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

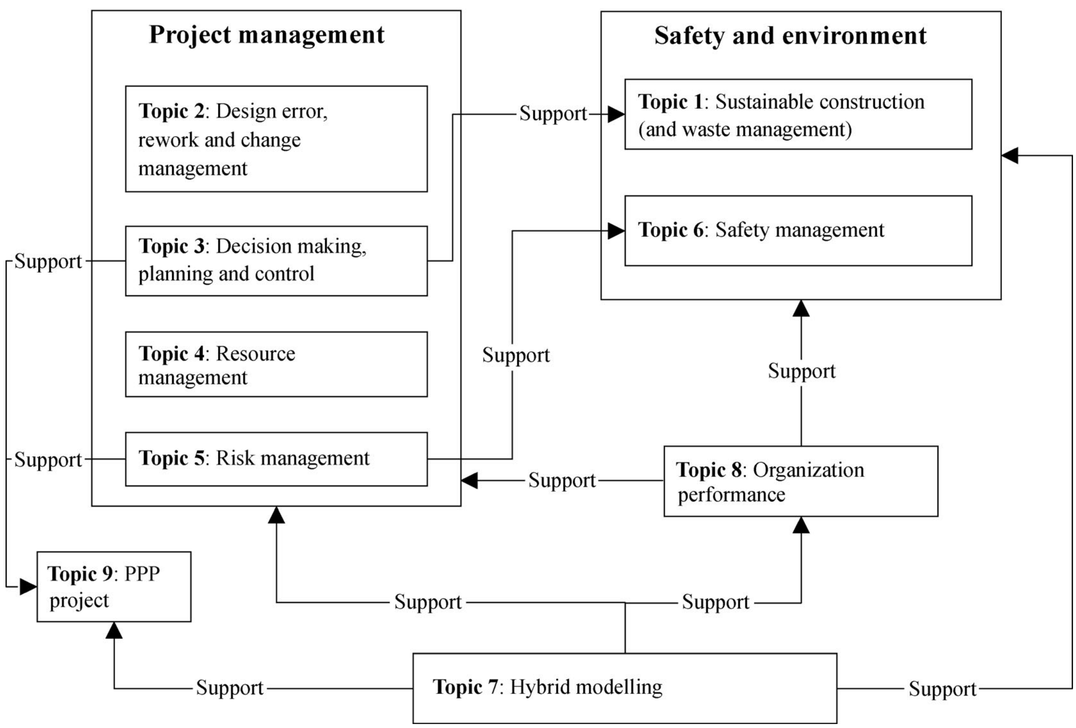

Fig. 7 Relationship among research topics.

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,

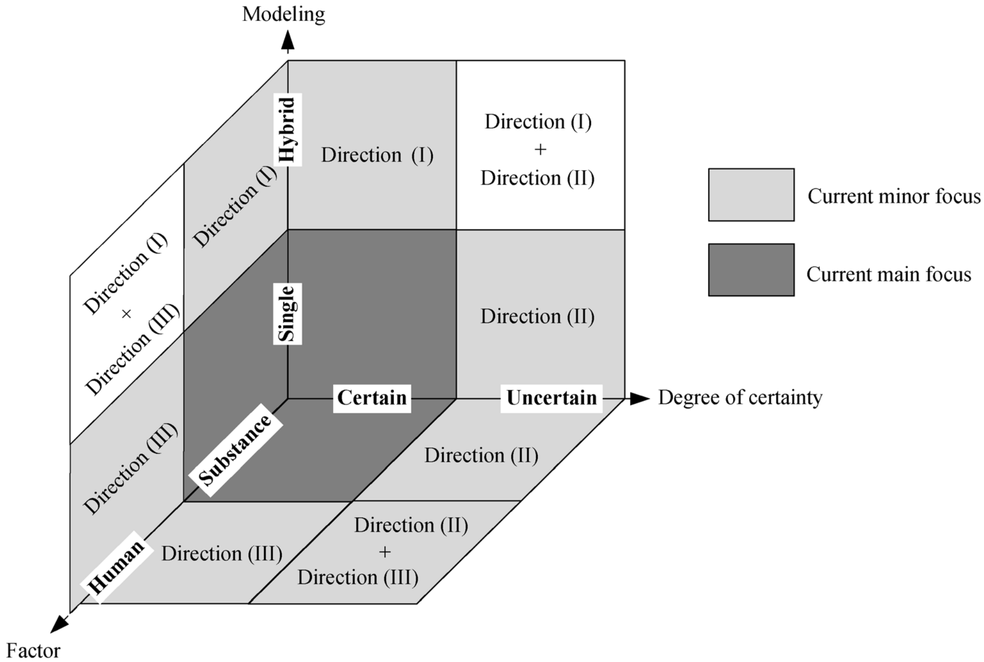

Fig. 8 Summary of future research directions of SD in construction project management.

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