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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

## 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

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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

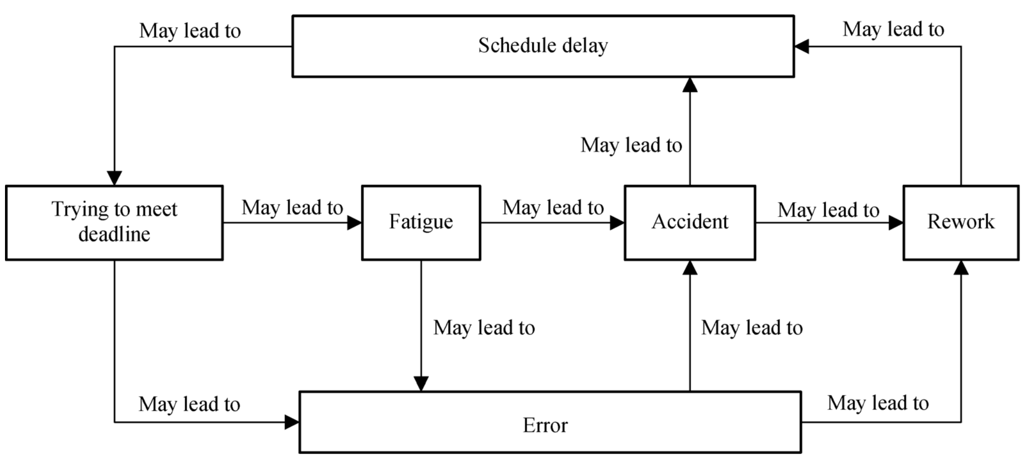



**Fig. 1** Schematic illustration of complex interactions between fatigue and schedule delay in a construction project.

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).

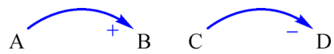



**Fig. 2** Schematic of causal loop.

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).

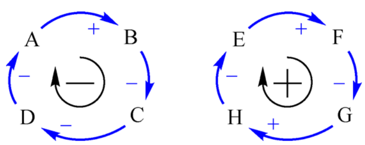
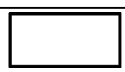
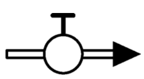
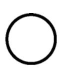
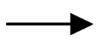



**Fig. 3** Schematic of feedback loop.

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) |

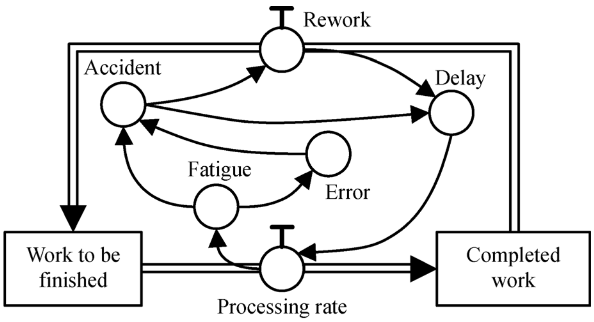



**Fig. 4** Sample stock-flow diagram.

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

1994 to 2018 is presented in Fig. 5. By statistical analysis, we can attain the matching linear coefficient and *p*-value (coefficient = 0.48, standard error = 0.052, *t*-value = 7.158, *p*-value = $4.67\times10^{-7}$), which indicates a strong relationship between the number of articles and time of publication. Although the absolute quantity of articles is small, it demonstrates an increasing trend, from 1 in 1994 to a maximum of 13 in 2016. This trend indicates the increasing amount of attention the SD in the construction management field received from researchers. Interestingly, a slow growth trend occurred in the first decade 1994–2004, where only one article was published annually, except in 2001. Since 2005, SD has gradually been valued by construction management-related researchers and plays an important role in construction management.

As presented in Table 2, *JCEM*, *IJPM*, and *JME* published the highest number of SD-related articles in the construction management field from 1994 to 2018. *JCEM* published 15 SD-related articles, followed by *IJPM* (11), *JME* (10), *CME* (9), *JCP* (7), and *ECAM* (6). The remaining journals have five or less related articles, with a large number of journals published only one article in the past 25 years. Among all the journals listed in Table 2, SD-related articles published by *JCEM*, *IJPM*, *JME*, and *CME* account for roughly 43%.

### 4.2 Key journals, papers, and their contributions

The top 10 articles sorted by the number of citations per year according to Google Scholar are listed in Table 3. As shown, *IJPM* and *WM* published most of these articles. Although *WM* published only three SD-related articles, two of them are the most cited articles.

As presented in Table 3, several of the most frequently cited papers are related to waste management, construction change, and rework. Specifically, Yuan et al. (2012) proposed an SD model for simulating effects of different waste management strategies on construction and demolition waste reduction. As mentioned in this study, most previous studies usually overlook the interdependent and dynamic natures of the whole waste reduction system. The research provided innovation and contribution in the form of a new perspective for waste management from research methodology. Similarly, Yuan et al. (2011) developed an SD model that can serve as a platform for cost–benefit analysis of waste management. Moreover, SD was applied to analyze difficult-to-quantify social impact issues in waste management (Yuan, 2012).

The articles related to construction change and rework ranked third, seventh, eighth, and tenth. Love et al. (2002) employed an SD model to describe how construction change and rework can impact the project management system. This study was also the first to quantitatively analyze project management with SD. In addition, this research highlighted the importance of identifying project dynamics. Love et al. (2008) presented a forensic management approach on the basis of SD. The SD model developed in their study can determine how and why rework occurs. Motawa et al. (2007), on the other hand, integrated a fuzzy logic-based change prediction model with the SD model. They demonstrated the possibility of combining SD with other research methods. Love et al. (1999) first investigated construction rework on the basis of SD. This study highlighted the causal structure of rework influences. However, this research had explored the relationship among factors affecting project management on the basis of quantitative analysis. Therefore, the most effective rework prevention strategies cannot be identified.

The remaining three articles ranked second, sixth, and ninth. Zhang et al. (2014) developed an improved SD model for the assessment of construction project sustainability. Technological advancement and changes in the public perceptions are considered in the SD model. However, they did not consider the uncertainty of variables in the model. Rodrigues and Bowers (1996) first introduced SD in project management. They mentioned that each element of project is assumed to be isolated, and

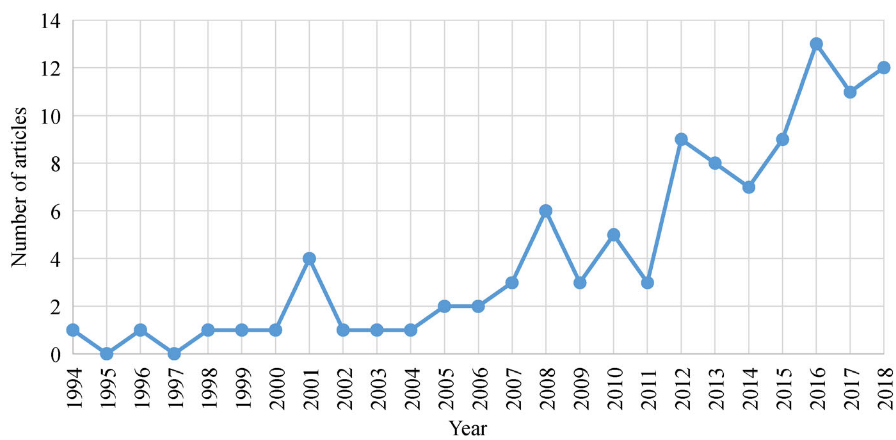



**Fig. 5** Number of SD-based construction management articles published annually from 1994 to 2018.

**Table 2** Number of SD-related articles in the construction management field published in different journals from 1994 to 2018

| Journals | Number |
|---|---|
| *JCEM* | 15 |
| *IJPM* | 11 |
| *JME* | 10 |
| *CME* | 9 |
| *JCP* | 7 |
| *ECAM* | 6 |
| *AC* | 5 |
| *Journal of Computing in Civil Engineering* | 5 |
| *Resources Conservation and Recycling* (*RCR*) | 4 |
| *International Journal of Civil Engineering* | 4 |
| *Safety Science* | 4 |
| *Accident Analysis and Prevention* | 3 |
| *Waste Management* (*WM*) | 3 |
| *Canadian Journal of Civil Engineering* | 2 |
| *Mathematical and Computer Modeling* | 2 |
| *Building and Environment* | 1 |
| *Computer-Aided Civil and Infrastructure Engineering* | 1 |
| *EJOR* | 1 |
| *IEEE Transactions on Engineering Management* | 1 |
| *Interfaces* | 1 |
| *Journal of Civil Engineering and Management* | 1 |
| *Journal of Enterprise Information Management* | 1 |
| *Journal of Environmental Engineering and Landscape Management* | 1 |
| *Journal of Industrial Engineering and Management* | 1 |
| *Journal of Operations Management* | 1 |
| *Journal of Professional Issues in Engineering Education and Practice* | 1 |
| *KSCE Journal of Civil Engineering* | 1 |
| *Production Planning & Control* | 1 |
| *Scientia Iranica* | 1 |
| *Technics Technologies Education Management* (*TTEM*) | 1 |
| Total | 105 |

this assumption made the model distant from the actual project. This study provided an overview of the project management areas that SD can be applied to. Lee et al. (2006b) combined SD model with network-based tools for the dynamic planning and control of construction project. They believed that SD holds the strength in strategic project management, rather than operational project management. Therefore, combining SD with other operational project management methods is necessary for effective project management. Under the guidance of this article, an increasing number of scholars have initiated investigating hybrid modeling.

### 4.3 Critical steps and issues when applying SD

#### 4.3.1 Model boundary

The initial step in SD modeling is defining a clear model boundary. Factor or variable identification is the main method for researchers to do so. Factors or variables can be divided into three categories, namely, endogenous, exogenous, and ignored (Ogunlana et al., 2003). Endogenous variables (or factors) are determined by the SD model, whereas exogenous variables (or factors) are determined by the factors outside the SD model. Ignored variables (or factors) can affect the SD model but are not considered according to research aims. Explicitly defining endogenous, exogenous, and ignored variables is important. If the three kinds of variables are confused with one another, SD may fail in achieving the research aims (Sterman, 2000). Literature review, workshop, interview, and specific process are the four methods for researchers to define variables, which are often combined or merged simultaneously.

Statistically, 95 of the 105 reviewed articles have utilized literature review for identifying variables. A total of 23 articles have identified variables on the basis of specific process, 20 articles have conducted interview, and three articles have used workshop. Note that 16 of the 105 articles (15.24%) failed to mention variable identification but directly presented CLD or stock-flow diagram. Although these articles may consider variable identification in model development, they cannot prove that the SD model contains all the important variables. Researchers should elaborate on variable selection for readers to fully understand the model boundary.

#### 4.3.2 Model development

In the construction management field, studies using SD have two kinds. One is qualitative analysis, and only CLD is used in this kind of research. For example, Love et al. (1999) used a CLD to determine the causal structure of rework influence. The other is quantitative analysis, which needs data for simulation. 97 of the 105 reviewed articles are quantitative analysis, indicating SD-based research with quantitative analysis is the focus in the construction management field. Regardless of whether the study is a qualitative or quantitative analysis, the CLD should be presented to illustrate the feedback structure of the system. However, 25 of the 105 reviewed articles (23.81%) failed to present the CLD. The most important thing in developing CLD is depicting the interrelations among identified variables. Literature review is the most popular method for studies to develop CLD (42 articles), followed by specific process (23 articles), interview (20 articles), and workshop (3 articles).

In most cases, only one method was applied to develop

**Table 3** Most-frequently cited papers

| Ranking | Author (year) | Journal | Document title |
|---|---|---|---|
| 1 | Yuan et al. (2012) | *WM* | A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste |
| 2 | Zhang et al. (2014) | *IJPM* | A prototype system dynamic model for assessing the sustainability of construction projects |
| 3 | Love et al. (2002) | *IJPM* | Using systems dynamics to better understand change and rework in construction project management systems |
| 4 | Yuan et al. (2011) | *RCR* | A model for cost-benefit analysis of construction and demolition waste management throughout the waste chain |
| 5 | Yuan (2012) | *WM* | A model for evaluating the social performance of construction waste management |
| 6 | Rodrigues and Bowers (1996) | *IJPM* | The role of system dynamics in project management |
| 7 | Motawa et al. (2007) | *AC* | An integrated system for change management in construction |
| 8 | Love et al. (1999) | *CME* | Determining the causal structure of rework influences in construction |
| 9 | Lee et al. (2006b) | *AC* | Dynamic planning and control methodology for strategic and operational construction project management |
| 10 | Love et al. (2008) | *TTEM* | Forensic project management: An exploratory examination of the causal behavior of design-induced rework |

CLD. However, complete information cannot be attained by a single method (Sterman, 2000). Future research should draw CLD by using multi-methods. In the process of constructing CLD, researchers must apprehend a clear distinction between causality and correlativity. For instance, although the sales of ice cream and the murder rate are positively correlated, a causal chain from the sales of ice cream to the murder rate cannot be contained in the SD model because temperature leads to correlativity, as shown in Fig. 6. Researchers should ensure that correlativity is non-existent in CLD.

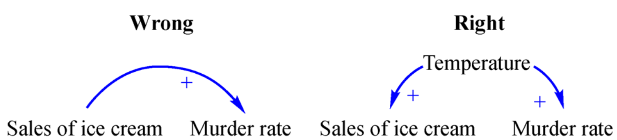



**Fig. 6** Causality and correlativity (Sterman, 2000).

Having defined CLD (structure of system), forming a stock-flow diagram is essential for the SD model to function on computers. Moreover, CLD and the stock-flow diagram are two different versions of the same model (Yuan, 2012). The difference is that the former is constructed in the hope of further understanding the structure of system, while the latter is in equations and computer code, which allows model simulation and quantitative analysis (Coyle, 1996). Therefore, equations and data are the core of a stock-flow diagram. The process of writing equations allows researchers to recognize vague concepts and contradictions that are not considered or discussed in CLD (Sterman, 2000). If researchers possess a deep understanding of the system boundary and the relationships among variables, constructing equations can be effortless. Compared with writing equations, collecting data for the SD model is difficult.

SD models in construction management have two kinds of variables. One is "hard" variable that is available as numerical data (Lee, 2017). The other one is "soft" variable that is descriptive, impressionistic, and has never been recorded (Sterman, 2000; Lee, 2017), such as "effectiveness of regulation execution", "safety awareness", "safety behavior", and so on. For "hard" variables, data can be collected from the real world, such as real projects. In articles conducting quantitative analysis, 95.88% (93 of 97) of studies have collected data from real projects. For "soft" variables, several methods have been used, including interview (85 of 97), questionnaire (9 of 97), on-site visit (11 of 97), and workshop (5 of 97). Given that "soft" variables are difficult to quantify, certain researchers suggest that a Likert-type scale structure can be applied for evaluating the performance of "soft" variables (Yuan et al., 2012; Wang et al., 2015). Evidently, no matter what method is applied, data reliability must be guaranteed. At the present stage, triangulated data sources can be a useful method to increase data reliability (Barratt et al., 2011).

#### 4.3.3 Model testing

According to strict testing standard, an SD model must pass both the model structure and behavior tests. However, certain previous studies focused only on behavior test and ignore the model structure test. Note that the model structure and behavior tests are equally important. The consistency test of model and real system behaviors becomes meaningful only when the confidence of the model structure is established.

Structure tests include direct structure tests and structure-oriented tests. Direct structure tests assess the validity of the model structure by comparing with knowledge on real system structure (Barlas, 1996), whereas structure-oriented tests assess the validity of the model structure by applying behavior tests on model-generated behavior patterns (Senge and Forrester, 1980). Direct structure tests contain structure-confirmation, parameter-confirmation, boundary adequacy, and dimensional consistency tests. The structure-confirmation test compares the causality and feedback of the model with the relationships that exist in the real system (Senge and Forrester, 1980). The parameter-confirmation test indicates the evaluation of the constant parameters against the knowledge of the real system in terms of conceptual and numerical confirmations (Senge and Forrester, 1980). Conceptual confirmation requires the model parameters to correspond with the elements in the real system, whereas numerical confirmation requires the sufficient accuracy of model parameters. The boundary adequacy test verifies whether the model contains all the important variables that affect the research objectives (Sterman, 2000). The dimensional consistency test verifies the right- and left-hand sides of each equation for dimensional consistency (Barlas, 1996).

Structure-oriented tests mainly include three tests. The first is the extreme-condition test, which compares the model-generated behavior with the anticipated behavior of the real system under several extreme conditions (Barlas, 1996; Balci, 1994). The second is the integral error test, which verifies whether the model behavior can change with the change in integration step (Sterman, 2000). The third is the behavior sensitivity test, which identifies the variables to which the model is sensitive by observing the change in model behavior through changing the variables in a reasonable range (Barlas, 1996). A sensitive variable must be highly accurate because its change can have an assignable effect on schedule.

Model behavior tests can then be conducted to measure how accurately the model can reproduce the behavior exhibited by the real system (Barlas, 1996). Numerous methods are used to measure the accuracy of model behavior, including $R$-square, mean absolute difference, mean absolute percentage error, mean square error, and Theil disequilibrium index. Analyzing the difference between model and real system behaviors is more crucial informing readers how accurate the SD model is.

By statistical analysis, the information of the model tests presented in the 97 articles conducting quantitative analysis is presented in Table 4. As shown, considerable existing research has not paid sufficient attention toward structure tests, especially toward integral error test. Due to the lack of historical data, 33 articles failed to conduct behavior test. To validate the SD model, these articles used expertise and literature to support the model. Note that the model test is a continuous process (Sterman, 2000). Researchers should constantly test the SD model to avoid considerable mistakes.

**Table 4** Issues related to SD model test

| Tested item | Number | Percentage (of 97) |
|---|---|---|
| Structure-confirmation test | 50 | 51.55% |
| Parameter-confirmation test | 45 | 46.39% |
| Boundary adequacy test | 47 | 48.45% |
| Dimensional consistency test | 44 | 45.36% |
| Extreme-condition test | 43 | 44.33% |
| Integral error test | 32 | 32.99% |
| Behavior sensitivity test | 44 | 45.36% |
| Behavior test | 64 | 65.98% |

#### 4.3.4 Model simulation

Once researchers have built confidence in the model structure and behavior, the SD model can be utilized to conduct a simulation. Under normal circumstances, SD model simulation is mainly used for designing and evaluating improvement policies and strategies. Among the reviewed articles, 53.61% (52 of 97) focus on policies and strategies simulation. Others concentrate on modeling dynamic performance of the real system (16.49%) and impact analysis (29.90%), which are the basis of policy and strategy simulation. Among the articles conducting such simulations, three articles are related to the structural adjustment of the SD model and six articles consider the combined effects of different policies and strategies. Sterman (2000) stated that policy and strategy designs do not only change model parameters but also create new model structures. In addition, interactions among different policies and strategies should be considered because the impact of comprehensive policies and strategies is not equal to the simple sum of each policy and strategy (Sterman, 2000).

### 4.4 Research topic areas that used SD

On the basis of the outcome of qualitative data analysis, nine topics are identified for the research interests of SD in this paper: (1) sustainable construction (and waste management); (2) design error, rework, and change management; (3) risk management; (4) resource management; (5) decision making, planning, and control; (6) hybrid modeling; (7) safety management; (8) PPP (Public–Private–Partnership) project; and (9) organization performance. The article entitled *The role of system dynamics in project management* is the first paper that systematically expounded the distinctive contribution that SD can provide to project management. This paper is considered critical in construction management and is not included in the nine research topics. The other articles are grouped under different main research topics. Notably, an article may cover more than one research topic. For example, the article entitled *Integrating system dynamics and fuzzy logic modeling for construction risk management* belongs to "risk management" and "hybrid modeling". Under this circumstance, the most suitable topic is selected. Table 5 displays the research topics in SD from the selected articles from 1994 to 2018.

The relationship among the nine research topics is shown in Fig. 7. Topics 2, 3, 4, and 5 belong to "project management", whereas topics 1 and 6 belong to "safety and environment". Note that "project management" and "safety and environment" are not independent of each other. For example, topics 3 and 5 can support topics 1 and 6, respectively. In addition, the research methods and findings of topics 3 and 5 can be applied in topic 9. Topic 8 can also contribute to "project management" and "safety management". As an investigation of research method, topic 7 can provide a new hybrid model for the development of other topics.

### 4.4.1 Sustainable construction (and waste management)

Sustainable construction, involving 20 articles, ranks first among the nine topics. Most research in this area focuses on waste management. As the most important contributor in this field, Yuan et al. (2011) first introduced SD method into construction and demolition waste management. Systematic analysis of construction and demolition waste

**Table 5** Research topics and their trends

| Research topic | 1994–1999 | 2000–2005 | 2006–2011 | 2012–2018 | Total |
|---|---|---|---|---|---|
| Sustainable construction (and waste management) | 0 | 0 | 2 | 18 | 20 |
| Design error, rework, and change management | 1 | 3 | 4 | 7 | 15 |
| Risk management | 0 | 0 | 4 | 10 | 14 |
| Resource management | 2 | 1 | 3 | 8 | 14 |
| Decision making, planning, and control | 0 | 3 | 6 | 5 | 14 |
| Hybrid modeling | 0 | 0 | 3 | 8 | 11 |
| Safety management | 0 | 1 | 0 | 8 | 9 |
| PPP project | 0 | 0 | 0 | 4 | 4 |
| Organization performance | 0 | 2 | 0 | 1 | 3 |
| Total | 3 | 10 | 22 | 69 | 104 |

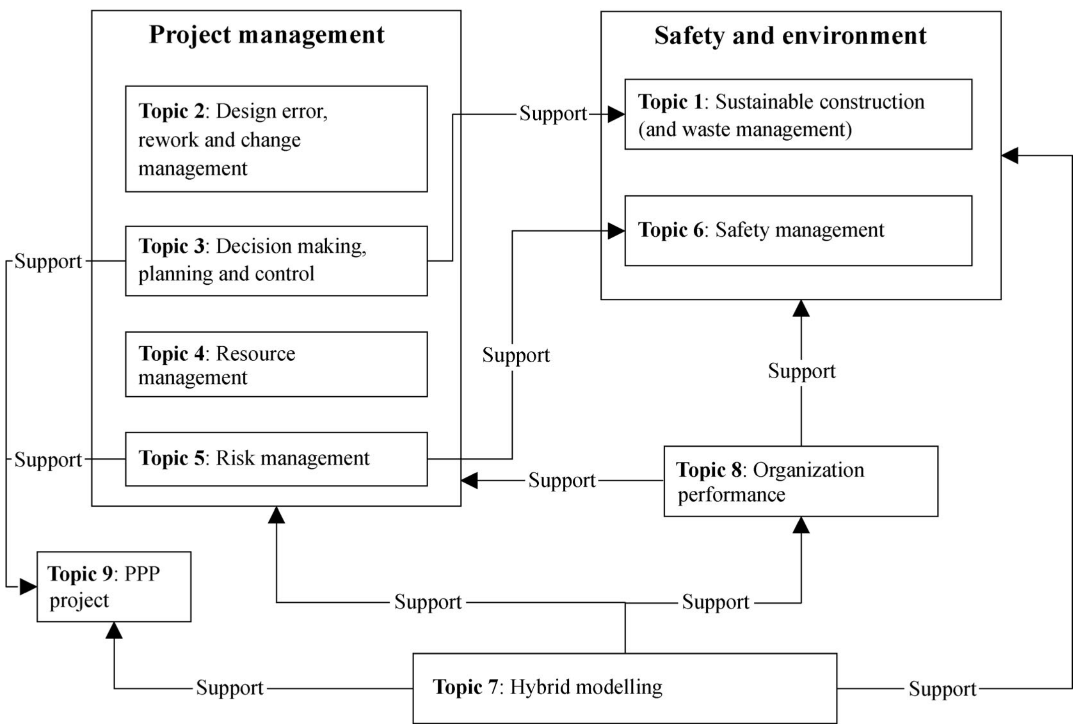



**Fig. 7** Relationship among research topics.

management was conducted from four aspects by using SD model, namely, cost-benefit (Yuan et al., 2011), social performance (Yuan, 2012), environmental performance (Ye et al., 2012), and disposal charging fee (Yuan and Wang, 2014). Inspired by Yuan’s research, Wang et al. (2015) proposed an SD model for quantitatively assessing the effect of different strategies and policies at the design stage on waste reduction. Li et al. (2014a) also developed an SD model for measuring the impact of prefabrication on construction waste reduction. Another sub-topic is sustainability assessment. SD is confirmed as an effective simulation method for modeling and analyzing complex, dynamic, and nonlinear systems and is suitable to simulate the assessment process of sustainable performance (Zhang et al., 2014). Therefore, the SD model is developed for assessing the sustainability of construction projects (Onat et al., 2014; Zhang et al., 2014) and construction method selection with sustainability considerations (Ozcan-Deniz and Zhu, 2016).

#### 4.4.2 Design error, rework, and change management

Iterative cycle caused by error and change is often the main reason for construction projects to be uncertain and complex in nature (Lee et al., 2006a). In addition, errors that occurred during the design process always lead to rework (Love et al., 1999). Therefore, design error, rework, and change are closely related. Research in this area began with the exploration for determining the causal structure of rework influences in construction (Love et al., 1999). From 2000 to 2005, Love et al. (2002) described how changes can impact the project management system by introducing SD, and Lee et al. (2005) focused on quality and change management for large scale concurrent design and construction projects. From 2006 to 2011, researchers began to integrate SD with other methods for error and change management. Motawa et al. (2007) presented a change management system integrating a fuzzy logic-basic change prediction model with SD to simulate the iterative cycle of concurrent design and construction resulting from unanticipated changes and their subsequent impacts. Lee et al. (2006b) developed dynamic planning and control methodology by integrating several existing methods around a core SD model for quality and change management. From 2012 to 2018, additional quantitative and sensitivity analyses were conducted for design error, rework, and change management by using SD models (Han et al., 2012; 2013; Li and Taylor, 2014; Parvan et al., 2015).

#### 4.4.3 Risk management

Risk management, divided into risk identification, analysis, evaluation, and treatment (Zou et al., 2007), has been in the central arena of construction management for decades (Choudhry et al., 2014). Perrenoud et al. (2016) stated that risks in different project stages vary and are dynamic. In addition, different risks can be interrelated through causal loops (Fang and Marle, 2012). Therefore, considering dynamic interactions among project risks when conducting risk management is imperative (Wang and Yuan, 2016). Considering the characteristics of SD, the method is mainly used for risk analysis and treatment. Nasirzadeh et al. (2008) presented an SD approach toward construction risk analysis. Subsequently, researchers in the field of project risk management have begun paying attention to SD. From 2012 to 2018, SD rapidly evolved in the risk management field and has become a powerful tool to response to risks. For example, Nasirzadeh et al. (2016) presented an SD-based approach for quantitative risk allocation; and Wang et al. (2016) combined SD, BBN, and smooth relevance vector machines to model tunnel construction risk dynamics for addressing the production versus protection problem.

#### 4.4.4 Resource management

The topic “resource management” has been receiving steady interest from scholars since 1994, indicating that SD is suitable for resource management. Resource in construction can be divided into two categories, namely, material and nonmaterial resource. Material resource include materials, machinery, and energy. Park (2005) pointed out that excess idling and low coverage of material resource can have impact on the achievement of project objectives. Therefore, SD model is mainly used to systematically manage material resource for ensuring project delivery in time and within budget in early studies (Park, 2005; Prasertrungruang and Hadikusumo, 2008; Feng and Hsieh, 2009; Cui et al., 2010). With the development of technology, the level of material resource management gradually increases, and research focuses gradually turn to nonmaterial resource management. Nonmaterial resource mainly include information, productivity, knowledge, and experience. From 2012 to 2018, Chen and Fong (2013) visualized the evolution of knowledge management capability with the help of SD, Nasirzadeh and Nojedehi (2013) presented an SD-based approach to model labor productivity, and Khan et al. (2016) used SD to improve the complexity management of information flow.

#### 4.4.5 Decision making, planning, and control

Decision making, planning, and control is a kind of SD-based topic that emerged in 2001. This topic contains macro and micro levels. At the macro level, the constructor’s bidding behavior and equilibrium price level in the construction market (Lo et al., 2007), strategies for design-build (Park et al., 2009), problematic behavior of construction activity (Mbiti et al., 2011), and production process inefficiencies in building service projects (Wan et al., 2013) are analyzed from a dynamic perspective. At the micro level, dynamic planning, decision making, and control methodology for building design, construction, and operation are presented (Peña-Mora and Li, 2001; Peña-Mora and Park, 2001; Lee et al., 2006b).

#### 4.4.6 Hybrid modeling

Hybrid modeling has been a new area of SD research since 2008. Researchers gradually realize that certain problems cannot be solved with SD. For example, Xu et al. (2018) pointed that although SD can provide the construction management with an edge in strategic management, SD cannot reflect the physical specifications of the construction process. Ding et al. (2018) believed that SD is a top-down approach and is usually employed to analyze problems at the macro level, rather than at the micro level. Therefore, SD is combined with discrete event simulation (DES) (Lee et al., 2009; Xu et al., 2018), ABM (Ding et al., 2018), fuzzy logic modeling (FLM) (Khanzadi et al., 2012), and differential-algebraic equations (DAE) (Shadpour et al., 2015).

#### 4.4.7 Safety management

No other research on safety management immediately followed that of Williams (2000) who quantified the effects of safety regulation changes. Nevertheless, two related papers were published in 2014, indicating that scholars have started recognizing the value of SD in safety management again. Previous studies indicate that an increasing awareness exists — the current safety management methods are becoming ineffective due to the complex nature of the safety system (Leveson et al., 2009; Ibrahim Shire et al., 2018). Ibrahim Shire et al. (2018) believed that various aspects of a complex system, such as the dynamic behavior and structural system properties, cannot be understood through traditional methods but can be studied with SD. Currently, the topic embraces three directions, namely, construction workers' safety behavior (Guo et al., 2015), their safety attitude (Shin et al., 2014), and the impact of production pressure on safety performance (Han et al., 2014).

#### 4.4.8 PPP project

With the rise of PPP construction projects, studies related to them have increased in recent years. Most PPP related research focuses on concession period and price because determining appropriate price and period is important to the success of PPP projects (Khanzadi et al., 2012; Xu et al., 2012). The performance of a PPP project can be influenced by various interrelated factors. Having been aware of the feature of PPP projects, Khanzadi et al. (2012) and Xu et al. (2012) developed SD-based model to determine the concession period and price for PPP projects. Xiong et al. (2015b) also explored the SD-based adjustment model to balance stakeholders' satisfaction in PPP projects, thereby broadening the horizon of the SD application in the field of PPP projects.

#### 4.4.9 Organization performance

Organization performance is influenced not only by organization structure that is complex with several interrelated components but also by formal and informal policies that an organization employs (Tang and Ogunlana, 2003). Therefore, considerable research has used SD to explore organization performance. For example, Tang and Ogunlana (2003) used SD to model the dynamic performance of a construction organization, and Ogunlana et al. (2003) used SD approach to explore organization performance enhancement.

### 4.5 Future research directions

To identify future research directions, a great amount of review effort is exerted. The limitations and future trends mentioned in the articles published in the last five years are reviewed. Moreover, the research trends of SD application in other fields (e.g., economic development, rural and urban planning, energy, and industry) are subject to analysis for reference and inspiration. On the basis of the results, three future research directions of SD in construction project management are proposed (Fig. 8), namely, hybrid modeling, uncertainty analysis, and human factor analysis.

Figure 8 presents 12 areas. The three areas with dark grey indicate the current main focuses. The researchers usually use pure SD to simulate the substance (e.g., sustainability, cost, time, and quality) with certain variables. The seven areas with light grey represent the current minor focuses. They contain three directions, namely, hybrid modeling (Direction (I)), uncertainty analysis (Direction (II)), and human factor analysis (Direction (III)). The two areas with white indicate the combination of future directions. For example, the developing hybrid dynamics model with uncertain variables.

#### 4.5.1 Hybrid modeling

The first direction is the hybrid/integration of SD with other methods, such as DES, ABM, building information modeling (BIM), FLM, DAE, BBN, and smooth relevance vector machines. From 2012 to 2018, eight articles are found related to hybrid modeling. These articles account for 8% of the total number of articles we collected,

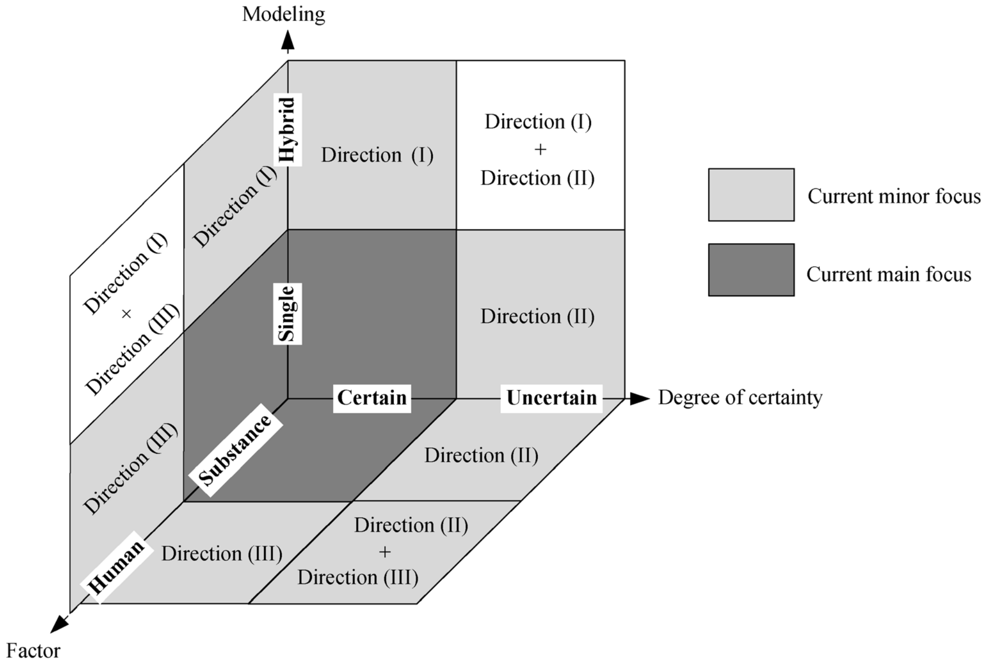



**Fig. 8** Summary of future research directions of SD in construction project management.

indicating that an increasing attention has been paid to hybrid models. SD has the advantage in macro project management. Nonetheless, SD cannot easily reflect microscopic details (Lee, 2017; Xu et al., 2018). Moreover, as researchers began to develop a profound understanding of construction management, numerous studies cannot be conducted only by SD, especially those related to fuzzy logic (Khanzadi et al., 2012). Therefore, researchers point out that certain difficulties in construction management can be solved if SD can be combined with other methods. In the future, researchers must pay attention to the compatibility of SD with other methods. For example, DES is triggered at discrete (fixed, predefined) points in time, whereas SD is triggered as needed (continuous). Therefore, discussing the time step setting and data exchange between SD and DES when using SD-DES models is important.

#### 4.5.2 Uncertainty analysis

The second direction of SD models in construction management is uncertainty analysis. Nowadays, construction projects involve an increasingly complex situation in the management process. This complexity increases the uncertainty of construction management (Wang and Yuan, 2016). Uncertain analysis with SD has become popular in construction management in recent years. However, conducting research is difficult because the data are inadequate for calculating the distribution probability of uncertain variables. With the development of the "Internet of Things" and "big data", a massive amount of construction project data can be attained, processed, and shared (Liang et al., 2016). Data will not be an obstacle to uncertain analysis in SD-related research.

The effects of strategies and policies can be affected by uncertainty, thus proposing strategies or policies without an uncertainty analysis is unrealistic. Many of the reviewed SD papers have mentioned the uncertainties of construction projects, such as the schedule, design error, and sustainability. However, the uncertainty of system behavior under the impact of feedback needs further examination. Thus, future research efforts should be directed to this aspect.

#### 4.5.3 Human factor analysis

SD has been employed in applications related to human factors, especially human behavior, attitude, and perception. As one of the main factors that influence construction performance, researchers heavily focus on human factors (Shin et al., 2014; Guo et al., 2015). Researchers gradually realize the complex feedback structures and influence relationships of human factors, and considerable quantitative research remains to be conducted. As noted by Han et al. (2014), the process by which human factors influence project performance, and to what extent, have not been fully explored. Therefore, this direction deserves additional research focus. In future studies, researchers should clearly define the variables related to human factors and search for the appropriate methods to collect related data.

## 5 Conclusions

SD is increasingly becoming popular in construction management research in the last two decades. The current study ascertains the current body of knowledge, points out the critical steps and issues, and forecasts future research trends and directions in this field by reviewing relevant articles published in major peer-reviewed journals in the past 25 years (1994–2018). A total of 105 articles are collected and analyzed in terms of the number of annually publications, key authors and their contributions, critical aspects of applying SD, topic areas, and future directions.

The results show that SD has received increasing attention from construction management researchers over the past five years. Moreover, several issues exist in SD application, which include model boundary, model development, model test, and model simulation. Nine categories have been identified as research interests, including (1) sustainable construction; (2) design error, rework, and change management; (3) risk management; (4) resource management; (5) decision making, planning, and control; (6) hybrid modeling; (7) safety management; (8) PPP project; and (9) organization performance. Three future research directions, namely, the hybrid and integration of SD with other methods, uncertainty analysis, and human factors analysis, are proposed. This study has certain limitations. As noted by Zheng et al. (2016), the categories of identified articles may be influenced by the subjective judgments of authors to an extent. Furthermore, the number of citations can be a controversial indicator because it can be influenced by the publication year, self-citation, and citation data source. This research does not eliminate all factors that may influence the number of citations. Although limitations exist, the information revealed in this study is valuable to researchers in the construction management field, which could help them understand not only the current status of the research topic areas with SD but also the critical issues and future research directions.

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