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REVIEW ARTICLE

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System dynamics analytical modeling approach for construction project management research: A critical review and future directions

Abstract Building and infrastructure construction projects can be viewed as a complex system consisting of many subsystems. Over the last two decades, considerable researches that use system dynamics (SD) as an analytical and modeling approach exist to address construction project management issues. However, only few critical reviews have been conducted to provide an in-depth understanding of SD application in construction project management. Moreover, many studies have failed to apply SD accurately. Therefore, the present study aims to gain an understanding of the current state of play and future directions in applying SD method in construction project management research, by undertaking a comprehensive review of 105 relevant articles published from 1994 to 2018. These articles are analyzed in terms of annual publication rate, key papers and their contribution, critical issues in SD application, and research topics. A significant increase in the number of publications in the last five years has been observed. When applying SD method to model construction system, the following aspects must be carefully considered: Model boundary, model development, model test, and model simulation. In addition, SD has been applied in a wide range of research topics, including (1) sustainable construction; (2) design error, rework, and change management; (3) risk management; (4) resource management; (5) decision making; (6) hybrid modeling; (7) safety management; (8) PPP project; and (9) organization performance. Based on the review findings, this study discusses three future research directions, namely, integration of SD with other methods, uncertainty analysis, and human factor analysis. This study can help researchers gain an in-depth understanding of the critical issues in the application of SD in construction management and the state-of-the-art of SD research.

Keywords system dynamics, construction management, problem and recommendation, research directions, literature review, human factor

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1 Introduction

Construction project management (construction management) stems from a feasibility study to design and construct, commission, and handover a physical building, bridge, highway, and high-speed rail system. Construction management can be viewed as a complex system with the combination of technology and management, consisting of many subsystems, including various integrated, systematic, and complex social activities, with large investments, long period, and multi-stakeholders (Wang and Yuan, 2016). Therefore, successfully managing construction projects to meet the requirements of time, cost, quality, environment, and safety is difficult (Zou et al., 2007). With the advancement of computer technology, numerous analytical models have been developed to facilitate construction management research, such as analytic hierarchy process, Monte Carlo simulation, structural equation modeling, social network analysis, Bayesian belief network (BBN), and so forth. These methods are used to understand and analyze the complexity of construction projects. However, most of these methods tend to assume each element of the project has been clearly understood (Rodrigues and Bowers, 1996). Rodrigues and Bowers (1996) pointed out that the interrelationships among the components are more complex than expected. The failure of achieving construction goals is usually attributed to various factors that are rarely independent of one another (Nasirzadeh and Nojedehi, 2013; Wang and Yuan, 2016). In addition, many types of information flow, such as material flow and cash flow exist during the process, which is a complex and dynamic system containing numerous feedback loops, uncertainties, and nonlinear relationships (Sterman, 2000). Take schedule as an example, many factors can affect a schedule. In Fig. 1, rectangles refer to factors that may have an impact on schedule, and arrows indicate the interaction among factors. These factors may interact with each other, and using a linear equation to express interactions (e.g., the interaction between fatigue and accident) may be difficult. In addition, a time delay exists among interactions (e.g., working overtime to meet the deadline may not lead to immediate fatigue, instead, may lead to fatigue at a later stage). In this example, not all factors are considered, and the scheduling is merely treated as a subsystem of the construction project. The actual construction management can be much more complex.

Therefore, research and practice require a new method to analyze the complexity of construction management. Under this background, system dynamics (SD), as an analytical modeling approach, is considered by researchers. On the basis of computer simulation technology and system theory, SD focuses on the structure of a complex system and its nonlinear behaviors over time. Compared with other traditional research methods, SD emphasizes the interrelationship among different components that have great impact on system behaviors. Although a multitude of efforts have been exerted on integrating several modeling approaches (e.g., integrating agent-based modeling (ABM) and SD), SD cannot be replaced by other research methods in many studies. Several merits that SD approach possesses over other modeling approaches exist, including:

1) Enabling researchers to model complex construction systems from the cause–effect perspective, rather than "black box" analysis;

2) Allowing researchers to identify feedback loops in the construction system;

3) Enabling researchers to include nonlinear relationships and time delay of the construction system.

Literature review in a specific field is generally considered a key method for not only helping researchers enrich the method's current body of knowledge but also stimulating researchers' inspirations for future research (Zheng et al., 2016). For example, Xiong et al. (2015a) conducted a critical review of 84 articles involving the use of structural equation modeling to address construction-related problems. They found the mistakes many research have caused. Zheng et al. (2016) reviewed 63 social network analysis-related articles in construction project management to ascertain the status of this research and identify future research directions. Ahmad et al. (2016) carried out a content analysis of SD-related articles in the electricity sector and highlighted SD contribution to electricity sector modeling. These reviews not only have provided researchers multi-dimensional understanding of a method in a discipline but also have presented certain potential research directions for the method application in future research. A method's literature review in a specific field is critical in allowing researchers to understand how the method can be used for research and what the new and noteworthy research directions of the method are.

For a researcher who aspires to apply SD modeling approach for solving a research problem in construction management, he or she must master the SD modeling methods, identify the mainstream, and track future directions. Over the past 20 years, a multitude of researchers in the construction management field have used the SD model. However, a thorough review of SD articles in this field is unavailable, which hinders researchers from having a comprehensive and systematic

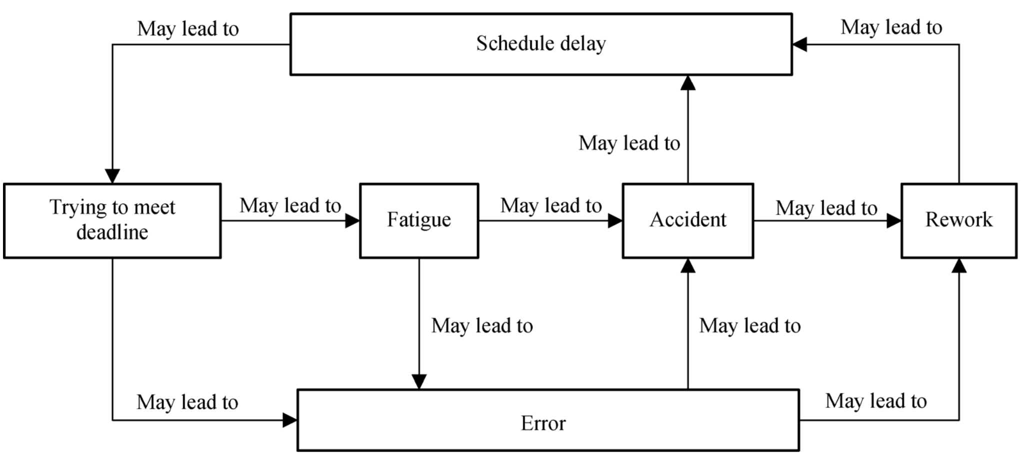

Fig. 1 Schematic illustration of complex interactions between fatigue and schedule delay in a construction project.

understanding of the research focuses and trends. Moreover, certain researchers fail to use SD correctly. Admittedly, SD application in construction management lags behind other fields, such as economic development, rural and urban planning, and energy and industry. Therefore, the current research aims to conduct a thorough review of SD-based articles published in major peer-reviewed journals in the construction management field. To achieve this aim, we answer the following research questions:

1) What are the critical issues of SD application in construction management research?

2) What are the state-of-the-art and future research directions of SD in construction management research?

This study provides a "panorama" of SD application in construction management. On the basis of this study, researchers can understand the current state and correct use of SD. It can also provide future directions in applying SD method in construction management research. The remainder of this paper is structured into four sections. Section 2 presents a detailed description of the SD method. Section 3 introduces the methodology for selecting and analyzing target articles. Section 4 presents the results, analysis, and discussion. Section 5 provides the conclusions.

2 System dynamics modeling approach

Proposed by Prof. J. W. Forrester, MIT, in the 1950s, SD is a discipline that focuses on the structure of complex systems and the relationship between function and dynamic behavior based on feedback control theory and computer simulation technology. SD is effective not only for examining the dynamic characteristic of a system but also for exploring the overall behavior of a complex system that is difficult to anticipate (Yuan and Wang, 2014). After nearly 60 years of development, SD has been widely used to deal with managerial, economic, environmental, and social systems of great complexity, such as economic development, military system management, energy and resources management, rural and urban planning, and construction management.

SD modeling process can be divided into four parts. The first is to determine the system boundaries according to problem articulation (Ahmad et al., 2016). Causal loop diagrams (CLD) are then drawn from a qualitative point of view. A schematic CLD is illustrated in Fig. 2. As shown in the figure, two kinds of arrow represent a cause–effect relationship between two variables, namely, positive (+) and negative (–). If the arrow-tail variable and the arrow-head variable changes toward the same direction, for example, the increase of A leads to the increase of B and the decrease of A leads to the decrease of B, then they have a positive correlation (Fig. 2 on the left). Otherwise, they have a negative correlation (Fig. 2 on the right).

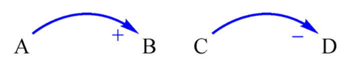

Fig. 2 Schematic of causal loop.

When the causal relationship constitutes a closed loop (the directions of arrows in the closed loop should be the same), a feedback loop can be found. The feedback loop is divided into two types: Positive and negative feedback. When the number of negative correlations in the feedback loop is an odd number, the feedback loop is considered negative (Fig. 3 on the left). Otherwise, it is considered a positive feedback loop (Fig. 3 on the right).

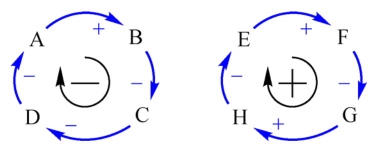

Fig. 3 Schematic of feedback loop.

CLD can only be used for qualitative analysis. If quantitative analysis is necessary, then CLD must be converted into a stock-flow diagram (Yuan and Wang, 2014). A complete stock-flow diagram contains four variables, namely, stock, flow, auxiliary, and connector (Table 1). A simple example for stock-flow diagram related to Fig. 1 is illustrated in Fig. 4. A stock variable, embracing tangible and intangible, shows the level of a system variable at a specific time (Ahmad et al., 2016), such as "work to be finished" and "completed work". A flow variable, attached to a stock, measures the rate of changes

Table 1 Basic blocks used in SD with icons

Building block	Symbol	Description
Stock (level)		The level of any variable in the system (Akhwanzada and Tahar, 2012; Ahmad et al., 2016)
Flow (rate)		The rate of changes in stock, which can cause the increase or decrease of a stock (Jin et al., 2016)
Auxiliary (convertor)		It connects stock and a flow in a complex setting, used for intermediate calculations (Akhwanzada and Tahar, 2012)
Connector		It denotes connection and control between system variables, showing the causality (Li et al., 2014a)

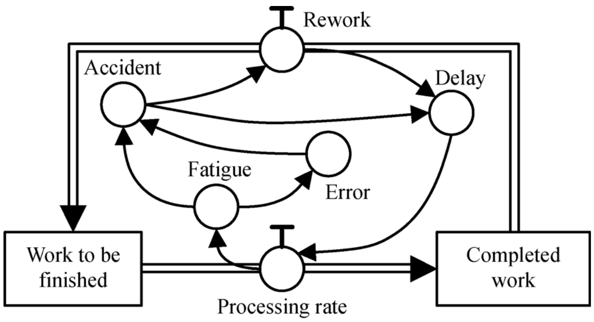

Fig. 4 Sample stock-flow diagram.

in a stock. For example, "processing rate" is the decrease rate of "work to be finished" and the increase rate of "completed work" (Fig. 4). Therefore, the "process rate" can directly influence the construction progress. Another flow variable "rework" can increase the amount of work. "Work to be finished", "processing rate", "completed work", and "rework" form a feedback loop. An auxiliary variable serves as an intermediary for miscellaneous calculations (Li et al., 2014a), such as "fatigue", "delay", and "error". They can be considered the impact factors of "processing rate" and "rework". A connector indicates connection and control between two variables (Ahmad et al., 2016).

Rigid model tests should be conducted to prove that the developed SD model can reflect the real-world situation. Therefore, the SD model, including direct structure test (DST), structure-oriented behavior test (SOBT), and behavior test (BT) are tested in the fourth stage (Barlas, 1996). The final stage of modeling process is simulation, which consists of scenario, uncertain, and sensitive analyses (Sterman, 2000; Jin et al., 2016). For example, the impact of error on schedule and corresponding strategies can be simulated through the stock-flow diagram in Fig. 4.

3 Research method

3.1 Article selection

The review methods of previous research (Yuan and Shen, 2011; Li et al., 2014a; Xiong et al., 2015a; Zheng et al., 2016) provide valuable guidance in the selection of target academic articles. Xiong et al. (2015a) stated that construction research can be viewed as a combination of multiple disciplines involving technical and managerial topics. Therefore, selecting target academic articles from only one academic database for providing a comprehensive search of SD application in construction management is insufficient. For example, *Automation in Construction* (*AC*), *Journal of Cleaner Production* (*JCP*), and *European Journal of Operational Research* (*EJOR*) are published by Elsevier and cannot be found in the American Society of Civil Engineers (ASCE) library, Taylor & Francis, and Emerald. Web of Science, as a scientific citation indexing service platform, provides access to multiple academic databases. For example, *AC* from Elsevier, *Journal of Construction Engineering and Management* (*JCEM*) from the ASCE library, and *Engineering, Construction and Architectural Management* (*ECAM*) from Emerald can be found in Web of Science. Therefore, Web of Science is used in the first step. Note that Wing (1997) listed five leading journals (including *JCEM*, *International Journal of Project Management* (*IJPM*), *Construction Management and Economics* (*CME*), *ECAM*, and *Journal of Management in Engineering* (*JME*)), which have been widely accepted by researchers in the field of construction management. However, *CME* is not included in Web of Science. Therefore, all the SD-related articles in the construction management field from *CME* are collected in the second step.

In the first step, we set the search theme and retrieve articles according to "system dynamics" and "construction project", and 251 articles are collected. Each of these records is examined to identify whether SD is used as the main method, the problems targeted are related to construction management, and articles are from a peer-reviewed journal (Xiong et al., 2015a). Finally, 96 articles remain. In the second step, the same search method is used via Taylor & Francis, and 9 articles published in *CME* are collected.

3.2 Article classification

SD-related articles in construction management have witnessed a sustainable increase over the past two decades. The research domain is also diverse, from sustainable construction to safety management. To identify all topics from the collected articles, a qualitative data analysis software named NVivo is applied. All collected articles are treated as "sources" and imported into NVivo. The "node" function in the software is then used to analyze sources. References with similar topics are categorized into the corresponding node, which is called "coding" (Li et al., 2014b). Take the article entitled *A prototype system dynamic model for assessing the sustainability of construction projects* as an example, we can generate a node named "sustainable construction" for the article. Note that initial codes may be iteratively revised and refined throughout the coding process (Li et al., 2014b). To ensure the reliability and validity of the result, several rounds of "coding" should be conducted.

4 Results and discussion

4.1 Number of publications

The number of SD-related articles published annually from