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Application of system dynamics for assessment of sustainable performance of construction projects*

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Abstract: Sustainable performance is expected to become a major factor when examining the feasibility of a construction project in terms of its life cycle performance. The study on which this paper is based developed a simulation model, using system dynamics methodology, to assess the sustainable performance of projects. Three major factors are used to examine project sustainable performance (PSP): the sustainability of economic development (*E*), the sustainability of social development (*S*), and the sustainability of environmental development (*En*). Sustainable development ability (*SDA*) was used as a prototype to evaluate the degree of sustainable performance. The simulation software 'ithink' was used to help with the application of the model to a real life case. This paper explains and demonstrates the procedures used to develop the model and finally offers an approach for assessing the feasibility of a construction project in terms of its sustainable performance.

Key words: Construction project, Project life cycle, Project sustainable performance (PSP), Sustainable development ability (*SDA*), System dynamics, Simulation
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INTRODUCTION

Sustainable development is commonly defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). All industries, including the construction industry should contribute to the mission. Compared to other industries, construction activities are generally considered to have more impact on the environment, which provides the basic conditions for the sustainability and development of life on the Earth. The impact caused by construction activities on the environment occurs throughout a project's life cycle. At the initial stage, a construction project consumes multiple types of environmental resources including soil, minerals, water, plants and animals in all their biological and genetic diversity. During the construction stage, typical environmental impacts from implementing a project include air pollution, the emission of sulfur dioxide, and the degradation of water quality, noise pollution, and the generation of solid waste. During its operation, a construction project consumes a vast amount of energy and environmental resources. At the end of a construction project's life cycle, the demolition activities generate a large volume of various construction wastes. Such construction generated environmental impacts are common in both developed and developing countries and regions. According to CIB (1998), 54% of the energy consumed in the USA is directly or indirectly related to buildings and construction activities. The MOC report (1999) shows that about 25% of the energy consumed in China is directly caused by producing building materials and implementing construction activities. In addition, Poon *et al*.(2001) suggested that the solid wastes from the demolitions of buildings are 10~20 times by

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weight as much as the wastes generated from the construction of new buildings. The considerable impact from construction activities on the environment shows potential of making significant contribution to protecting the environment and attainting sustainable development by properly implementing a construction project.

Research had been conducted to determine a properly implemented construction project's contribution to sustainable development. Hill and Bowen (1997) introduced a framework of key principles of sustainable construction for enabling construction activities to contribute to sustainable development. The major components of the framework include project environmental assessment, environmental policy, organizational structure, and environmental management program and external/internal audit of environmental performance. According to CIB (1999), the paradigm for assessing the feasibility of construction projects is extended from the traditional feasibility study approach, which focuses mainly on cost, time and quality, to integrating resource consumption and environmental impacts within a global contour. In addition, there are some other studies presenting various methods for promoting environmental management and enabling better sustainability in implementing construction projects across their life cycle (Brochner *et al*., 1999; Heerwagen, 2000; Tam *et al*., 2002; Wyatt, 1994).

In further search for ways to improve the contribution of construction projects to sustainable development, Shen *et al*.(2002) developed a model for assessing the sustainable performance of a construction project. By using this model, the sustainable development value (*SDV*) and sustainable development ability (*SDA*) in implementing a construction project in its life cycle can be quantified through calculations. *SDA* is used to measure the contribution of a project to the attainment of sustainable development, and is recommended as a major criterion for examining the feasibility of a project. It is suggested that using *SDA* for analyzing the feasibility of a construction project is more acceptable than the traditional feasibility study method. However, a major limitation in using the *SDA* model is that it does not consider the impacts of various dynamic factors on project performance through a project life cycle. In fact, a construction project's development is a dynamic process. Love *et al*.(2002) presented a model demonstrating that there are various dynamic factors affecting project performance. It is considered that the effectiveness of project feasibility study cannot be assured without considering the impacts of dynamic factors. This paper extends the *SDA* model by Shen *et al*.(2002) to a dynamic *SDA* model that can incorporate the impacts of dynamic factors. Dynamic systems methodology was used as a tool for establishing the *SDA* dynamic prototype in this study.

DYNAMIC FACTORS AFFECTING PROJECT SUSTAINABLE PERFORMANCE

Sidwell (1990) suggested that construction projects follow a life cycle that is goal oriented but subject to the impact of various dynamics. Ford (1995) contended that the difficulties of performing and managing construction business activities are due to the fact that construction projects are technically complicated and interact with a large number of dynamic, social, and environmental factors. EI-Rayes and Moselhi (1999) considered a construction project as a dynamic system and investigated the approach of optimizing project performance by using a dynamic programming technique. Adeli and Karim (1997) developed a neural dynamics model to identify solutions for optimizing the time-cost performance in implementing a construction project. Love *et al*.(2002) suggested a conceptual framework for helping to understand the dynamics that affects construction project performance. In the framework, dynamic factors affecting project performance are classified into attended dynamics and unattended dynamics. Both attended and unattended dynamics are considered as having either a positive or negative impact on project performance. The study concluded that more management effort should be devoted to finding ways for mitigating the negative impact of dynamic factors.

Project performance traditionally refers to the outcomes of construction cost, construction time, and construction quality; the identification of dynamic factors in the existing studies mainly concerns these three aspects. When the contents of project performance are extended to incorporating project sustainable performance, factors affecting project performance need to be reviewed. As it is to be measured by the contribution of the construction project concerned, to attain sustainable development, factors affecting project sustainable performance can be identified through examining the attributes to which a construction project contributes for attaining sustainable development. According to the general principle of sustainable development, there are three contributors to sustainable development; these are the sustainability of economic development (*E*), the sustainability of social development (*S*), and the sustainability of environmental development (*En*) (WCED, 1987). These three contributors are used in this study to examine the sustainable performance of a construction project.

During implementation of a construction project, the performance of the three attributes, *E*, *S*, and *En*, are affected by various factors at different stages across its life cycle. In a typical classification, the life cycle of a construction project is divided into five stages, which are inception stage, construction stage, commission stage, operation stage, and demolition stage (Shen *et al*., 2002). Some studies have examined the factors affecting *E*, *S* and *En* at different stages of a project (Hill and Bowen, 1997; Shen *et al*., 2002). By referring to such studies, a list of dynamic factors affecting project sustainable performance can be identified; these factors are shown in Table 1.

FORMULATING A DYNAMIC SUSTAINABLE DEVELOPMENT ABILITY (SDA) PROTOTYPE USING SYSTEM DYNAMICS

System dynamics is widely used to gain understanding of a system with complex, dynamic and nonlinearly interacting variables. Existing studies presented examples of applying system dynamics method for identifying solutions for improving construction project management effectiveness. Love *et al*.(2002) presented a framework using system dynamics for dealing with dynamic feedbacks in managing complex projects. Ford (1995) identified various dynamic factors affecting project development process, which provide useful reference for improving the effectiveness of project development by properly responding to those major factors.

By using system dynamics method, Pena-More and Li (1999) introduced a dynamic planning procedure for implementing design-and-build type construction projects. This procedure enables a dynamic plan that incorporates dynamic feedbacks and responds accordingly to the impacts of various dynamics. Chritamara *et al*.(2002) developed a model by using system dynamics principles for evaluating project management procedures, with application of the model being aimed at mitigating time and cost overruns. System dynamics approach was used as a typical simulation technique for evaluating the decision-making performance. Dolol and Jaafarl (2002) used system dynamics approach as a simulation tool to establish the baseline value of a construction project. This approach provides an alternative method for optimizing investment decisions when project performance is assessed across the project life cycle.

By applying the *SDA* model developed by Shen *et al*.(2002), the contribution of a construction project to the attainment of sustainable development can be measured by the three attributes: *E*, *S*, and *En*. The model is described as follows:

$$\begin{cases} SDV(t) = f(E(t), S(t), En(t)) \\ SDA(t) = \int_0^t SDV(t)\mathrm{d}t \end{cases} \tag{1}$$

Table 1 Major variables affecting *SDA* of a construction project

Project stage	*E*(*t*)	*S*(*t*)	*En*(*t*)
Inception	Budget; Investment; Local economy; …	Protection of cropland; Public safety; Housing policy; …	Assessment of environment; Bio-diversity; Land pollution; …
Construction	Capital; Cost; Profit; …	Employment; Working safety; Energy resources; …	Building materials; Pollution; Waste; …
Commission	Marketing; Profit; Finance; …	Community communication; Transport to site; Internal decoration; …	Virescence; Paperless advertisement; Decoration materials; …
Operation	Cash flow; Salary; Maintenance cost; …	Employment; Provision of product; Working health; …	Pollution; Toxicoids; Ecology regeneration; …
Demolish	Compensation; Labor cost; Remains value; …	Public safety; Operation safety; Land re-assortment; …	Waste; Toxicant; Recycle materials; …

where $E(t)$, $S(t)$ and $En(t)$ denote respectively the contribution of developing a construction project to the three sustainable development contributors, namely, economic development, social development, and environmental development. These three parameters are defined as deterministic functions with time by considering that the relations between values of the parameters and time can be established across a project's life cycle.

However, the functions $E(t)$, $S(t)$ and $En(t)$ should not be considered as deterministic as the relationships between the performance of the parameters and time are uncertain due to the impacts of dynamic factors. Therefore, the application of the *SDA* model has limited effect. To go around this weakness, system dynamics is used to simulate the impacts of uncertain factors on the value of the three sustainable development attributes.

System dynamics has four elements defined within the system: (a) stock; (b) flow; (c) converter; and (d) connector, as shown in Fig.1 (HPS, 1997; Mohapatra, 1994). A stock collects all those in-flows and also serves as the source from where out-flows come. A flow serves as a vehicle to deliver information to or drain information from the stock. The value of a flow can be positive or negative. A positive flow is an in-flow and will filling in the stock, and a negative flow is an out-flow draining the stock. A convertor has a utilitarian role in selecting proper values and functions of parameters in the model. The connector is an information transmitter connecting elements. A more complex system has more connectors.

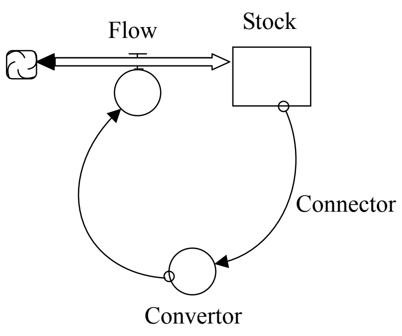


Fig.1 A model of system dynamics approach

In Fig.1, the volume of stock will change at different time points as both in-flows and out-flows will be generated when time goes on. The relationship between the stock and flow are established as follows:

$$Stock(t) = Stock(t - \mathrm{d}t) + (Flow)\mathrm{d}t \qquad (2)$$

and

$$Stock = \int (Flow)\mathrm{d}t \qquad (3)$$

For assessing the sustainable performance of a construction project by using system dynamics approach, the measure *SDA* is considered as a stock, and an impact from dynamic factors on the value of *SDA* can be considered as a flow. Therefore, an increase or decrease of the parameters $E(t)$, $S(t)$ and $En(t)$ discussed above can be considered as the flows to *SDA*. For example, when a project brings economic gain, namely, an increase in $E(t)$, a positive impact on the value of *SDA* is received. This will produce an in-flow to the stock, and the volume of *SDA* will increase. An increase in *SDA* indicates that a positive contribution to attainment of sustainable development is received. On the other hand, *SDA* will decrease if an out-flow occurs, indicating negative impact on the attainment of sustainable development is received. This may be due to the fact that environmental pollution is induced in implementing a project. A convertor is employed to define the level of influence of each flow on the stock *SDA*, or the way in which the flow influences the value *SDA*. To simplify the analytical process, the calculation of the value *SDA* is proposed as a weighted value between the three dynamic attributes $E(t)$, $S(t)$ and $En(t)$, which can be written as the following dynamic model:

$$\begin{cases} SDA(t) = \int_0^t W_E(t)I_E(t)\mathrm{d}t + \int_0^t W_S(t)I_S(t)\mathrm{d}t \\ \qquad + \int_0^t W_{En}(t)I_{En}(t)\mathrm{d}t \\ W_E(t) + W_S(t) + W_{En}(t) = 1 \\ I_E, I_S, I_{En} \in [-100, 100] \end{cases} \qquad (4)$$

where $E(t)$, $S(t)$ and $En(t)$ denote respectively the dynamic functions of generating economic impact, social impact and environmental impact from implementing a construction project. The values of the variables I_E, I_S and I_{En} are defined as relative measures within the interval [−100,100]. Variables W_E, W_S and W_{En} denote respectively the weights of economic impact, social impact and environmental impact on *SDA*. By applying these parameters to the model defined in Fig.1, a prototype model of *SDA* using system dynamics method can be developed as shown in Fig.2.

In Fig.2, the stock (*SDA*) collects three types of flows, namely, economic impacts (I_E), social impacts (I_S) and environmental impacts (I_{En}). The three convertors (W_E, W_S and W_{En}) can adjust the volume of the three types of flows. This adjustment implies that efforts can be devoted to improve I_E, I_S and I_{En}. It is noticed that feedback loops exist from the stock *SDA* to the three attributing factors (economic factor, social factor and environmental factor), and from *SDA* to three flows I_E, I_S and I_{En}. The feedback loops are used to indicate that whilst *SDA* is determined by the three flows, the volume of *SDA* will also influence the flows in return. For example, when *SDA* is large, the flows can be adjusted by a reduction from the three flows. Thus the values of I_E, I_S and I_{En} are changeable by applying adjustment measures (i.e. the convertors "?" in Fig.2). The existing volume of *SDA* and other dynamic factors will decide the value of adjustment.

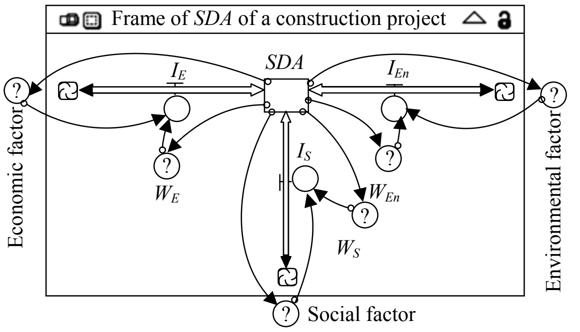


Fig.2 Prototype model of *SDA* using system dynamics

In fact, all the variables I_E, I_S, I_{En}, W_E, W_S and W_{En} are changeable. To demonstrate the principle of the model *SDA* in a simple way, it is assumed that the weighting factors, W_E, W_S and W_{En}, are constants. Therefore the connections between the stock and weighting factors in Fig.2 become redundant. And model Eq.(4) can be revised as the following *SDA* prototype model Eq.(5), and Fig.2 can be modified into Fig.3.

$$\begin{cases} SDA(t) = W_E \int_0^t I_E(t)\mathrm{d}t + W_S \int_0^t I_S(t)\mathrm{d}t \\ \qquad + W_{En} \int_0^t I_{En}(t)\mathrm{d}t \\ W_E + W_S + W_{En} = 1 \\ I_E, I_S, I_{En} \in [-100, 100] \end{cases} \tag{5}$$

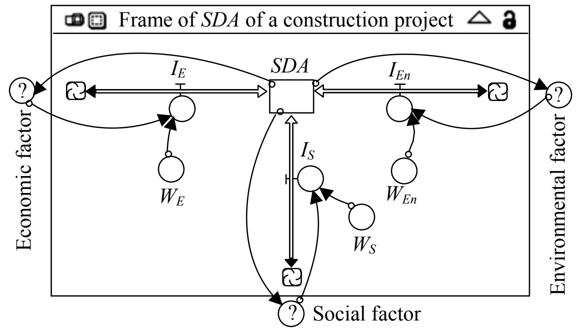


Fig.3 A simplified prototype model of *SDA* using system dynamics

APPLICATION OF THE SDA PROTOTYPE MODEL USING SIMULATION METHODOLOGY

The application of the *SDA* prototype model Eq.(5) needs the provision of values for various parameters. As assumed, the weighting factors W_E, W_S and W_{En} are constants, and decision makers give their values. Different decision makers may allocate weighting values differently after considering the characteristics of different types of projects. For example, when the environmental impact is considered more important, the weight of environmental impact, W_{En}, will be more than 1/3. In another application, all the three weighting factors may be considered equally important and be given with the same value (namely, 1/3). On the other hand, the parameters I_E, I_S and I_{En} are time functions, indicating that the implementation of a construction project will have different social, economic and environmental impacts at different stages across the project life cycle. The values of I_E, I_S, I_{En} are determined respectively by economically related factors, social factors and environmental factors. Furthermore, the relationships between system elements including stock, flows, convertors and connectors need to be established in a specific application of *SDA* prototype. These relationships can be adjusted in different applications.

To simulate a system dynamics model such as the above prototype model Eq.(5), there are existing computer software, such as DYNAMO, 'ithink', and Matlab. ithink was developed as an effective simulation tool by High Performance Systems, Inc. (HPS, 1997). This software was selected for supporting the analysis in this study. The procedures for applying the software 'ithink' to the model Eq.(5) are presented in Fig.4.

A real-life case is used to demonstrate the application of the simulation procedures defined in Fig.4. The project in question, the FD NaCN Innovation Project, is located in Chongqing, China. It is a resettlement of a previous nitrogenous fertilizer plant, which was demolished due to the implementation of the Three Gorges Project. The new plant will be much larger in scale. The data used for application in this study are from the project feasibility study, which includes economic, social, environmental, and technical assessments.

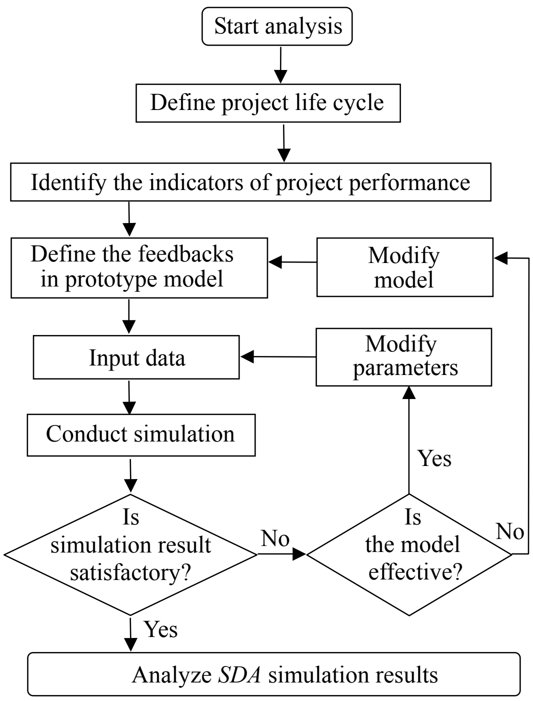
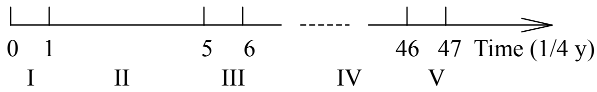


Fig.4 Procedures for simulating *SDA* prototype model using system dynamics

Defining a construction project life cycle

According to the feasibility study of the FD NaCN Innovation Project, the project life cycle is defined to include (I) inception stage (1/4 year); (II) construction stage (1 year); (III) commission stage (1/4 year); (IV) operation stage (10 years); and (V) demolition stage (1/4 year). The time framework of the project life cycle is graphically shown in Fig.5.



I: Inception stage; II: Construction stage; III: Commission stage; IV: Operation stage; V: Demolition stage

Fig.5 The life cycle of FD NaCN Innovation Project

Identifying the indicators for assessing project performance

The project performance is assessed from three aspects, namely, economic performance (*E*), social performance (*S*) and environmental performance (*En*). Referring to the project feasibility study, the indicators for assessing the project performance are identified as shown in Table 2.

Defining the feedbacks in the *SDA* prototype model

In the *SDA* prototype model shown in Fig.3, the feedbacks indicate that the stock *SDA* and project performance flows will interact with each other. For example, if *SDA* value is reduced and becomes lower than specification, actions or measures will be taken to reduce out-flows (negative impacts) or to increase the in-flows (the positive impacts). If *SDA* is very high, increase of certain level of negative impacts (out-flows) may be allowed, and management efforts

Table 2 Project performance indicators through a project's life cycle

Stage	Project performance indicators		
	Economic (*E*)	Social (*S*)	Environmental (*En*)
I	CF	CRC, PS	Bio-diversity
II	CF	EOPMI,CECE, WCR	Air (including SO_2, CO_2, TSP, NO), Water (including pH, SS, BOD_5), Noise
III	CF	CC, SoS	–
IV	CF	PF, EOPMI, CECE	Air (including SO_2, CO_2, TSP, NO), Water (including pH, SS, BOD_5), Noise
V	CF	PS	Waste, RM, Toxicant

BOD_5: Biological oxygen demand within a sealed container at 20 °C; CC: Community communication; CECE: Comprehensive energy consumption efficiency; CF: Cash flow; CRC: Consumption ratio of cropland; EOPMI: Employment opportunity per 1 million (RMB) investments; PF: Provision of fertilizer; PS: Public safety; RM: Recycled materials; SoS: Society safety; SS: Suspended solid; TSP: Total suspended particulate; WCR: Water consumption ration can be allowed to focus on economic aspects.

For FD NaCN Innovation Project, when *SDA* is less than its lower limit, denoted by *L4SDA* (with “*L4*” denoting “lower limit for”), an adjustment *LA* (“lower limit adjustment”) will be applied to reduce the negative impacts (out-flows) and increase the positive impacts (in-flows). On the other hand, when *SDA* is more than its upper limit, denoted by *U4SDA* (with “*U4*” denoting “upper limit for”), an adjustment *UA* (“upper limit adjustment”) will be applied to allow for certain negative impacts (out-flows) and reduce the positive impacts (in-flows). In a simulated environment, for example, assume that *L4SDA*=−50 and *LA*=15% are applied. When *SDA*<−50, the convertors will decrease 15% from those negative impacts and increase 15% from those positive flows. These adjustment values will be applied to all five stages across the project life cycle. The processes of adjusting *SDA* value in the prototype are graphically presented in Fig.6.

There are other codes used in Fig.6. For examples, *I4E*, *II4E*, *III4E*, *IV4E* and *V4E* denote respectively the economic impact of the project at stage 1, 2, 3, 4, and 5; *I4S*, *II4S*, *III4S*, *IV4S* and *V4S* denote respectively the social impact at stage 1, 2, 3, 4, and 5; *I4En*, *II4En*, *III4En*, *IV4En* and *V4En* denote respectively the environmental impact at stage 1, 2, 3, 4, and 5; *I4E0*, *II4E0*, *III4E0*, *IV4E0*, and *V4E0* denote respectively the initial values of *I4E*, *II4E*, *III4E*, *IV4E* and *V4E*; *I4S0*, *II4S0*, *III4S0*, *IV4S0*, and *V4S0* denote respectively the initial values of *I4S*, *II4S*, *III4S*, *IV4S* and *V4S*; *I4En0*, *II4En0*, *III4En0*, *IV4En0*, and *V4En0* denote respectively the initial values of *I4En*, *II4En*, *III4En*, *IV4En* and *V4En*.

For processing the simulation analysis on the model, all the initial values need to be provided.

Data inputting

According to the project feasibility study report, the total investment of the project development is RMB 50 million. The operation of the project is expected to produce NaCN with annual production of 4000 tons. The total land occupied by the plant is 30000 m^2. The annual coal consumption is expected to be 13663 tons during the project operation period. In order to collect the initial values of these parameters, an interview with project client was conducted, and the results are shown in Table 3. In fact, the initial values of impact parameters are affected by many factors, and they can be revised as needed.

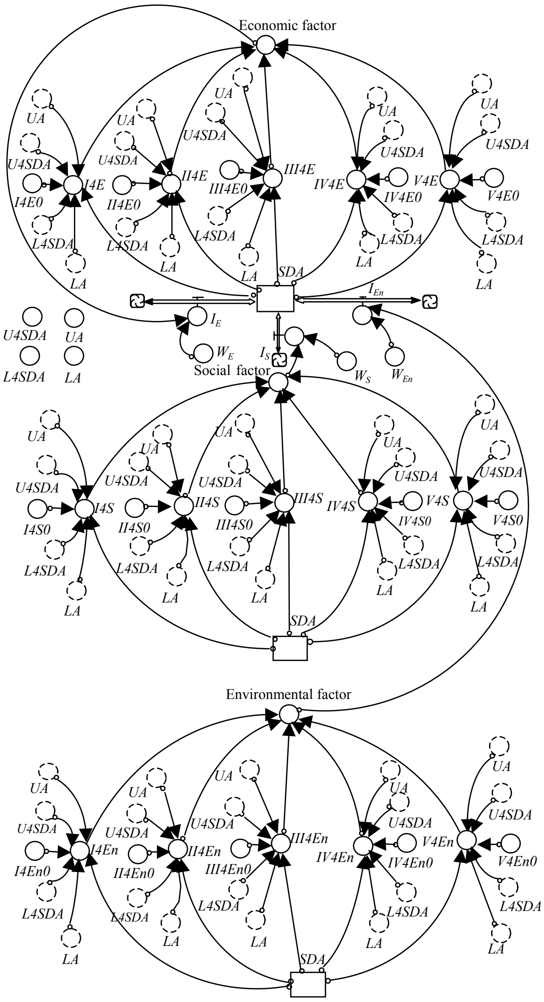


Fig.6 Modeling *SDA* for FD NaCN innovation project

Table 3 The initial values of project performance indicators for FD NaCN Innovation Project

Stage	Period (1/4 y)	Economic (*E*)	Social (*S*)	Environmental (*En*)
I	(0, 1]	−10 (*I4E0*)	−60 (*I4S0*)	−50 (*I4En0*)
II	(1, 5]	−100 (*II4E0*)	+50 (*II4S0*)	−80 (*II4En0*)
III	(5, 6]	0 (*III4E0*)	−20 (*III4S0*)	0 (*III4En0*)
IV	(6, 46]	+60 (*IV4E0*)	+30 (*IV4S0*)	−70 (*IV4En0*)
V	(46, 47]	+10 (*V4E0*)	−50 (*V4S0*)	−100 (*V4En0*)

Concerning weighting parameters (W_E, W_S, W_{En}), four scenarios are considered: (1) W_E=W_S=W_{En}=1/3, indicating that the economic, social and environmental impacts are considered as equally important; (2) W_E=1/2, W_S=W_{En}=1/4, considering that the economic impact is more important than social and environmental impacts; (3) W_S=1/2, W_E=W_{En}=1/4, considering that the social impact is more important than economic and environmental impacts; and (4) W_{En}=1/2, W_E=W_S=1/4, considering that the environmental impact is more important than economic and social impacts. For the control limit, the lower limit *L4SDA*=−50 and the upper limit *U4SDA*=100 are adopted. The adjustment values *LA*=15% and *UA*=10% are used. To simplify the demonstration, it is assumed that the parameters *L4SDA*, *U4SDA*, *LA* and *UA* are constants across the project life cycle. The values of these parameters are summarized in Table 4.

Table 4 The values of SDA prototype model parameters for FD NaCN Innovation Project

Item	Values
Scenarios	(1) W_E=W_S=W_{En}=1/3
	(2) W_E=1/2, W_S=W_{En}=1/4
	(3) W_S=1/2, W_E=W_{En}=1/4
	(4) W_{En}=1/2, W_E=W_S=1/4
Parameters	*LA*=15%
	L4SDA=−50
	UA=10%
	U4SDA=+100

LA: Lower limit adjustment; *L4SDA*: Lower limit for SDA; *UA*: Upper limit adjustment; *U4SDA*: Upper limit for *SDA*

Processing simulation

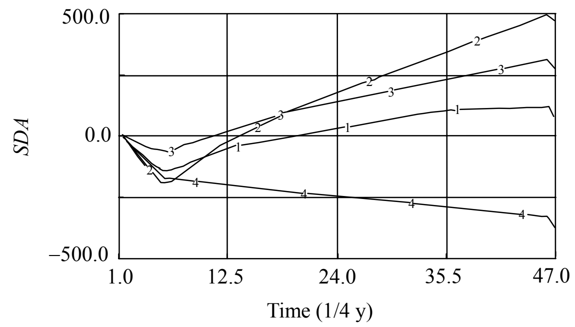
The data defined in the above discussion enables us to conduct the simulation through the model Eq.(5). The functions in Eq.(5) can be established by inputting the data in Table 3:

$$I_E(t)=\begin{cases}-10 & t\in(0,1]\\ -100 & t\in(1,5]\\ 0 & t\in(5,6]\\ 60 & t\in(6,46]\\ 10 & t\in(46,47]\end{cases} \tag{6}$$

$$I_S(t)=\begin{cases}-60 & t\in(0,1]\\ 50 & t\in(1,5]\\ -20 & t\in(5,6]\\ 30 & t\in(6,46]\\ -50 & t\in(46,47]\end{cases} \tag{7}$$

$$I_{En}(t)=\begin{cases}-50 & t\in(0,1]\\ -80 & t\in(1,5]\\ 0 & t\in(5,6]\\ -70 & t\in(6,46]\\ -100 & t\in(46,47]\end{cases} \tag{8}$$

When Eqs.(6)~(8) and the parameter values in Table 4 are inputted to the software 'ithink', simulation results are outputted. The core formulae of using the software 'ithink' in this application are listed in the Appendix A. The simulation results on the value *SDA* are given in Table 5 and presented graphically in Fig.7.



(1) Scenario one: W_E=W_S=W_{En}=1/3; (2) Scenario two: W_E=1/2, W_S=W_{En}=1/4; (3) Scenario three: W_S=1/2, W_E=W_{En}=1/4; (4) Scenario four: W_{En}=1/2, W_E=W_S=1/4

Fig.7 Simulation results on SDA for FD NaCN Innovation Project

Discussion of the simulation results

The following discussions are based on the simulation results presented in Table 5 and Fig.7.

1. Scenario one: W_E=W_S =W_{En}=1/3

Curve 1 in Fig.7 represents the simulation results of the value *SDA* for the project FD NaCN Innovation Project when the scenario W_E=W_S=W_{En}=1/3 is considered. It can be seen that Curve 1 is flat, indicating that the sustainability development ability of the project is relatively consistent across the project life cycle. According to Table 5, the value of *SDA* is 78.29 at the end of the project life cycle. This implies that the project is acceptable from the viewpoint of sustainability attainment across the project life cycle when the decision-maker gives equal weights to the economic, social and environmental impacts of the project.

Table 5 Simulation results of *SDA* for FD NaCN Innovation Project

Time (1/4 y)	Scnario (1)	Scenario (2)	Scenario (3)	Scenario (4)
1	0.00	0.00	0.00	0.00
2	−32.50	−43.75	−11.25	−42.50
3	−70.08	−91.97	−31.25	−86.28
4	−101.92	−137.09	−51.25	−127.16
5	−133.75	−182.22	−60.75	−168.03
6	−145.96	−196.69	−69.5	−181.44
7	−136.37	−176.56	−56.91	−185.41
8	−121.71	−148.31	−40.84	−189.28
9	−107.04	−120.06	−28.34	−193.16
10	−92.37	−91.81	−15.84	−197.03
11	−77.71	−63.56	−3.34	−200.91
12	−63.04	−39.44	9.16	−204.78
13	−48.37	−19.44	21.66	−208.66
14	−41.71	0.56	34.16	−212.53
15	−35.04	20.56	46.66	−216.41
16	−28.37	40.56	59.16	−220.28
17	−21.71	60.56	71.66	−224.16
18	−15.04	80.56	84.16	−228.03
19	−8.37	100.56	96.66	−231.91
20	−1.71	115.06	106.78	−235.78
21	4.96	129.56	114.53	−239.66
22	11.63	144.06	122.28	−243.53
23	18.29	158.56	130.03	−247.41
24	24.96	173.06	137.78	−251.28
25	31.63	187.56	145.53	−255.16
26	38.29	202.06	153.28	−259.03
27	44.96	216.56	161.03	−262.91
28	51.63	231.06	168.78	−266.78
29	58.29	245.56	176.53	−270.66
30	64.96	260.06	184.28	−274.53
31	71.63	274.56	192.03	−278.41
32	78.29	289.06	199.78	−282.28
33	84.96	303.56	207.53	−286.16
34	91.63	318.06	215.28	−290.03
35	98.29	332.56	223.03	−293.91
36	102.29	347.06	230.78	−297.78
37	103.63	361.56	238.53	−301.66
38	104.96	376.06	246.28	−305.53
39	106.29	390.56	254.03	−309.41
40	107.63	405.06	261.78	−313.28
41	108.96	419.56	269.53	−317.16
42	110.29	434.06	277.28	−321.03
43	111.63	448.56	285.03	−324.91
44	112.96	463.06	292.78	−328.78
45	114.29	477.56	300.53	−332.66
46	115.63	492.06	308.28	−336.53
47	78.29	468.13	270.66	−375.19

2. Scenario two: W_E=1/2, W_S=W_{En}=1/4

Curve 2 in Fig.7 gives the simulation results when it is assumed that W_E=1/2 and W_S=W_{En}=1/4. It can be seen that the value *SDA* increases when the project proceeds. According to Table 5, *SDA* is 468.13 by the end of the project life. It indicates that the sustainability of this project is very good when the economic impacts are given higher weights than those given to social and environmental impacts. In fact, it was found from the discussion with the project client that much higher weight was given to the economic impacts of the project. This project can be considered feasible and good in contributing to the attainment of sustainable development.

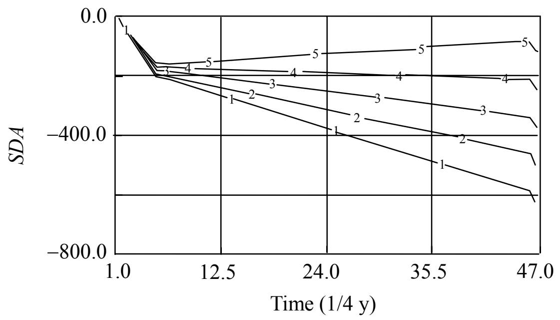
3. Scenario three: W_S=1/2, W_E=W_{En}=1/4

When the scenario of W_S=1/2, and W_E=W_{En}=1/4 is considered, the simulation results are generated and represented by Curve 3 in Fig.7. It can be seen that the value of *SDA* increases when the project proceeds, but the slope of the increase is lower compared to the results in scenario two. By the end of the project life cycle, the value *SDA* is 270.66, indicating that the sustainability of this project is good and acceptable when the social impacts of the project are given higher weights than that given to economic and environmental impacts.

4. Scenario four: W_{En}=1/2, W_E=W_S =1/4

Curve 4 in Fig.7 represents the *SDA* simulation results when it is considered that W_{En}=1/2, and W_E=W_S=1/4. It can be seen that the *SDA* decreases when the project proceeds. According to Table 5, the value of *SDA* by the end of the project life is −375.19. It indicates that the sustainability of this project is very poor when the environmental impacts of the project are given higher weight. This project may not be acceptable in an environment where environmental protection is emphasized or have higher priority.

Furthermore, the parameters in the prototype model 5, including W_E, W_S, W_{En}, *L4SDA*, *LA*, *U4SDA* and *UA*, can be provided with different values based on the project conditions, project nature and client requirements. Sensitivity analysis can be conducted by applying different values of these parameters. Assuming that the parameters *L4SDA*, *U4SDA* and *UA* retain their values (namely, *L4SDA*=−50, *U4SDA*=+100 and *UA*=10%), the weighting parameters are W_E=W_S=1/4 and W_{En}=1/2. Sensitivity analysis can then be conducted by changing the value of the parameter *LA* to 5%, 10%, 15%, 20%, and 25%. The simulation results of the sensitivity analysis generated accordingly are shown in Fig.8. It can be seen that the value *SDA* of the project will be improved when *LA* increases. In fact, the value *SDA* becomes positive and the project becomes feasible when *LA* assumes the value of 25%.



1 for *LA*=5%; 2 for *LA*=10%; 3 for *LA*=15%; 4 for *LA*=20%; 5 for *LA* =25%

Fig.8 Results of sensitivity analysis on parameter *LA* for FD NaCN Innovation Project

CONCLUSION

There is a pressing need to find ways of improving the contribution of construction projects to the attainment of sustainable development. As the level of such contribution is now considered to be an important criterion in determining the feasibility of a construction project, it is important to find a mechanism to measure the level of this contribution. A prototype model proposed in this study provides a method to assess the contribution of a construction project to sustainable development, by measuring the sustainable development ability (*SDA*). The simulation model presented in this paper shows that a project's contribution to sustainable development can change largely due to the impact of various dynamic variables throughout its life cycle. This indicates that the sustainability attainment from implementing a construction project can be improved by properly controlling the various dynamic variables. A system dynamics approach was applied to help analysis of the prototype. It can be seen that through a simulation process, the *SDA* prototype model is appropriate for assessing the dynamic impact of a construction project on economic development, social development and environmental development. By using the prototype, sensitivity analysis on the dynamic impacts of a project on sustainability attainment can also be undertaken. Simulation results and sensitivity analysis can provide a wide range of information to help with the decision-making process when considering the feasibility of implementing a construction project. The procedures for applying the *SDA* prototype model have been formulated and their effectiveness has been demonstrated by applying them to a real-life case. From the case, it was found that when different weightings for the three sustainable development contributors are applied, the sustainability attainment is different. This study provided an approach to assessing a construction project's sustainability, which can be used as reference for further study into improving the sustainability of construction projects.

References

Adeli, H., Karim, A., 1997. Scheduling-cost optimization and neural dynamics model for construction. *Journal of Construction Engineering and Management*, **123**(4): 450-458.

Brochner, J., Ang, G.K.I., Fredriksson, G., 1999. Sustainability and the performance concept: encouraging innovative environmental technology in construction. *Building Research & Information*, **27**(6):367-372.

Chritamara, S., Ogunlana, S.O., Bach, N.L., 2002. System dynamics modeling of design and build construction projects. *Construction Innovation*, **2**:269-295.

CIB, 1998. Sustainable Development and the Future of Construction. CIB Report Publications, USA, p.5-7.

CIB, 1999. Agenda on Sustainable Construction. CIB Report Publications, USA, p. 41-43.

Dolol, H.K., Jaafarl, A., 2002. Toward a dynamic simulation model for strategic decision-making in life-cycle project management. *Project Management Journal*, **33**(4):23-38.

EI-Rayes, K., Moselhi, O., 1999. Optimizing resource utilization for repetitive construction projects. *Journal of Construction Engineering and Management*, **127**(1):18-27.

Ford, D.N., 1995. The Dynamic Project Management: An Investigation of the Impacts of Project Process and Coordination on Performance, PhD Thesis. MIT, USA.

Heerwagen, J.H., 2000. Green building, organizational success and occupant productivity. *Building Research & Information*, **28**(5/6):351-367.

Hill, R.C., Bowen, P.A., 1997. Sustainable construction: principles and a framework for attainment. *Journal of Construction Management and Economics*, **15**(3): 223-239.

HPS (High Performance Systems, Inc.), 1997. Ithink Technical Documentation. High Performance Systems, Inc.

Love, P.E.D., Holt, G.D., Shen, L.Y., Li, H., Irani, Z., 2002. Using systems dynamics to better understand change and rework in construction project management systems. *International Journal of Project Management*, **20**(6):425-436.

MOC (Ministry of Construction, PRC), 1999. A Guide to Sustainable Development Construction in China. The Ministry of Construction, Beijing, PRC, p.27-30 (in Chinese).

Mohapatra, P.K.J., 1994. Introduction to System Dynamics modeling, Sangam Books, London, p.25-43.

Pena-More, F., Li, M., 1999. Dynamic planning and control methodology for design/build fast-track construction projects. *Journal of Construction Engineering and Management*, **127**(1):1-17.

Poon, C.S., Yu, A.T.W., Ng, L.H., 2001. On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling*, **32**(1):157-172.
Shen, L.Y., Wu, M., Wang, J.Y., 2002. A model for assessing the feasibility of construction project in contributing to the attainment of sustainable development. *Journal of Construction Research*, **3**(2):255-269.
Sidwell, A.C., 1990. Project management: dynamics and performance. *Journal of Construction Management and Economics*, **8**(2):159-178.
Tam, C. M., Tam, V.W.Y., Zeng, S.X., 2002. Environmental performance evaluation (EPE) for construction. *Building Research & Information*, **30**(5):349-361.
Wang, Y.W., Guan, K., 1994. Construction Systems Engineering. Chinese Construction Industry Publications, Beijing, p.89-106 (in Chinese).
WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, UK, p.1-23.
Wyatt, D.P., 1994. Recycle and Serviceability: The Twin Approach to Securing Sustainable Construction. Proceeding of 1st International Conference of CIB TG 16 on Sustainable Construction, Tampa, Florida, p.69-78.

APPENDIX A

The core formulae using the software 'ithink' to simulate the *SDA* prototype model

- SDA(t) = SDA(t - dt) + (IE + IEn + IS) * dt
  INIT SDA = 0
  INFLOWS:
  - IE = Economic_Factor*WE
  - IEn = Enviromental_Factor*WEn
  - IS = Social_Factor*WS
- Economic_Factor = if(time<=1) then I4E else (if(time<=5) then II4E else (if(time<=6) then III4E else (if(time<=46) then IV4E else V4E)))
- Social_Factor = if(time<=1) then I4S else (if(time<=5) then II4S else (if(time<=6) then III4S else (if(time<=46) then IV4S else V4S)))
- Enviromental_Factor = if(time<=1) then I4En else (if(time<=5) then II4En else (if(time<=6) then III4En else (if(time<=46) then IV4En else V4En)))
- I4E = if (SDA<L4SDA) then I4E0*(1+I4E0/ABS(I4E0)*LA) else (if(SDA>U4SDA) then I4E0*(1–I4E0/ABS(I4E0)*UA) else I4E0)
- II4E = if (SDA<L4SDA) then II4E0*(1+II4E0/ABS(II4E0)*LA) else (if(SDA>U4SDA) then II4E0*(1–II4E0/ABS(II4E0)*UA) else II4E0)
- III4E = if (SDA<L4SDA) then III4E0*(1+III4E0/ABS(III4E0)*LA) else (if(SDA>U4SDA) then III4E0*(1–III4E0/ABS(III4E0)*UA) else III4E0)
- IV4E = if (SDA<L4SDA) then IV4E0*(1+IV4E0/ABS(IV4E0)*LA) else (if(SDA>U4SDA) then IV4E0*(1–IV4E0/ABS(IV4E0)*UA) else IV4E0)
- V4E = if (SDA<L4SDA) then V4E0*(1+V4E0/ABS(V4E0)*LA) else (if(SDA>U4SDA) then V4E0*(1–V4E0/ABS(V4E0)*UA) else V4E0)
- I4S = if (SDA<L4SDA) then I4S0*(1+I4S0/ABS(I4S0)*LA) else (if(SDA>U4SDA) then I4S0*(1-I4S0/ABS(I4S0)*UA) else I4S0)
- II4S = if (SDA<L4SDA) then II4S0*(1+II4S0/ABS(II4S0)*LA) else (if(SDA>U4SDA) then II4S0*(1–II4S0/ABS(II4S0)*UA) else II4S0)
- III4S = if (SDA<L4SDA) then III4S0*(1+III4S0/ABS(III4S0)*LA) else (if(SDA>U4SDA) then III4S0*(1–III4S0/ABS(III4S0)*UA) else III4S0)
- IV4S = if (SDA<L4SDA) then IV4S0*(1+IV4S0/ABS(IV4S0)*LA) else (if(SDA>U4SDA) then IV4S0*(1-IV4S0/ABS(IV4S0)*UA) else IV4S0)
- V4S = if (SDA<L4SDA) then V4S0*(1+V4S0/ABS(V4S0)*LA) else (if(SDA>U4SDA) then V4S0*(1-V4S0/ABS(V4S0)*UA) else V4S0)
- I4En = if (SDA<L4SDA) then I4En0*(1+I4En0/ABS(I4En0)*LA) else (if(SDA>U4SDA) then I4En0*(1-I4En0/ABS(I4En0)*UA) else I4En0)
- II4En = if (SDA<L4SDA) then II4En0*(1+II4En0/ABS(II4En0)*LA) else (if(SDA>U4SDA) then II4En0*(1-II4En0/ABS(II4En0)*UA) else II4En0)
- III4En = if (SDA<L4SDA) then III4En0*(1+III4En0/ABS(III4En0)*LA) else (if(SDA>U4SDA) then III4En0*(1-III4En0/ABS(III4En0)*UA) else III4En0)
- IV4En = if (SDA<L4SDA) then IV4En0*(1+IV4En0/ABS(IV4En0)*LA) else (if(SDA>U4SDA) then IV4En0*(1-IV4En0/ABS(IV4En0)*UA) else IV4En0)
- V4En = if (SDA<L4SDA) then V4En0*(1+V4En0/ABS(V4En0)*LA) else (if(SDA>U4SDA) then V4En0*(1–V4En0/ABS(V4En0)*UA) else V4En0)
- I4E0 =–10
- II4E0 =–100
- III4E0 = 0.0001
- IV4E0 = 60
- V4E0=10
- I4S0=60
- II4S0=50
- III4S0=–20
- IV4S0=30
- V4S0=–50
- I4En0=–50
- II4En0=–80
- III4En0 =0.0001
- IV4En0=–70
- V4En0=–100
- WE=1/3
- WS=1/3
- WEn=1/3
- U4SDA=100
- L4SDA=–50
- UA= .1
- LA= .15