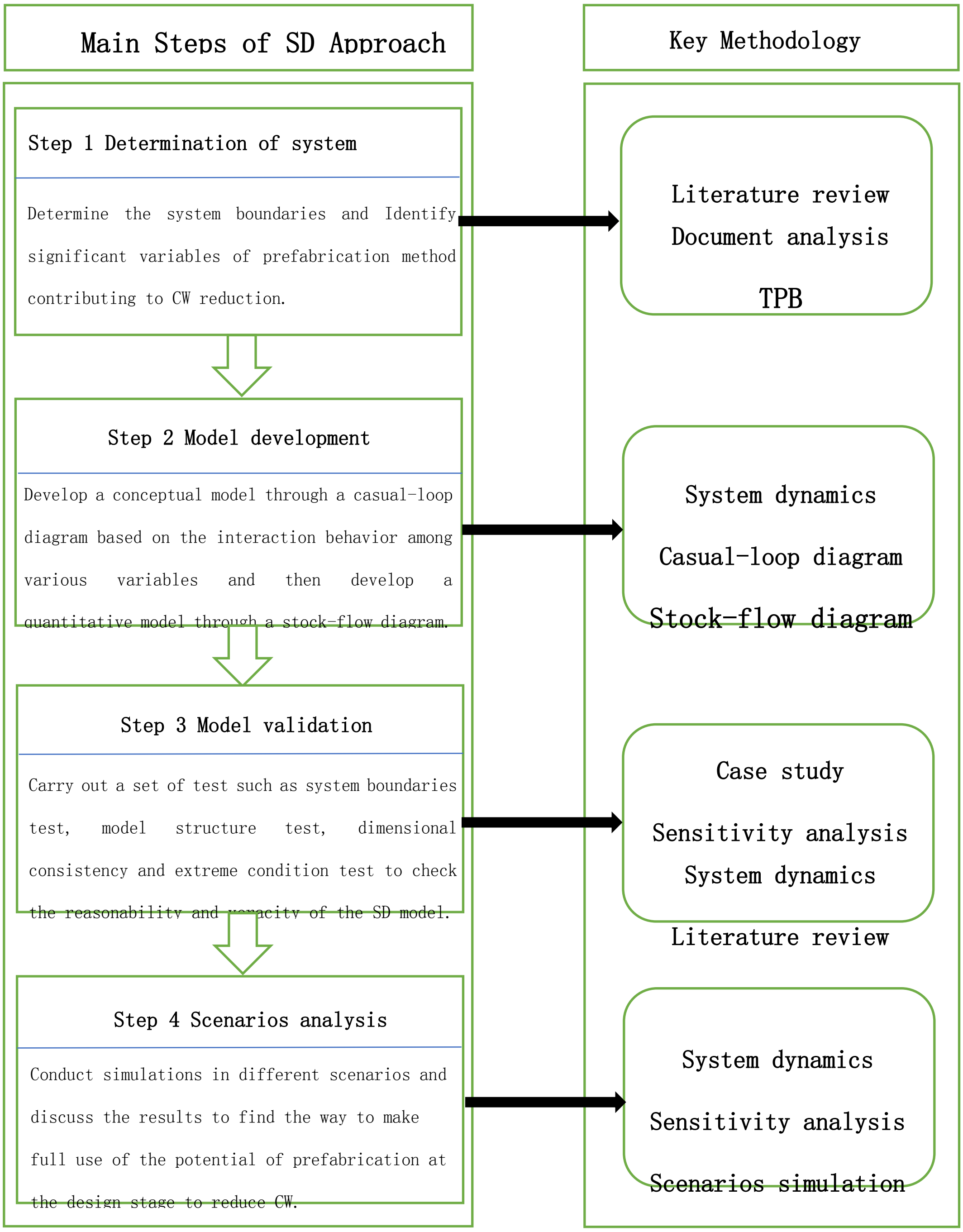


Figure 1. Research frame diagram

According to the qualitative model, a quantitative model was formulated using a stock-flow diagram. The model was then validated to check the reasonability and veracity of its structure and to test the behavior of the system. Finally, the tested model was applied to assess the effect of various measures to make full use of the potential of prefabrication for CW reduction.

All these steps operate in a cyclic process, which may require the revision of the previous step or even of the initial defined problem. The SD approach is therefore a highly iterative process.

3.1 Determination of system boundaries

Prior to establishment of the qualitative model, TPB [22] was introduced to determine the system boundaries reported in Figure 2. The increase of CW generation will prompt the designer to reduce waste, which will be reflected in behavior intended to reduce CW. Policies along with the designer’s ability can contribute to CW reduction indirectly [23]. Therefore, the attitude and behavior of designers forms a negative feedback loop in the system dynamics model.

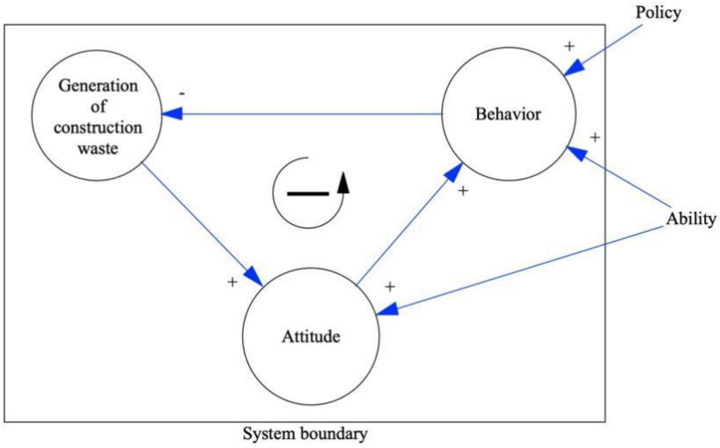


Figure 2. Feedback loop diagram of CW generation and designer’s attitude and behavior

3. 2 Causal-loop diagram qualitative analysis

According to the determined system boundaries, major factors were identified and a causal-loop diagram built to represent their underlying interaction relationships. The diagram is an abstract and conceptual model that describes the interaction relationships among major factors. To facilitate the analysis of complex interaction relationships in the model, most of the qualitative variables are defined as positive factors.

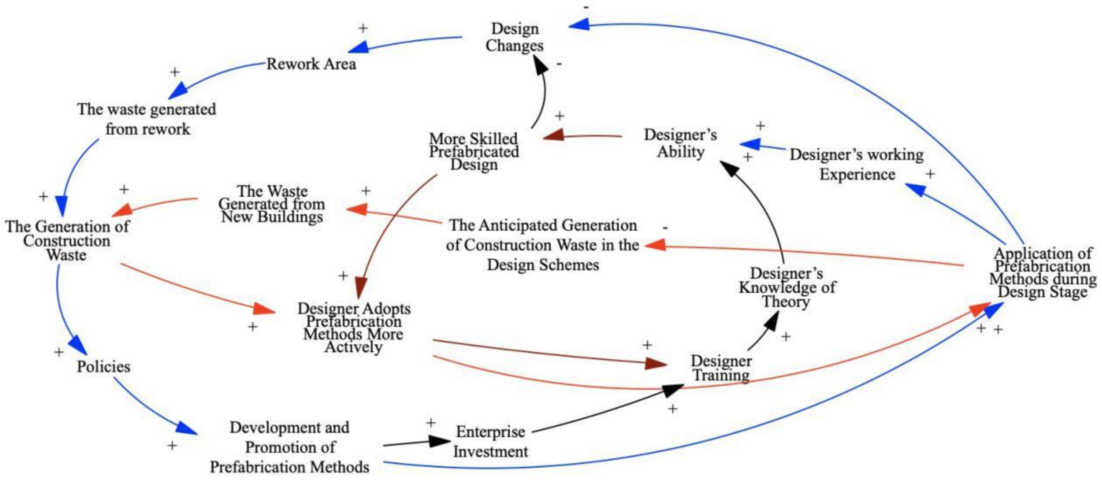


Figure 3. Causal loop diagram of prefabrication contributing to CW reduction at the design stage

As shown in Figure 3, there are four feedback loops in the causal-loop diagram, which consists of three negative feedback loops and one positive feedback loop. The detailed interaction behavior of variables in each feedback loop is explained as follows.

Loop 1 is a negative loop. Increasing CW generation will encourage designers to increase the rate of adoption of prefabrication methods at the design stage. This will benefit the environment through a reduction of waste at the project level and ultimately through a decrease in the total amount of generated CW.

Loop 2 is a negative loop. Increasing CW generation will stimulate policy strengthening and promote the application of prefabrication. In this situation, enterprises will invest more in training on the use of prefabrication, which will enrich designers' theoretical knowledge and thus strengthen their ability to conduct skilled modular design. In this way the rate of design changes will decrease along with a reduction of CW generated from rework.

Loop 3 is a negative loop. Increasing CW generation will stimulate policy strengthening to encourage the application of prefabrication at the design stage, which will contribute to CW reduction through reducing the rate of design changes similar to Loop 2.

Loop 4 is a positive loop. A positive attitude towards prefabrication will encourage designers to apply prefabrication more often. This will help designers to accumulate more experience and strengthen their abilities in prefabrication methods, which in turn means that they will be more willing to use prefabrication in future designs.

3.3 Stock-flow diagram-quantitative analysis

Figure 4 shows a stock-flow diagram of the contribution of prefabrication to CW reduction at the design stage. It is based on the causal-loop diagram and was established using Vensim software package by defining all the main variables in Table 1. Some dimensionless variables are qualitative variables with values that range between 0 and 1, with 0 indicating narrowly adopted and 1 indicating widely adopted.

Table 1. Depiction of variables used in the model

No.	Acronym	Variable Definition	Variable Type	Units
1.	ACWGPUARA	The Amount of Construction Waste Generated Per Unit Area of Reworked Area	Constant	Ton/m^2
2.	ARPC	Adoption Rate of Prefabricated Components	Stock	Dmnl
3.	APMDS	Application of Prefabrication Method at the Design Stage	Auxiliary variable	Dmnl
4.	BAP	Building Area of Project	Constant	m^2
5.	BBWRR	Bricks and Blocks Waste Reduction Rate	Auxiliary variable	Dmnl
6.	CARPC	Change of Adoption Rate of Prefabricated Components	Flow	1/Month
7.	CDA	Change of Designer's Ability	Flow	1/Month
8.	CDBA	Change of Designer's Behavior and Attitude	Flow	1/Month
9.	CDKT	Change of Designer's Knowledge of Theory	Flow	1/Month
10.	CWRR	Concrete Waste Reduction Rate	Auxiliary variable	Dmnl
11.	CWR	Construction Waste Reduction	Stock	Ton
12.	DA	Designer's Ability	Stock	Dmnl
13.	DBA	Designer's Behavior and Attitude	Stock	Dmnl
14.	DWE	Designer's Work Experience	Stock	Dmnl
15.	DKT	Designer's Knowledge of Theory	Stock	Dmnl
16.	DPPM	Development and Promotion of Prefabrication Method	Auxiliary variable	Dmnl
17.	DPTF	Designers' Professional Training Funds	Auxiliary variable	Yuan
18.	DPTPM	Designer Professional Training of Prefabrication Method	Auxiliary variable	Dmnl
19.	DPTC	Designer Professional Training Cost	Constant	1/Yuan
20.	EC	Enterprise Culture	Auxiliary variable	Dmnl
21.	ECWR	Effect of Construction Waste Reduction	Auxiliary variable	Dmnl
22.	EDAt	Effect of Designer's Attitude	Auxiliary variable	Dmnl

23.	EDAb	Effect of Designer’s Ability	Auxiliary variable	Dmnl
24.	EDKT	Effect of Designer’s Knowledge of Theory	Auxiliary variable	Dmnl
25.	EDWE	Effect of Designer’s Work Experience	Auxiliary variable	Dmnl
26.	EIPCAR	Effect of Increasing Prefabricated Components Adoption Rate	Auxiliary variable	Dmnl
27.	IDA	Improving Designers’ Ability	Auxiliary variable	Dmnl
28.	IDKT	Improving Designers’ Knowledge of Theory	Auxiliary variable	Dmnl
29.	IDWE	Increasing Designers’ Work Experience	Flow	1/Month
30.	IFARPC	Influence Factors of Adoption Rate of Prefabricated Components	Constant	Dmnl
31.	IFUCW	Influence Factors of Unit Construction Waste	Constant	1/Ton
32.	IVBBWGPUA	Initial Value of Bricks and Blocks Waste Generation Per Unit Area	Constant	Ton/m^2
33.	IVCWGPUA	Initial Value of Concrete Waste Generation Per Unit Area	Constant	Ton/m^2
34.	IVDBA	Initial Value of Designers’ Behavior and Attitude	Constant	Dmnl
35.	IVDA	Initial Value of Designers’ Ability	Constant	Dmnl
36.	IVDKT	Initial Value of Designers’ Knowledge of Theory	Constant	Dmnl
37.	IVDWE	Initial Value of Designers’ Work Experience	Constant	Dmnl
38.	IVDPPM	Initial Value of Development and Promotion of Prefabrication Method	Constant	Dmnl
39.	IVDPTPM	Initial Value of Designer Professional Training of Prefabrication Method	Constant	Dmnl
40.	IVEC	Initial Value of Enterprise Culture	Constant	Dmnl
41.	IVMoWGPUA	Initial Value of Mortar Waste Generation Per Unit Area	Constant	Ton/m^2
42.	IVMeWGPUA	Initial Value of Metal Waste Generation Per Unit Area	Constant	Ton/m^2
43.	IVPIDPT	Initial Value of Proportion of Investment in Designers’ Professional Training	Constant	Dmnl
44.	IVRDCR	Initial Value of Reduced Design Changes Rate	Constant	Dmnl

45.	IVAPMDS	Initial Value of Application of Prefabrication Method at the Design Stage	Constant	Dmnl
46.	IVWWGPUA	Initial Value of Wood Waste Generation Per Unit Area	Constant	Ton/m^2
47.	MD	Modular Design	Auxiliary variable	Dmnl
48.	MoWRR	Mortar Waste Reduction Rate	Auxiliary variable	Dmnl
49.	MeWRR	Metal Waste Reduction Rate	Auxiliary variable	Dmnl
50.	P	Policies	Stock	Dmnl
51.	PC	Policy Change	Flow	1/Month
52.	PIDPT	Proportion of Investment in Designers' Professional Training	Auxiliary variable	Dmnl
53.	PDBA	Promoting Designers' Behavior and Attitude	Auxiliary variable	Dmnl
54.	PI	Policy Influence	Auxiliary variable	Dmnl
55.	RWGR	Reducing the Waste Generation from Rework	Flow	Ton/Month
56.	RDCR	Reduced Design Changes Rate	Auxiliary variable	Dmnl
57.	RRA	Reduced Rework Area	Auxiliary variable	M^2
58.	RWGBB	Reduced the Waste Generation of Bricks and Blocks	Flow	Ton/Month
59.	RWGC	Reduced the Waste Generation of Concrete	Flow	Ton/Month
60.	RWGMe	Reduced the Waste Generation of Metal	Flow	Ton/Month
61.	RWGMo	Reduced the Waste Generation of Mortar	Flow	Ton/Month
62.	RWGW	Reduced the Waste Generation of Wood	Flow	Ton/Month
63.	SP	Strengthen Policies	Constant	Dmnl
64.	TPI	Total Project Investment	Constant	Yuan
65.	WWRR	Wood Waste Reduction Rate	Auxiliary variable	Dmnl

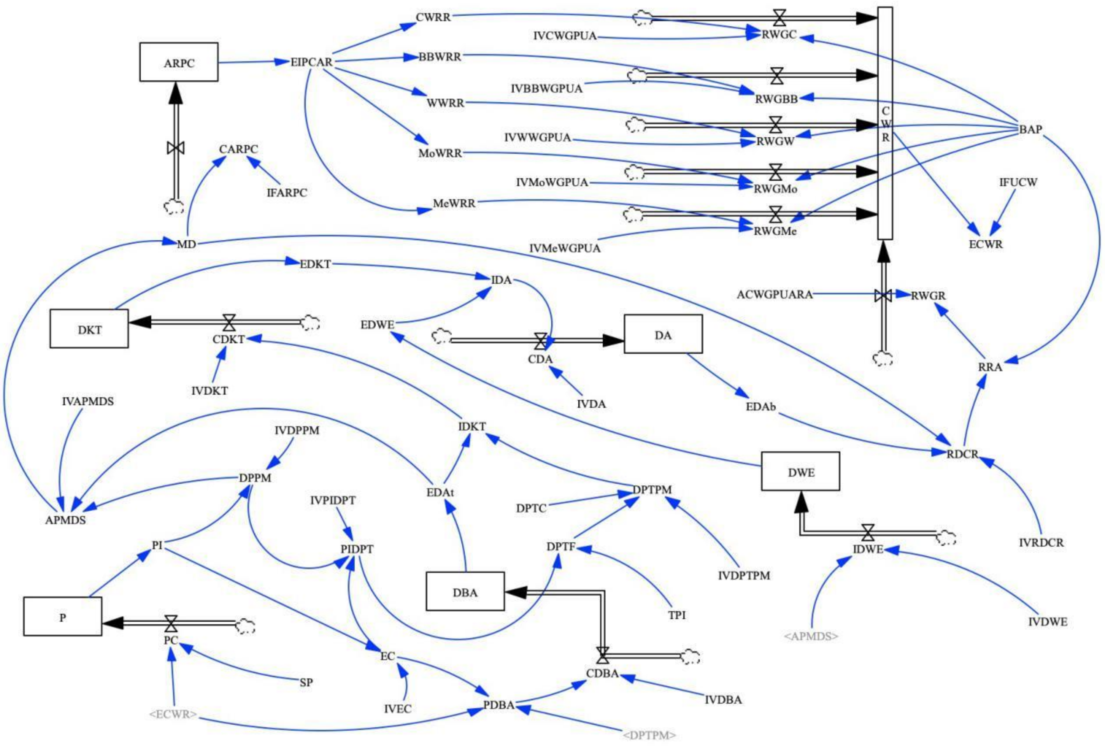


Figure 4. Stock-flow diagram of prefabrication method contributing to CW reduction at the design stage

4. Model validation

4.1 Data collection and quantification

All the significant variables and feedback loops are quantified through using the data collected from a construction project in Suzhou, mainland China. The project is a 26-story residential building covering a construction area of approximately 10700m^2, which is expected to take 20 months to complete.

Data was primarily collected through a literature review and interviews with various experts who are knowledgeable in CW management and prefabrication methods. A questionnaire was designed as an auxiliary tool to determine the values of some important parameters. The results are shown in Table 2.

Table 2. Inputted data on significant parameters in the model

Variables	Values	Units
ACWGPUARA	0.0166	Ton/m^2
IFARPC	0.7	Dmnl
IFUCW	0.0025	Dmnl
IVBBWGPUA	0.0017	Ton/m^2
IVCWGPUA	0.0185	Ton/m^2
IVDBA	0.43	Dmnl
IVDA	0.25	Dmnl
IVDKT	0.11	Dmnl
IVDWE	0.32	Dmnl
IVDPPM	0.55	Dmnl
IVDPTPC	0.36	Dmnl
IVEC	0.303	Dmnl
IVMoWGPUA	0.0014	Ton/m^2
IVMeWGPUA	0.0045	Ton/m^2
IVPDIPT	0.07	Dmnl
IVRDCR	0.135	Dmnl
IVUPCDS	0.2	Dmnl
IVWUPUA	0.0076	Ton/m^2
SP	0.25	Dmnl

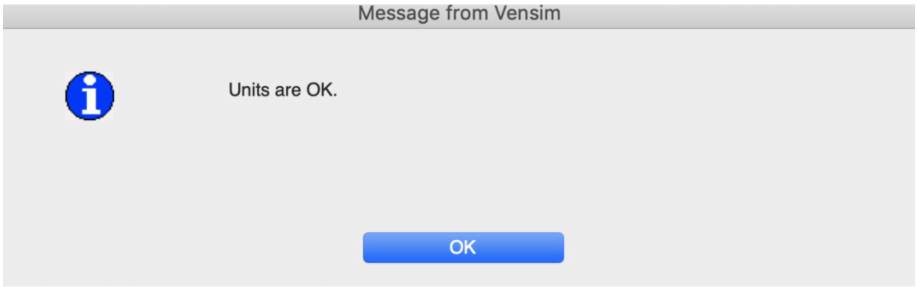
4.2 Model test

Prior to quantitative analysis and scenario simulation, it is critical to check the reasonability and veracity of the established SD model through a set of tests proposed by Sterman (2000) [24-25]: (1) the causal-loop diagram applied to describe major variables influencing the effects of prefabrication on CW reduction at the design stage must correspond to the statement of the research problem; (2) the equations in the stock-flow diagram must be consistent with the causal-loop diagram; (3) the SD model must be dimensionally consistent; and (4) the model should pass the extreme condition test.

Test 1 is concerned with whether the model contains all significant variables that correspond to the aim of research, while excluding other variables irrelevant to the research purpose. It is conducted through checking all the variables embodied in the causal-loop diagram. Eventually, it is found that every variable selected according to the system boundaries based on TPB is closely related to the research purpose, which is to investigate the potential of prefabrication method on CW reduction at the design stage.

Test 2 is concerned with whether the fundamental structure of the model is reasonable. This structural validation is conducted through referring back to the causal-loop diagram. It is obvious that all cause-and-effect chains and feedback loops in the diagram are based on established knowledge and viewpoints.

Test 3 is concerned with whether units of all variables in the established SD model are consistent in dimension. The test is conducted through the ‘units check’ function of the Vensim software package after units of all variables are confirmed. The result is shown in Figure 5.



Units are OK.

Figure 5. Result of units check

Test 4 investigates the behavior pattern of the SD model under extreme conditions in the extreme condition test. Extreme values are updated to specific variables and then the simulation results of the model are compared with the actual system behavior.

Due to space limitations, it is not practicable to demonstrate the complete testing process of the extreme condition test. However, for the purposes of explanation the variable ‘rate of prefabricated components’ is taken as a typical example. The main purpose of the test on this example is to investigate how CW reduction will change when extreme values are assigned to the rate of prefabricated components. In the model, values of both the rate of prefabricated components and CW reduction should be greater than 0. The test involves simulation of the following four scenarios: scenario 1 (ARPC= 5.4%, this is the base run); scenario 2 (ARPC = 25%); scenario 3 (ARPC = 50%); and scenario 4 (ARPC = 75%). The results are shown in Figure 6 and Table 3.

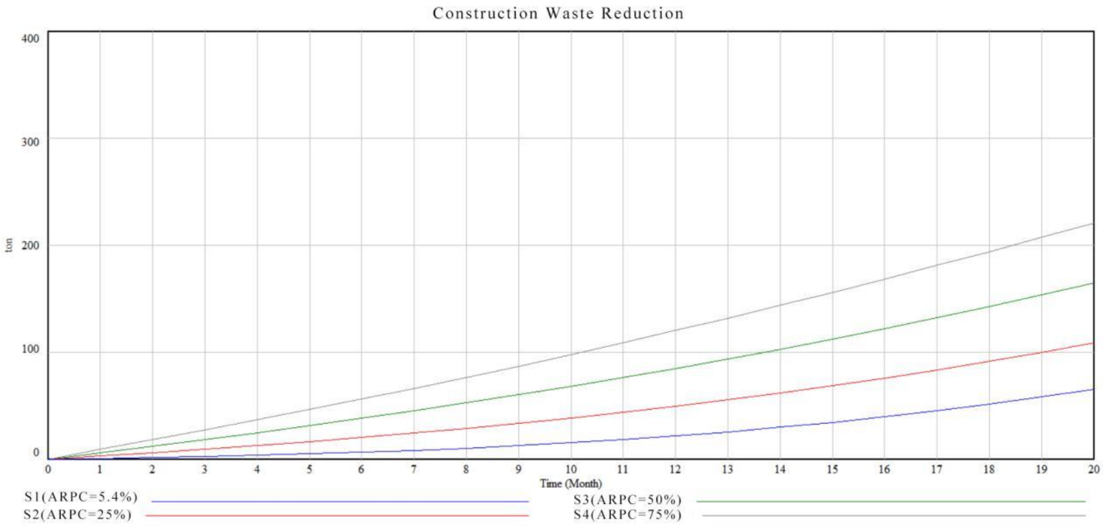


Figure 6. Simulation results of extreme condition test

Table 3. Simulation results of extreme condition test

Scenarios	S1(ARPC=5.4%)		S2(ARPC=25)		S3(ARPC=50)		S4(ARPC=75)	
	Reduction(ton)	rate	Reduction(ton)	rate	Reduction(ton)	rate	Reduction(ton)	rate
Concrete waste	4.73	6.1%	5.72	28.5%	7.01	57.3%	8.30	86.3%
Brick and block waste	0.33	6.1%	0.40	28.5%	0.49	57.3%	0.58	86.3%
Mortar waste	0.23	6.4%	0.28	30.4%	0.34	57.7%	0.41	86.8%
Metal waste	0.51	6.1%	0.61	28.%	0.75	57.4%	0.87	86.5%
Wood waste	0.86	6.1%	1.04	28.5%	1.27	57.3%	1.51	86.3%
Rework waste	1.13	4.9%	1.33	22.6%	1.57	45.4%	1.83	68.6%
Overall CW	65.28	22.6%	108.98	104.7%	164.77	209.2%	220.603	341.3%

In each scenario, CW reduction keeps going up over time. The increase is slow at first and the curve is approximately linear. However, nonlinearity becomes more and more obvious over time so that CW reduction is more significant in the middle and later stages of the project. It can also be seen that the higher the adoption rate of prefabricated components, the more CW reduction there is. This demonstrates that prefabrication can be considered as an efficient approach at the design stage to reduce CW of a project. Furthermore, the effects of prefabrication on different kinds of CW is different. For example, adoption of prefabrication at the design stage is more efficient for reducing concrete waste, but less so for reducing metal waste and wood waste. These findings are consistent with those of other related studies [7][10].

5. Scenario analyses

To understand the effect on CW of alternative strategies for strengthening the impacts of prefabrication at the design stage, the following two strategy options are chosen as scenarios: Scenario A increasing investment in designers' professional training, and Scenario B strengthening policies. The initial adaption rate of prefabricated components is set at 25% for both scenarios.

5.1 Scenario A: Increasing investment in designers' professional training

Currently most designers in China are not familiar with prefabrication methods of construction, which has negative impacts on application of prefabrication at the design stage. Providing sufficient professional training on prefabrication is therefore really important because it can enrich designers' theoretical knowledge and thus strengthen their abilities. In this way, designers will become more skilled in modular design based on prefabricated components, resulting in fewer design changes and therefore less CW generated from rework.

In this scenario, the initial value of proportion of investment on designers' professional training is set to 0.05 (Scenario A1, base run). The value is increased to 0.10(A2), 0.15(A3), 0.20(A4), 0.25(A5) and then to 0.30(A6). The proportion of investment in designers' professional training is increased to examine the effect on CW. The simulation results are shown in Figure 7 and Table 4.

Figure 7. Simulation results of Scenario A

Table 4. Simulation results of Scenario A

PIDPT	0.05	0.1	0.15	0.2	0.25	0.3
CW Reduction	108.98	115.53	120.34	123.32	124.84	125.59
Improving Rate	0	6.01%	10.42%	13.16%	14.55%	15.24%

The results show that increasing investment in designers' professional training contributes to a reduction in CW. The total amount of CW reduction goes up from 108.98 to 123.32 as the proportion of investment in designers' professional training (PIDPT) increases from 0.05 to 0.20. However, the speed of improvement decreases with an increasing PIDPT. In fact, when PIDPT reaches 0.25, if construction enterprises continue to increase spending on designers' professional training, the CW reduction will change little. That suggests there is some kind of upper limit to how much designers can enrich their knowledge and strengthen their abilities through professional training. Once the upper limit is reached, which means designers have sufficient knowledge of prefabrication methods, more investment in professional training makes little sense.

Increasing investment in designers' professional training on prefabrication methods contributes to a reduction of CW but there is an upper limit to the training. Further cost benefit analysis is required to determine the optimum level of investment.

5.2 Scenario B: Strengthening policies

A reasonable policy is helpful for promotion of prefabrication at the design stage to help reduce CW. Strengthening policies will encourage designers to adopt prefabricated components in their designs so as to reduce CW, while at the same time influencing the culture of construction enterprises towards prefabrication. Mangers of these enterprises will then invest more funds in designers' professional training to strengthen their abilities in the area of prefabrication. This will reduce CW by reducing the need for design changes and rework.

China's central government has actually introduced policies to promote prefabrication in the construction industry. For example, the Jiangsu provincial government has set a goal that 30% of newly-constructed buildings should be prefabricated by 2020.

In this scenario, the initial value of strengthening policies is set to 0.25 (scenario B1, base run). To examine variations in CW reduction, the value is increased to 0.40(B2), 0.65(B3) and then to 0.80(B4). The simulation results are shown in Figure 8 and Table 5.

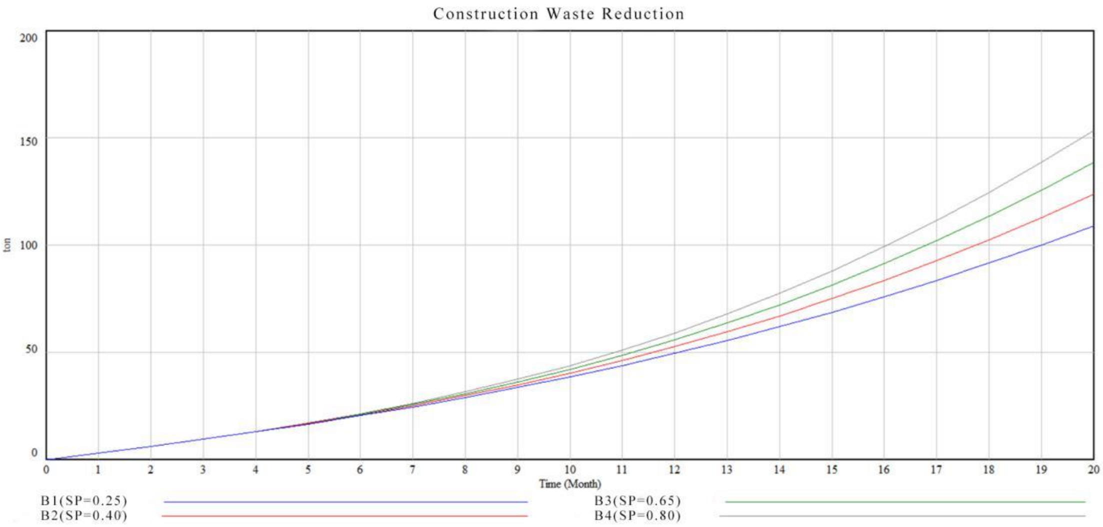


Figure 8. Simulation results of Scenario B

Table 5. Simulation results of Scenario B

SP	0.25	0.40	0.65	0.80
CW Reduction	108.98	123.75	136.61	153.56
Improving Rate	0	13.55%	25.35%	40.91%

Increasing the value of strengthening policies to 0.40 increases total CW reduction by about 123.75 tons, which constitutes an approximate 13.55% increase over the base run scenario. A value of 0.65 of the strengthen policies increases the reduction of CW by about 136.61 tons, which constitutes an approximate 25.35% improvement compared with the base run scenario. When the value of strengthening policies goes up to 0.80, the amount of CW reduction is about 153.56 tons, achieving a 40.91% improvement over the base run.

After the strengthening the policy, the positive effect of prefabrication on CW at the design stage significantly improves. Accordingly, strengthening policies can be considered as an incentive strategy for promotion of prefabrication and CW reduction.

6. Conclusions

As an efficient strategy for CW reduction at the design stage, prefabrication as a viable construction method has drawn considerable attention. However, the interaction behavior of the factors influencing the application of prefabrication and its effect on CW reduction have not hitherto been considered. The study on which this paper is based therefore developed a dynamic simulation model to assess the potential of prefabrication at the design stage for reducing project CW. The research objectives were to: (1) Determine the system boundaries and identify major factors affecting the application of prefabrication and CW reduction; (2) Develop a casual-loop diagram and stock-flow diagram that effectively describes the interaction among these identified factors; and (3) Simulate different scenarios to find strategies for making better use of prefabrication at the design stage for reducing CW. The simulation results indicate that an increase in the value of prefabricated components at the design stage has a strong effect on CW reduction, especially for concrete waste. It was also found that there are two strategies that efficiently promote the use of prefabrication at the design stage: (1)

increasing investment in designers' professional training, and (2) strengthening policies. This paper demonstrates the benefits of applying a SD approach to understand the process of prefabrication at the design stage and its potential for reducing CW. On one hand the causal-loop diagram facilitates an in-depth understanding of the interaction of key factors that affect the application of prefabrication and consequential CW reduction. On the other hand, the stock-flow diagram serves as a powerful tool for quantitative assessment of the impacts of prefabrication at the design stage in order to reduce CW over time. Being able to simulate different prefabrication design scenarios with the SD model, not only provides insights into the CW benefits of applying prefabrication at the design stage but also allows designers and policy makers to compare the dynamic outcomes under various strategies and policies ahead of operation. Future research could examine the effects of prefabrication on CW reduction throughout the whole life cycle of a construction project by adjusting the SD model to take account of characteristics at different stages of a project.

7. Acknowledgements

The authors wish to acknowledge the financial support from the Research Development Fund (2016-01-32), Xi'an Jiaotong-Liverpool University (XJTLU), Key Special Fund Exploratory Research Programme, XJTLU 2018-E-29, Suzhou Industrial Park (2018-E-29), and Suzhou Soft Science Fund (2019).

References

[1] Ghisellini, P., Ji, X., Liu, G., & Ulgiati, S. (2018). Evaluating the transition towards cleaner production in the construction and demolition sector of China: A review. Journal of Cleaner Production, 195, 418-434.

[2] Menegaki, M. & Damigos, D. (2018). A review on current situation and challenges of construction and demolition waste management. Current Opinion in Green and Sustainable Chemistry, 13, 8-15.

[3] Yuan, H. P., Shen, L. Y., Hao, J. J., & Lu, W. S. (2011). A model for cost–benefit analysis of construction and demolition waste management throughout the waste chain. Resources, conservation and recycling, 55(6), 604-612.

[4] Yuan, H., Chini, A. R., Lu, Y., & Shen, L. (2012). A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. Waste management, 32(3), 521-531.

[5] Wong, P. S., Kanellopoulos, M. P., & Edmonson, L. (2018). An Empirical Analysis of the Effect of Prefabrication on Fostering Sustainable Construction. In Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate (pp. 185-195). Springer, Singapore.

[6] Pujadas-Gispert, E., Sanjuan-Delmás, D., & Josa, A. (2018). Environmental analysis of building shallow foundations: The influence of prefabrication, typology, and structural design codes. Journal of Cleaner Production, 186, 407-417.

[7] Jaillon, L., Poon, C. S., & Chiang, Y. H. (2009). Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. Waste management, 29(1), 309-320.

[8] Lu, W. & Yuan, H. (2013). Investigating waste reduction potential in the upstream processes of offshore prefabrication construction. Renewable and Sustainable Energy Reviews, 28, 804-811.

[9] Wang, J., Li, Z., & Tam, V. W. (2014). Critical factors in effective construction waste minimization at the design stage: a Shenzhen case study, China. Resources, Conservation and Recycling, 82, 1-7.

[10] Wang, J., Li, Z., & Tam, V. W. (2015). Identifying best design strategies for construction waste minimization. Journal of Cleaner Production, 92, 237-247.

[11] Finch, G. & Marriage, G. (2019). Eliminating Building and Construction Waste with Computer-Aided Manufacturing and Prefabrication. In Advances in Informatics and Computing in Civil and Construction Engineering (pp. 805-814). Springer, Cham.

[12] Forrester, J. W. (1968). Theory series || industrial dynamics-after the first decade. Management Science, 14(7), 398-415.

[13] Sedarati, P., Santos, S., & Pintassilgo, P. (2018). System Dynamics in Tourism Planning and Development. Tourism Planning & Development, 1-25.

[14] Faezipour, M. & Ferreira, S. (2018). A system dynamics approach for sustainable water management in hospitals. IEEE Systems Journal, 12(2), 1278-1285.

[15] Ahmad, S., Tahar, R. M., Muhammad-Sukki, F., Munir, A. B., & Rahim, R. A. (2016). Application of system dynamics approach in electricity sector modelling: A review. Renewable and Sustainable Energy Reviews, 56, 29-37.

[16] Walters, J. P., Archer, D. W., Sassenrath, G. F., Hendrickson, J. R., Hanson, J. D., Halloran, J. M., & Alarcon, V. J. (2016). Exploring agricultural production systems and their fundamental components with system dynamics modelling. Ecological modelling, 333, 51-65.

[17] Faezipour, M. & Ferreira, S. (2018). A system dynamics approach for sustainable water management in hospitals. IEEE Systems Journal, 12(2), 1278-1285.

[18] Ahmad, S., Tahar, R. M., Muhammad-Sukki, F., Munir, A. B., & Rahim, R. A. (2016). Application of system dynamics approach in electricity sector modelling: A review. Renewable and Sustainable Energy Reviews, 56, 29-37.

[19] Hao, J. L., Hills, M. J., & Huang, T. (2007). A simulation model using system dynamic method for construction and demolition waste management in Hong Kong. Construction Innovation, 7(1), 7-21.

[20] Yuan, H. (2012). A model for evaluating the social performance of construction waste management. Waste Management, 32(6), 1228.

[21] Yuan, H. & Wang, J. (2014). A system dynamics model for determining the waste disposal charging fee in construction. European Journal of Operational Research, 237(3), 988-996.

[22] Conner, M. & Armitage, C. J. (1998). Extending the theory of planned behavior: A review and avenues for further research. Journal of applied social psychology, 28(15), 1429-1464.

[23] Ding, Z., Zhu, M., Tam, V.W.Y., Yi, G., & Tran, C.N.N. (2018). A system dynamics-based environmental benefit assessment model of construction waste reduction management at the design and construction stages. Journal of Cleaner Production, 176, 676-692.

[24] Sterman, J. D. (2000). Business dynamics: systems thinking and modeling for a complex world (No. HD30. 2 S7835 2000).

[25] Yuan, H. & Wang, J. (2014). A system dynamics model for determining the waste disposal charging fee in construction. European Journal of Operational Research, 237(3), 988-996.