Journal of Cleaner Production 121 (2016) 33–44

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A system dynamics model for construction method selection with sustainability considerations

Gulbin Ozcan-Deniz [a, *], Yimin Zhu [b, 1]

[a] College of Architecture and the Built Environment, Philadelphia University, Philadelphia, PA 19144, USA
[b] Louisiana State University, 3135-B Patrick F. Taylor Hall, Department of Construction Management, Baton Rouge, LA 70803, USA

A R T I C L E I N F O

Article history:
Received 31 March 2015
Received in revised form
28 January 2016
Accepted 28 January 2016
Available online 8 February 2016

Keywords:
System dynamics
Construction method selection
Decision-making
Sustainability

A B S T R A C T

Construction projects have project conditions that change over time, like the availability of resources. These changes have the potential to influence the selection of construction methods, which in turn significantly affects the chance of successfully accomplishing project objectives, such as the time of completion, cost, and sustainability. In addition, project conditions are dynamic, and their impact on construction methods and project objectives are difficult to predict intuitively. Therefore, there is a need for an analytic procedure to understand the impact of different project conditions on the decision-making process of construction professionals. This analytical procedure will better inform construction professionals during the selection of construction methods. The authors applied systems dynamics to simulate and analyze the changing project conditions and their influence on the selection of construction methods when decision-makers are constrained by time, cost and environmental impact objectives. Two highway case studies were considered to demonstrate the effectiveness of the system dynamics model. The results of the case studies suggest that the proposed systems dynamics model has the potential to effectively simulate decision-making processes in construction under changing project conditions while outputting the most feasible construction methods. Furthermore, the study shows that project conditions have an impact on the flow of construction processes.

1. Introduction

The presence of multiple and often conflicting objectives in construction has resulted in significant studies in the area of project optimization (El-Rayes and Kandil, 2005). Traditionally, researchers have focused on project-specific objectives, such as time, cost, safety, quality, and sustainability, to complete a project successfully within the constraints set by external factors (Kandil et al., 2010). However, recently, sustainability has increasingly become a new criterion of project success (e.g., Ofori, 1992; Selih, 2007).

The inclusion of sustainability as a new project performance indicator, which is often expressed in terms of environment impacts, has led to the requirement of a better understanding of project sustainability and its impact on the performance of construction projects (Cole, 2005). Project conditions, a collective term for describing project external factors, play a significant role in influencing both project sustainability considerations and project performance (Ozcan-Deniz and Zhu, 2015). For example, project condition changes, such as the unit cost of resources or market conditions affecting bidding procedures, were rated as "high to very high" risk items (Skorupka, 2008). It is challenging to predict the behavior of project conditions because they change within the entire context of a construction project. Therefore, it is critical to have a comprehensive analytic procedure that connects project conditions (i.e., external factors) and project objectives (i.e., internal considerations). The connection will help better understand the impact of different project conditions on the decision-making processes of construction professionals regarding the impact of construction method selection on project objectives, such as time, cost and environmental impacts (TCEI).

Although construction professionals often have many alternative construction methods from which to choose, due to the complexities involved in foreseeing the impact of the alternatives on project objectives, some alternatives are often ignored during construction planning. It is common for construction professionals

* Corresponding author. Tel.: +1 215 951 2793.
E-mail addresses: denizg@philau.edu (G. Ozcan-Deniz), yiminzhu@lsu.edu (Y. Zhu).
[1] Tel.: +1 225 578 5373.

http://dx.doi.org/10.1016/j.jclepro.2016.01.089

to choose a construction method based on previous experience, which potentially misses an opportunity to apply a better construction method. Previous studies have developed analytic approaches to help solve such a problem. For example, different types of artificial intelligence (AI) systems, such as expert systems, artificial neural networks (ANNs), and support vector machines (SVMs), were studied for use in the selection of a construction method. However, these approaches showed limitations, such as lacking self-learning and having a time-consuming acquisition process (Shen et al., 2005).

Thus, the aim of this research is to determine a comprehensive approach for analyzing changing project conditions and their impact on TCEI objectives, i.e., an approach that also helps decision-makers select the most appropriate construction methods (Tsai et al., 2013). System dynamics (SD) modeling, a method that can be used to "select the most suitable method for a given purpose and objective" (Lorenz and Jost, 2006), was found to be successful in solving complex system problems (e.g., Sterman, 2000; Sahin et al., 2015). Therefore, the authors propose a SD model to establish connections between project conditions and TCEI objectives to study the selection of construction methods. The proposed SD model and the simulation process are demonstrated using two case studies that share the same construction method alternatives for three highway construction activities: milling, paving, and laying the friction course.

The authors organized the paper into four parts. In the first part, the authors discuss the state-of-the-art knowledge regarding decision-making with multi-agents and SD modeling. In the second part, the authors explain the proposed SD model in detail. The third part contains the description of the two case studies and a validation of the proposed SD model using the case studies. The final part includes conclusions and recommendations for future studies.

2. Overview of multi-agent decision-making and system dynamics

There are two major technical pieces involved in this research: a multi-agent decision-making component and the SD model. The multi-agent decision-making component, which is part of the SD model, simulates a decision process for selecting construction methods based on different project conditions. The SD model provides the overall architecture of this research.

2.1. Decision-making with multi-agent systems

In general, an agent can be defined as anything that can perceive its environment through sensors and can act through effectors (Russell and Norvig, 2002). Multi-agent systems (MAS) are defined as a group of agents that attempt to maximize their own effectiveness while cooperating with other agents to achieve the desired objectives (Jennings et al., 1999). Agents in this study are modeled as project parties who determine the most appropriate construction operations to deliver projects.

Agents in the life cycle of construction projects include parties for both the design and construction phases. Different researchers have categorized construction parties in different manners. For example, in the MASCOT system (Ren and Anumba, 2002), agents were limited to clients, contractors and engineers in the implementation phase; in contrast, Ugwu et al. (2005) defined project agents as also including client and design team agents (such as subcontractors, construction engineers, and manufacturers). Alternatively, Xue et al. (2005) listed construction supply-chain agents as owners, general contractors, and designers together with sub-agents, such as sub-contractors and suppliers. Thabrew et al. (2009) considered agents to be contactors, local authorities, housing authorities, and manufacturers in life cycle assessment (LCA). Li et al. (2010) summarized agents in supply-chains as raw material suppliers, component suppliers, manufacturers, and retailers.

In summary, the decision process of parties at the design and construction phase can be modeled using MAS, which allows for the integration of decision-making with other construction modeling and simulation applications.

2.2. Concept of systems dynamics, modeling and applications

System dynamics (SD), "the investigation of the information-feedback character of industrial systems and the use of models for the design of improved organizational form and guiding policy" (Forrester, 1961), is a method for studying and managing complex systems (e.g., Forrester, 1985; Sterman, 2000). The concept combines the theory, methods, and philosophy required to analyze the behavior of complex systems and understand changes of system behavior over time (Forrester, 1994).

In general, SD models have three types of elements: (1) stock elements (state variables); (2) flow elements; and (3) auxiliary variables and constants (Garcia, 2006). These elements permit the simulation of changes over time and the feedback of information (Richardson and Pugh, 1981). Stocks, flows, and feedback loops are the basic elements to model the flow of work and resources through a project for the cause and effect analysis (Ogunlana et al., 2003).

A typical SD model structure includes project features, a rework cycle, project control feedbacks, and ripple and knock-on effects. Project features represent the development tasks or work packages, as they flow through a project (Lyneis et al., 2001). A rework cycle shows the iterative flow of work packages with respect to time. Several rework structures have been developed (e.g., Ford and Sterman, 1998) and applied to explain different problems (e.g., Ford and Sterman, 2003) in the literature. Feedback loops are used to control a project's performance. For example, Lyneis and Ford (2007) used "Add People," "Work More," and "Work Faster/Slack Off" feedback loops to meet a project deadline. Ripple and knock-on effects are side effects that are caused by actions taken to close a gap between project performance and targets.

There are many SD applications in the literature, including work in construction project management (Table 1).

3. Model development

3.1. Overview of the SD model for construction method selection

The authors model a construction system using two sub-systems, a decision-making and a project sub-system, as shown in Fig. 1. The decision-making sub-system simulates a decision-making process of selecting the most feasible construction method (CM) under the impact of changing project conditions. In this study, project conditions are considered external factors that can influence the decision-making of involved parties and their choice of construction methods. Therefore, they are included as one of the main parameters in the decision-making sub-system.

The project sub-system contains models of the resources and the processes related to a project and includes the calculation procedure of TCEI. The parameters used by the project sub-system include the project objectives, time, cost and environmental impacts of the CMs. All of these parameters constrain the selection of the CMs. The project sub-system reflects the properties of each project and uses different CM alternatives that are selected by the decision-making sub-system to calculate the TCEI values. Using this method, the TCEI values are calculated for different scenarios of