A SIMULATION MODEL FOR ASSESSING CONSTRUCTION PROJECTS SUSTAINABILITY PERFORMANCE

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ABSTRACT

Sustainability has become a concerned issue within all built environment stakeholders. Construction projects play a major role in the sustainability of the world as any construction project should ensure that the great investment achieves good sustainability performance. It is essential to be able to assess a construction project’s sustainability performance. This paper presents the development of a simulation model by using system dynamics to be used to assess construction projects’ sustainability performance to integrate social, environmental, and economic factors. Whilst this development contributes significantly to the promotion of sustainable construction, it is also important that the levels of sustainability performance actually achieved can be widely understood and easily communicated within the main stakeholders.

Keywords: model, performance, simulation, sustainability, and system dynamics.

1. INTRODUCTION

Sustainability has become a concerned issue within all built environment stakeholders. Construction projects play a major role in the sustainability of the world. It is well recognised that the construction industry is one of the major contributors to the depletion of natural resources and a major cause of pollution (Augenbroe and Pearce, 1998; HKCIRC, 2001; Treloar et al, 2003). Construction projects should ensure that the great investment achieves good sustainability performance. It is essential to be able to assess a construction project’s sustainability performance quantitatively and qualitatively.

In recent years, social, economic and environmental pressures to measure construction projects sustainability performance have led to an emphasis on sustainability development ability model (Shen et al 2004; Tam et al 2005). Sustainable construction addresses the responsibility of the construction industry for attaining sustainable development widely referred to as the sustainability of economic development, social development and environmental development (Ofori, 1992; WCED, 1987; UNCHS, 1996). The shortage of methods to assess sustainability performances presents the barrier of assessing whether the implementation of a project will or not contribute acceptable level of sustainability performance. Although sustainable development ability (SDA) model was developed by Shen et al in 2002 to measure the contribution of a project to the attainment of sustainable development, it was recognized by Shen et al in 2004 that a major limitation of the SDA model is that the measure did not consider the impacts of various dynamic factors. According to the general principle of
sustainable development, economic, social and environmental developments are the main contributors (WCED, 1987). As social, economic, environmental and institutional processes have become increasingly interwoven (Hill et al, 1997; Kein et al, 1999), it is necessary to take integration into consideration when measuring the sustainability performance of construction projects.

To improve the scientific understanding of integrated systems, a system dynamic simulation model could explicitly shed light on the dynamics and complexity of assessing sustainable performance as it is capable of analysing the interrelationship between all the disciplines involved in the process (Hao et al 2006). Therefore, the focus of this paper is to demonstrate how a system dynamic simulation model, SDA, was developed to integrate social, economic, and environmental factors by using system dynamics to assess sustainable performance of a construction project.

2. SUSTAINABLE CONSTRUCTION

The report by the Hong Kong Construction Industry Review Committee (HKCIRC, 2001) identified the construction industry as among the worst polluters. This has been widely echoed by many researchers, for example, Tse (2001), Shen and Tam (2002), Treloar (1996), Baba (1998), Griffith (1999), CIB (1998), Sjostrom and Bakens (1999). While these findings demonstrate the significant adverse impacts of construction businesses on the environment, they also reflect the tradition of managing a construction project for focusing on controlling cost, time and quality but less attention to environmental and social performance in implementing the project. The realization of these facts has led to the growth of studies on sustainable construction solutions across a project life cycle (Hill and Bowen, 1997; Brochner et al, 1999; Heerwagen, 2000; Tam et al, 2002). Whilst safety and environmental management have been added into the context of construction management (Griffith, 2002), their effectiveness has been limited in practice. This is partly due to the profit-driven culture in the industry where the cost, quality and schedule have been the determinants ensuring maximum benefits to the construction business. It is also due to the difficulty of measuring the contribution of a construction project to environmental performance.

The existing literature also provides rich information on the application of sustainable construction, for example, the UK Building Services Research and Information Associations’ Environmental Code of Practice for Buildings and their Services (Halliday, 1994). Hill and Bowen (1997) presented a framework for attaining sustainable construction. In this framework, a systematic understanding of the principles of sustainable construction is provided, which are divided into four ‘pillars’ of sustainability, namely, social, economic, biophysical, and technical. Wyatt (1994) proposed an approach for promoting sustainable construction by managing the service provision of a building during its lifetime from inception to eventual deconstruction, recycling resources and reducing the waste stream during the building’s lifetime. A study by Tam et al (2002) examined the obstacles in promoting sustainable construction, and has found that one of the key obstacles is the lack of performance evaluation criteria. The above mentioned are not the only models. Other researchers have developed various approaches and methods for promoting sustainable construction, for example, Brochner et al (1999); Heerwagen (2000); and Griffith
A recent study (Kattz et al, 2005) more precisely looks into sustainable development implemented within the construction process. These works have contributed to the theoretical platform of sustainable construction studies. Nevertheless, none of these has provided any method for assessing the level of sustainability performance of a construction project by integrating economic, social and environmental factors through system dynamics.

3. DEVELOPMENT OF A SIMULATION MODEL

Modelling method and software
System dynamics was developed by Forrester (1957), and has achieved world-wide recognition as a well established methodology for studying and managing complex construction related systems and environmental systems (Dyson and Chang, 2005; Ford, 1995; Hao and Scott, 2001; Love et al, 2002; Rodrigues and Bowers, 1996; Sterman, 2000).

This study will employ system dynamics approach which has been widely used in analyzing systems that are complex, dynamic and has many nonlinear interactions. Several major works provide useful references in using the approach for conducting simulation, for example, Pena-More and Li (1999), and Dolol and Jaafarl (2002). To simulate a system dynamics model, there are existing computing softwares, for example, DYNAMO, VENSIM, Stella, and Matlab. Stella has been developed as an effective simulation tool by High Performance Systems, Inc (HPS) (HPS, 2005) as the mapping, modelling, and simulation capabilities of the software can transform an exercise in linear extrapolation into a powerful learning experience that captures the dynamic complexity of sustainable construction.

Structure of the simulation model
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 to the value 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 an economic gain, namely, an increase in \(E(t)\), a positive impact to the value 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 the attainment of sustainable development is received. On the other hand, SDA will decrease if an out-flow occurs, indicating that a negative impact to the attainment of sustainable development is received. This may be due to 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:
Where \( I_E(t), I_S(t) \) and \( I_{En}(t) \) 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 to SDA. By applying these parameters to the model defined, a prototype model of SDA using system dynamics method can be developed as shown in Figure 1.

A simulation model using ‘Stella’ software is developed shown in Figure 1. The values of the economic sustainability (\( E(t) \)), social sustainability \( S(t) \) and environmental sustainability \( En(t) \) are seen as ‘flows’. When there are in-flows to the stock, the sustainability performance value will increase, indicating a positive contribution to sustainable development (for example, a new environmental protection measure). Otherwise, if out-flows occur, the sustainability performance will decrease, indicating a negative contribution to sustainable development, for example, the project pollutes the environment. The converter serves a utilitarian function, determining the relative weightings between system variables. It defines how much influence of the flow variables has on the sustainability performance. The three flows \( E(t), S(t) \) and \( En(t) \) will carry different weights in terms of their impacts on the sustainability performance value. Connectors show the connections between model elements.

To run the model, all values for various parameters need to be provided. As assumed, the weighting factors \( W_E, W_S \) and \( W_{En} \) are constants, and their values are given by decision makers. Different decision makers may allocate weighting values differently with 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 given with the same value (namely, 1/3). On the other hand, the parameters \( I_E, I_S, I_{En} \) are time functions, indicating that the implementation of a construction project will have different social, economic and environmental impacts at different stages across project life cycle. The values of \( I_E, I_S, I_{En} \) are determined respectively by economic 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 the simulation model. These relationships can be adjusted in different applications.
Figure 1 Structure of the simulation model

The data used to develop this simulation model are from a project feasibility study which includes economical, social and environmental assessment. The project is a renovation project located in Chongqing, China.
4. SIMULATION RESULTS

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 the annual production of 4000 ton. The total land occupied by the plant is 30,000 m². The annual coal consumption is expected to be 13,663 ton during 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 1. In fact, the initial values of impact parameters are affected by many factors, and they can be revised as needed.

Table 1
The initial values of project performance indicators for FD NaCN Innovation Project

<table>
<thead>
<tr>
<th>Stage</th>
<th>Period (1/4y)</th>
<th>Economic (E)</th>
<th>Social (S)</th>
<th>Environmental (En)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception</td>
<td>(0, 1]</td>
<td>-10 (I4E0)</td>
<td>-60 (I4S0)</td>
<td>-50 (I4En0)</td>
</tr>
<tr>
<td>Construction</td>
<td>(1, 5]</td>
<td>-100 (II4E0)</td>
<td>+50 (II4S0)</td>
<td>-80 (II4En0)</td>
</tr>
<tr>
<td>Commission</td>
<td>(5, 6]</td>
<td>0 (III4E0)</td>
<td>-20 (III4S0)</td>
<td>0 (III4En0)</td>
</tr>
<tr>
<td>Operation</td>
<td>(6, 46]</td>
<td>+60 (IV4E0)</td>
<td>+30 (IV4S0)</td>
<td>-70 (IV4En0)</td>
</tr>
<tr>
<td>Demolish</td>
<td>(46, 47]</td>
<td>+10 (V4E0)</td>
<td>-50 (V4S0)</td>
<td>-100 (V4En0)</td>
</tr>
</tbody>
</table>

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 limitation, the lower limitation \( L_{4SDA}=-50 \) and the upper limitation \( U_{4SDA}=100 \) are adopted. The adjustment values \( LA=15\% \) and \( UA=10\% \) are used. To simplify the demonstration, it is assumed that the parameters \( L_{4SDA}, U_{4SDA}, LA \) and \( UA \) are constants across project life cycle.

Table 2 Simulation results of SDA for the Renovation Project

<table>
<thead>
<tr>
<th>Year</th>
<th>SDA - Scenario (1)</th>
<th>SDA - Scenario (2)</th>
<th>SDA - Scenario (3)</th>
<th>SDA - Scenario (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-133.75</td>
<td>-182.22</td>
<td>-60.75</td>
<td>-168.03</td>
</tr>
<tr>
<td>3</td>
<td>-107.04</td>
<td>-120.06</td>
<td>-28.34</td>
<td>-193.16</td>
</tr>
<tr>
<td>4</td>
<td>-48.37</td>
<td>-19.44</td>
<td>21.66</td>
<td>-208.66</td>
</tr>
<tr>
<td>5</td>
<td>-21.71</td>
<td>60.56</td>
<td>71.66</td>
<td>-224.16</td>
</tr>
<tr>
<td>6</td>
<td>4.96</td>
<td>129.56</td>
<td>114.53</td>
<td>-239.66</td>
</tr>
<tr>
<td>7</td>
<td>31.63</td>
<td>187.56</td>
<td>145.53</td>
<td>-255.16</td>
</tr>
<tr>
<td>8</td>
<td>58.29</td>
<td>245.56</td>
<td>176.53</td>
<td>-270.66</td>
</tr>
<tr>
<td>9</td>
<td>84.96</td>
<td>303.56</td>
<td>207.53</td>
<td>-286.16</td>
</tr>
<tr>
<td>10</td>
<td>103.63</td>
<td>361.56</td>
<td>238.53</td>
<td>-301.66</td>
</tr>
<tr>
<td>11</td>
<td>108.96</td>
<td>419.56</td>
<td>269.53</td>
<td>-317.16</td>
</tr>
<tr>
<td>12</td>
<td>114.29</td>
<td>477.56</td>
<td>300.53</td>
<td>-332.66</td>
</tr>
</tbody>
</table>
After the parameter values are provided, simulation process can be conducted. The simulated results on the value SDA for the case project can be presented either by graphs or tables which are built in features within Stella. Concerning weighting parameters \((W_E, W_S, W_{En})\), four scenarios are considered. To simplify the demonstration, it is assumed that the parameters L4SDA, U4SDA, LA and UA are constants across project life cycle. Based on these conditions, Table 2 is produced to show the results with four different scenarios for the renovation project across the project’s life cycle.

Scenario (1) \(W_E=W_S=W_{En}=1/3\), indicating that the economic, social and environmental impacts are considered as equally important. The value of SDA is 114.29 at the end of the project life cycle. This indicates that the project is acceptable from the viewpoint of sustainability attainment through the project life cycle when decision maker gives equal weights to the economic, social and environmental impacts of the project.

Scenario (2) \(W_E = 1/2, W_S = W_{En} = 1/4\), considering that the economic impact is more important than social and environmental impacts. SDA is 477.56 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 that given to social and environmental impacts. In fact, it was found from the discussion with project client that much higher weight was given to the economic impacts of the project. Therefore, this project can be considered feasible and good in contributing to the attainment of sustainable development.

Scenario (3) \(W_S = 1/2, W_E = W_{En} = 1/4\), considering that the social impact is more important than economic and environmental impacts. The value SDA is 300.53, 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.

Scenario (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 limitation, the lower limitation L4SDA=-50 and the upper limitation U4SDA=100 are adopted. The adjustment values LA=15% and UA=10% are used. According to Table 1, the value of SDA by the end of the project life is -332.66. 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 in higher priority consideration.

5. CONCLUSION

In an effort to address how to assess a construction project’s sustainability, the simulation model presented here is applicable to be used as an integrated means to improve understanding of the complexity involved in sustainability assessment. Such a simulation model is aimed at testing the effectiveness of various policy strategies, and estimating trade-offs among different policy options. The model can be helpful in monitoring and examining the goals and criteria set to measure sustainability.
In view of the growing complexity of attaining sustainability while constructing a project, there is a definite need for integrated approaches that assist decision makers and stakeholders in this undertaking. The purpose of this paper was to demonstrate a simulation model developed by using system dynamics methodology. The model considers that the contribution of a construction project to sustainable development can change largely due to the impacts of various dynamic variables across project life cycle. This indicates that the sustainability attainment from implementing a construction project can be improved by properly controlling various dynamic variables. System dynamics approach was found applicable in assisting in the prototype analysis. Through a simulation process, the model enables users to assess the dynamic impacts of implementing a construction project on economic development, social development and environmental development.

The integrated simulation model can be instrumental in formulating and underpinning targets for a more sustainable development of a project by balancing the economical, social and environmental factors. The procedures of applying the SDA simulation model are formulated and their effectiveness has been demonstrated by a practical example. From this demonstration example, it was found that when different weights are given among the three sustainable development contributors, namely, \( E \), \( S \), and \( En \), the sustainability attainment from implementing a construction project will be different. This study provides valuable reference for further study on improving the sustainability attainment of a construction project.

6. REFERENCES


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