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Analysis of System Dynamics Models in Construction Management Research: Current State and Prospects

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Research Article
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Abstract.

Research in the field of construction management (CM) has made more use of system dynamics modelling (SDM) to delve into intricate causal links across many tiers of the management and construction processes, all brought about by the rising complexity of the construction industry. A comprehensive analysis is required to determine the current status and future directions of SDM applications due to the exponential expansion of the field over the last 20 years. The findings of a systematic review and meta-analysis of 103 articles published in 41 journals from 1997 to 2016 are presented in this study. We begin by organising and formulating the studies' contributions according to publication year, software used, approaches integrated, and study design. First, sustainability; second, project planning and control; third, performance and effectiveness; fourth, strategic management; fifth, site and resource management; sixth, risk analysis and management; seventh, knowledge management; and eighth, organization and stakeholder management are the eight research topics that were identified with the help of a keyword co-occurrence network analysis. These topics involve varying degrees of internal and external complexity. The results show that SDM is crucial for simplifying various complex casual relationships across all eight topics and levels of activity, project, and industry. It also has great potential for revealing how complex contextual conditions affect project planning and control, performance and effectiveness, strategic management, and sustainability. Finally, suggestions for future CM research and trends in SDM applications are presented. This article summarises current research on SDM as it pertains to CM applications, as well as future prospects, helpful references, and insights.

Keywords: system dynamics modeling, construction management, review.

Introduction

In order to better understand the feedback and interaction of elements in construction activities, system dynamics modelling (SDM) has been widely used in construction management (CM) research over the last twenty years. This trend is seen in Figure 2, which will be discussed further. The complexity and process dynamics of construction activities and projects have risen due to ever-changing construction settings and increasing construction scales, which poses a comparable challenge to construction engineering and management (Ogun-lana, Li, & Sukhera, 2003). From a theoretical standpoint, these construction systems may be seen as an intricate web of interconnected parts, with various feedback mechanisms and nonlinear relationships among them. ties (Nasrallah & Zhu, 2016). To better understand feedback processes and the causal linkages between them, as well as to model the relationships in complex building systems, SDM is an invaluable tool. In order to guarantee performance and efficiency in building, such a strategy is crucial.

Looking at the construction system via a systems lens reveals a dynamic behavioural process of on-site progress and resources that must respond to input in order to sustain performance levels that are necessary (Lyneis & Ford, 2007). In particular, SDM excels at handling the behavioural aspects of construction systems and how they interact with the processes involved in building (Rod-rigues & Bowers, 1996). massive project completion. According to Love, Holt, Shen, Li, and Irani (2002), conventional modelling approaches like as work breakdown structures, Gantt charts, PERT/CPM networks, project failure analysis, and trade-off analysis are incapable of achieving this benefit because of their restricted capabilities.

No comprehensive evaluation of SDM's use in CM research has been carried out so far, despite the method's importance in solving construction-related issues and the care required in its proper application. Consequently, this research thoroughly examines SDM's practical uses by means of a rigorous content analysis of articles published in scholarly journals. This research seeks to accomplish the following via an extensive literature review:

(1) calculate the yearly output of SDM research published in top CM journals from 1997 to 2016.
(2) determine the scope of SDM studies addressing various CM complexity problems; (3) investigate SDM's integration with other approaches and the primary study methodology used; and (4) pinpoint potential future uses of SDM in CM.

1. SDM uses in CM studies

By determining the feedback structures and resulting behaviour of a complex system, SDM provides a complete understanding of the system (Ster-man, 2000). Forrester first suggested the technique in 1958 while working at MIT to investigate the workings of industrial systems. A key approach to modelling the behaviour and features of complex systems in terms of internal feedback, SDM has progressed over the last two decades (Sterman, 1992, 2000; Yuan & Wang, 2014). The approach can handle big-picture issues without getting caught up in the nitty-gritty of little ones (Sterman, 2000; Ko & Chung, 2014). Modern enterprises and social organisations are examples of multi-level complex systems (Ko & Chung, 2014).

The combination of systems theory and computer simulation has made SDM an important area in construction engineering and related fields, becoming more popular than quantitative system modelling methods (Lyneis & Ford, 2007; Lee, Han, & Peña-Mora, 2009; Moradi, Na-sirzadeh, & Golkhoo, 2015). Simulating the behaviour of a system's primary outputs across time, it may encompass the technical, organisational, human, and environmental elements involved in dynamic system operations (Lyneis & Ford, 2007). Rapid software development in the last 20 years has allowed SDM to be used more and more in construction engineering fields like gas engineering, transportation engineering, mining engineering, and Yang, Love, Brown, & Spickett (2012).

According to Sternman (2000) and Thomas, Menassa, and Kamat (2016), SDM is well-suited for CM research due to its capacity to analyse complex systems' interrelationships and feedbacks. Problems in systems with complex interactions may be handled using it. processes including dynamic interdependent parts, including flows and stocks, delays in time, nonlinearities, and feedback loop architectures (Terouhid & Ries, 2016). Furthermore, considering the project organization as a complex system, SDM may create interconnected sub-systems that work together to achieve the project's objectives (Love et al., 2002; Sheng & Lin, 2018). Thus, due to the features and structure of the building process, SDM may be extensively used in CM research. Construction project managers can comprehend the effects of changes on the project system as a whole and respond accordingly with the use of SDM modelling (Love et al., 2002). Numerous studies have proposed the incorporation of SDM into contemporary CM research, including studies conducted by Rodrigues & Bowers (1996), Love, Mandal, & Li (1999), Love, Mandal, Smith, & Li (2000), Love et al. (2002), and Nasirzadeh, Afshar, & Khanzadi (2008a).

3. Approach to the study

2.1. Gathering Information

Research in CM draws from a wide range of academic fields to address both technical and management issues (Xiong, Skitmore, & Xia, 2015). Consequently, there has to be a system in place to search all SDM journal publications thoroughly. At the same time, a thorough procedure was required for the identification papers to be chosen as the basis of the investigation.

Xiong et al. (2015), the Scopus database (Ke, Wang, Chan, & Cheung, 2009; Zhang, Chan, Feng, Duan, & Ke, 2016b), and other journals publishing CM articles are part of it, therefore it is employed as a search source in stage 1 to guarantee search comprehensiveness. Review articles, editorials, and papers presented at conferences were not considered for inclusion in this research. The majority of evaluations of CM research rely only on journal articles because of the superior quality and breadth of material they often provide (Zhao, 2017). The search terms "system dynamics" and "construction" were used, using the same procedure as Xiong et al. (2015). The whole set of search parameters is this: (COLUMN (many)) AND DOCTYPE (ar OR re) AND LANGUAGE (english) AND TITLE-ABS-KEY ("system dynamics"). Choose one: ceng, chem, engineering, art, engineering, environmental, math, physics, mult, arts, business, deci, economics, psychology, or sociology.

(date: December 21, 2017).

From 1997 to 2016, 373 prospective SDM publications in CM were found using the aforesaid search. The following criteria was then used to conduct an additional evaluation of these papers: (a) the SDM is a primary research approach and (2) all publications are published in peer-reviewed journals and pertain to CM concerns. A total of 103 articles were ultimately culled as a result of this examination. After a thorough analysis, the results showed that

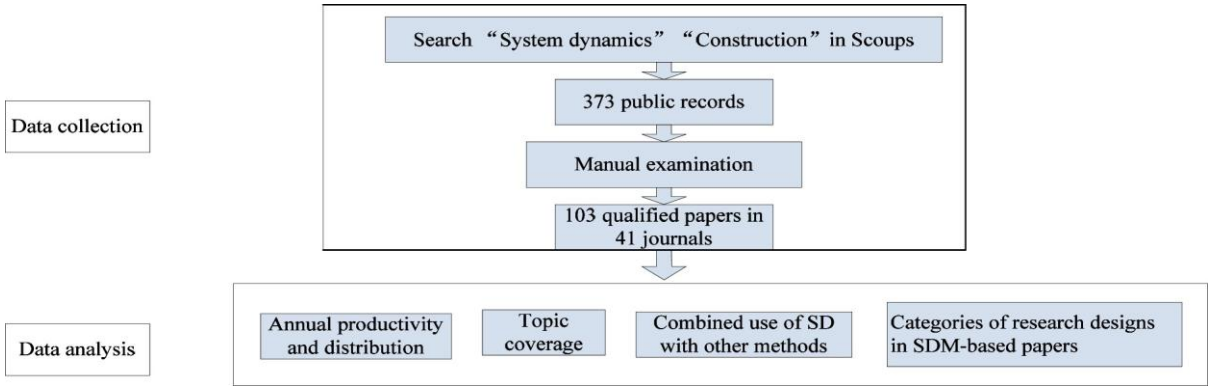


Figure 1. The research process

trends and topic coverage of SDM-based papers to obtain a holistic picture of the SDM applications involved.

1.1. Data analysis

All four goals were addressed by using a mixed research approach. To start, we looked at the overall trend and trends in SDM research from 2007 to 2016 by doing an annual productivity study. Zheng, Le, Chan, Hu, & Li (2016) and Hu, Xia, Skitmore, & Chen (2016) are only a few of the prior evaluations that have often endorsed this approach towards CM difficulties. Secondly, in order to uncover the possible applications of SDM, a topic coverage analysis was conducted to identify the main subjects. Recent reviews have increasingly advocated the use of CiteSpace software, which is one of the most commonly used scientometric techniques, to assist in analysing the papers' keyword co-occurrence network (Hosseini et al., 2018). Other reviews that have supported this approach include Zheng et al., 2016; Zhao, 2017; and Hosseini et al., 2018. A paper's keywords are an expression of its primary ideas and an indicator of the subject matter (Hosseini et al., 2018). Third, we looked at how SDM worked in conjunction with other cutting-edge methodologies; this might be a sign of the current trend toward using SDM in this way to get solid results. Finally, the research designs of the 103 publications that were found were thoroughly examined.
Figure 1 shows the whole method and technique of the study.

2. Discussion of the analysis results

2.1. Annual productivity of the SDM research

Figure 2 shows that the number of journal articles based on SDM has grown since 1997, while it has fluctuated during that time. This trend has been increasingly pronounced over the last decade, demonstrating the SDM's rising profile and widespread use in CM. From 1997 to 2016, the number of articles published each year is shown in Table 1. The vast majority may be found in prestigious CM journals, as the Jour-publication, the International Journal of Project Management, and the Journal of Construction Engineering and Management. Some other prestigious publications that have featured CM studies are System Dynamics Review (SDMR), Accident Analysis and Prevention (AAP), and the European Journal of Operational Research (EJOR). The distribution of articles and the proportion of detected papers in these journals are further shown in Table 1.

2.2. Complexity-related topic coverage

CiteSpace 5.1 R8 was used to visualize the keyword co-oc-currence network as shown in Figure 3. The results involve 104 nodes and 110 edges. The network's density is 0.0211, and thus it is regarded as a sparse network. The node size refers to the frequency of keyword co-occurrence and the edge refers to the two different keywords that together reflect a main theme. The 10 most frequently occurring keywords are "simulation", "project management", "per-formance", "Hong Kong", "waste management", "policy", "feedback", "demolition waste", "rework", and "sustainabil-ity". The high frequency keywords also include the United States and China, which indicates the popularity of SDM in CM research in these countries.

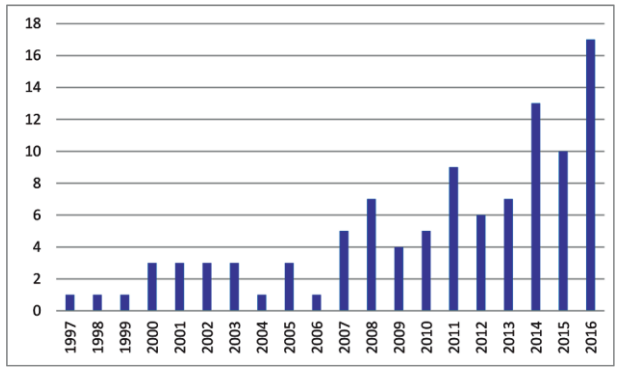


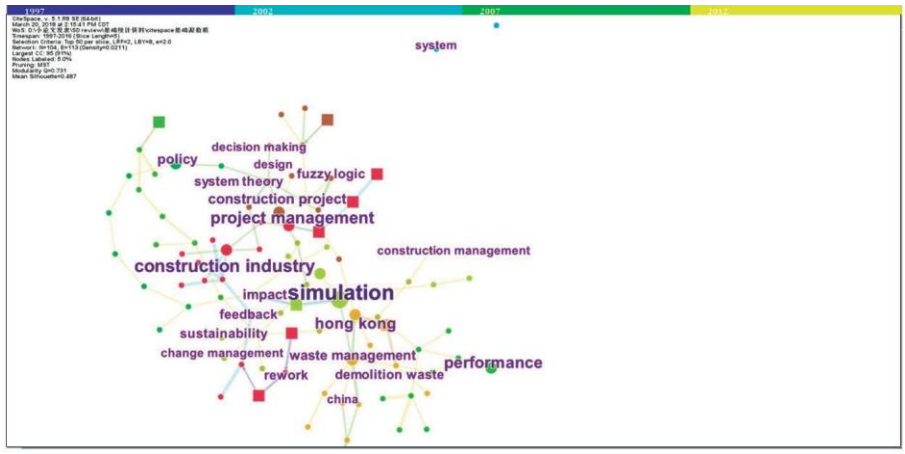
Figure 2. Number of related papers published between 1997 and 2016

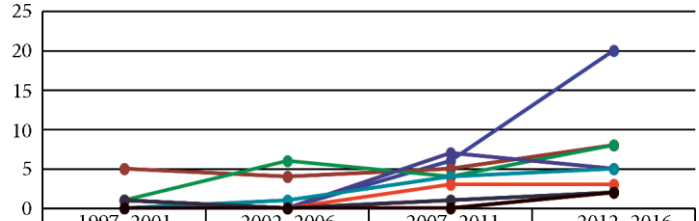
Table 1. Article distribution and percentage of identified papers in significant journals

	1997–2001	2002–2006	2007–2011	2012–2016	Total
JCEM	2	2	6	8	18
Percentage	1.94%	1.94%	5.83%	7.77%	17.48%
CME	2	2	3	1	8
Percentage	1.94%	1.94%	2.91%	0.97%	7.77%
IJPM	1	1	0	4	6
Percentage	0.97%	0.97%	0.00%	3.88%	5.83%
RCR	0	0	2	4	6
Percentage	0.00%	0.00%	1.94%	3.88%	5.83%
CI	0	3	2	0	5
Percentage	0.00%	2.91%	1.94%	0.00%	4.85%
ECAM	1	0	4	0	5
Percentage	0.97%	0.00%	3.88%	0.00%	4.85%
JME	0	0	2	3	5
Percentage	0.00%	0.00%	1.94%	2.91%	4.85%
AIC	0	2	2	0	4
Percentage	0.00%	1.94%	1.94%	0.00%	3.88%
AAP	0	0	0	3	3
Percentage	0.00%	0.00%	0.00%	2.91%	2.91%
CJCE	0	0	1	2	3
Percentage	0.00%	0.00%	0.97%	1.94%	2.91%
JCCE	0	1	1	1	3
Percentage	0.00%	0.97%	0.97%	0.97%	2.91%
WM	0	1	1	1	3
Percentage	0.00%	0.97%	0.97%	0.97%	2.91%
Other journals	3	1	8	22	34
Percentage	2.91%	0.97%	7.77%	21.36%	33.01%

Notes: JCEM – Journal of Construction Engineering and Management; CME – Construction Management and Economics; IJPM – International Journal of Project Management; RCR – Resources, Conservation and Recycling; CI – Construction Innovation; ECAM – Engineering, Construction and Architectural Management; JME – Journal of Management in Engineering; AIC – Automation in Construction; AAP – Accident Analysis and Prevention; CJCE – Canadian Journal of Civil Engineering; JCCE – Journal of Computing in Civil Engineering; WM – Waste Management.

Figure 3. Keyword co-occurrence network





	1997–2001	2002–2006	2007–2011	2012–2016
Sustainability	0	0	6	20
Project planning and control	5	4	5	8
performance and effectiveness	1	6	4	8
strategic management	1	0	7	5
Site and Resource management	0	1	4	5
Risk analysis and management	1	0	3	3
konwledge management	1	0	1	2
Organization and stakeholder management	0	0	0	2

Figure 4. Change in topic coverage over time

We used scientomet-ric technology to analyse each of the publications and determine their primary study subject. When an article covered more than one subject, the most appropriate one was chosen using the co-occurrence network's detected keywords and previous research (Hu, Chan, Le, & Jin, 2015; Zheng et al., 2016). When it comes to managing risk and organisational challenges, SDM is clearly the way to go when dealing with the complexity of CM (Luo, He, Jaselskis, & Xie, 2017). For the definition and categorisation of difficulty, this research used project complexity as a metric. For more information on this issue, read Hu et al. (2015). Additionally, this study evaluated the topic coverage of chosen SDM themes according to project complexity. The eight topics that were identified based on the results of the keyword co-occurrence network analysis are as follows: (1) sustainability; (2) project planning and control; (3) performance and effectiveness; (4) strate-gic management; (5) site and resource management; (6) risk analysis and management; (7) knowledge management; and (8) organization and stakeholder management. From 1997 to 2016, Figure 4 displays the trend in subject coverage across all four time-slices. The findings of the SDM in CM complexity study are shown in Table 2.

Table 2. The eight topics and types of complexity issues

Topics	Complexity	
	Internal	External
Sustainability	12	14
Project Planning and Control	21	1
Performance and Effectiveness	13	6
Strategic Management	6	7
Site and Resource Management	8	2
Risk Analysis and Management	7	0
Knowledge Management	4	0
Organization and Stakeholder Management	2	0
Total	73	30

From 2012 to 2016, there was a considerable rise in the number of articles focusing on sustainability, making it the most researched topic. From 2007 to 2011, trash and demolition management were the primary areas of sustainability, according to the study content analysis. In their analysis of the advantages and disadvantages of construction and demolition waste management, Yuan, Shen, Hao, and Lu (2011) used SDM to simplify internal relationships. From 2012 to 2016, SDM was extended to include carbon emission reduction, nuclear power development, prefabrication, and the interactions between management complexity and macro-policy complexity. It also continued to focus on the internal complexi-ties of waste management from material deterioration, resource availability, waste generation, and recycling (Thomas et al., 2016; Ozcan-Deniz & Zhu, 2016; Yuan & Wang, 2014).

Second most popular is project planning and control, namely topics like change management and cost/schedule control. There has been a fair amount of consistency in the quantity of articles published on this subject throughout all four 5-year intervals. As shown in Table 2, SDM is often used in these research to investigate the intricate connections between internal actions and their feedback in problem-solving (e.g., Sing, Love, Edwards, & Liu, 2016; Parvan, Rahmandad, & Haghani, 2015). Examining the decline in design output due to staff changes, Chapman's (1998) research piloted the use of SDM in this domain. From 1997 to 2001, dynamic planning and construction rework were the primary areas of attention for SDM applications in this field. Using SDM as a foundation, Pena-Mora and Park (2001) and Pena-Mora and Li (2001) created dynamic planning techniques to expedite building construction projects. In contrast, Love et al. (1999) investigated the causes and effects of construction rework. Various applications of SDM have been developed over the years, including web-enabled SDM, early-warning and forecasting systems, cash flow management methods, and decision making from an integrated system. (Love, Edwards, & Irani, 2008) and learning (Motawa, Anumba, Lee, & Peña-Mora, 2007). From 2012 to 2016, SDM was heavily used to tackle novel ideas (like lean manufacturing) and CM problems on a global level. As an example, Ko and Chung (2014) suggested a new SDM-based design process that makes use of lean ideas to streamline design labour, decrease the number of needless design mistakes, and increase the dependability of the design. Macroscopic study of design and construction project schedule delays and cost overruns was conducted using an SDM-based model (Han, Lee, & Pena-Mora, 2012).

According to Moonseo and Peña-Mora (2003), SDM contributes to the optimisation of management plan adjustments and policy making in order to improve project performance in a real-world context, and it is rated third in terms of efficacy and performance, with 19 publications included. Infrastructure maintenance systems are notoriously complicated, with many feedback loops, and the first users of SDM were Chasey, Garza, and Drew (1997). Afterwards, a growing amount of research focused on this issue, particularly studies that examined organisational performance. Using an SDM-based case study of a publicly listed construction company as an example, Tang and Ogunlana (2003a, 2003b) investigated, from the viewpoint of a senior management, how to create and execute improvement strategies to boost organisational performance. In contrast, Ogunlana et al. (2003) used SDM to mimic the efficiency of construction companies by combining engineering procedures with local influencing elements. Project-level performance evaluations also made use of SDM. These included assessments of construction ERP system performance (Tatari, Cas-tro-Lacouture, & Skibniewski, 2008), bidding management effectiveness (Lo, Lin, & Yan, 2007), construction quality management (Nasirzadeh, Khanzadi, Afshar, & Howick, 2013), labour productivity (Nasirzadeh & Nojedehi, 2013), the effect of design rework on project performance (Li & Taylor, 2014), and green innovation effectiveness (Hsueh & Yan, 2013). These studies show that SDM may reduce the effects of internal and external complexity on project and organisational performance.

With thirteen papers, strategic management takes fourth place. Projects in the construction industry are notoriously fluid and unpredictable since they are man-made, goal-oriented open systems. According to Rodri-gues and Bowers (1996), SDM offers a systematic knowledge of the strategic difficulties involved in building projects, which are impacted by subjective human variables.

These elements are disruptive and cannot be exclusively handled by individual experience. The topic's SDM applications may be classified into two levels: macro and micro. Prior research at the macro level has concentrated on value-engineering policies at the government and company levels (Park, Ahn, Lee, & Yoon, 2012), changes to urban-land use policies (Wu, Zhang, & Shen, 2011), design-build industry strategies (Park, Ji, Lee, & Kim, 2009), and strategic-operational CM (Peña-Mora, Han, Lee, & Park, 2008), which aims to probe the external complexities of project management. Analysing internal complexities is the main use of SDM at the micro level. This includes design strategies for construction waste minimisation, managing the consequences of cost overruns and schedule delays, and the complex interactions of construction operations. Consequently, SDM is applicable to this subject on both a macro and micro scale, allowing for the analysis of construction projects' strategic objectives via the integration of external and internal complexity.

With ten papers, site and resource management takes fifth place, a topic that is connected to safety and resource management. In this field, SDM was mostly used for managing dynamic resources (Park, 2005), equipment (Prasertrungruang & Hadikusumo, 2009), construction operations (Lee et al., 2009), and safety (Han, Saba, Lee, Mohamed, & Peña-Mora, 2014). From a systems viewpoint, safety management is especially pertinent to the following topics: an integrated method for safety performance in construction operations (Han et al., 2014), safety attitudes and behaviours of workers (Shin, Lee, Park, Moon, & Han, 2014), and patterns of construction safety behaviour (Guo, Yiu, & González, 2015). In safety management, "systems thinking" is generally acknowledged as a useful method for conceptualising a set of complex aspects and the dynamics between them (Guo et al., 2015). Eight out of ten studies on the subject deal with the ins and outs of construction operations, particularly as they pertain to safety management (see, for example, Guo et al., 2015; Shin et al., 2014; Han et al., 2014).

Among the many useful areas of SDM is risk analysis and management. Many risk analysis treatments, including tunnel construction risk analysis (Wang, Ding, Love, & Edwards, 2016) and risk allo-cation between owners and their contractors (Nasirzadeh, Khanzadi, & Rezaie, 2014), make use of SDM, which is well-suited to analysing complex casual-loop relationships, which are typical of many risk factors. Table 2 shows that the SDM solutions in this area mostly address the aspects of risk associated with internal complexity.

Even though four articles were involved, knowledge management hardly got a passing mention. A learning organization employed SDM in its early days to stand in for both single-loop and double-loop learning (Senge, 1991). Strategic learning in a dynamic environment (Chen & Fong, 2013) and experience transfer in complex learning systems (Lê & Low, 2009) are two examples of the many SDM papers that have focused on knowledge management since the year 2000, particularly when combined with organisational behaviour (Bajracha-rya, Ogunlana, & Bach, 2000).

There are only two papers that use SDM as a basis for discussing organization and stakeholder management. Both delve into intricate internal causal links that pertain to organisational capacities and excellence (Terouhid & Ries, 2016) and employee work-family conflict management (Wu, Duan, Zuo, Yang, & Wen, 2016). Organization Future SDM applications could do well to focus on adaptability, which is defined as the capacity to adjust to changes in the complexity of the surrounding environment (Luo et al., 2017).

According to the previous talks, all eight subjects covered in the SDM articles entail concerns of internal and external complexity. One clear benefit of SDM in dealing with CM complexity difficulties is seen in Table 2. Figure 4 shows that during the four time periods from 1997 to 2016, two subjects remained consistent: project planning and control and performance and effectiveness. Based on these results, it seems that academics in these fields acknowledge SDM's dominating methodological importance. Also, difficulties with site and resource management, knowledge management, project planning and control, performance and effectiveness, organization and stakeholder management, risk analysis and management, and internal complexity in CM were covered in 71% of the 103 publications that were found. When it comes to industrial policy, sustainability, and strategic management, SDM applications center on problems with external complexity.

2.3. Combined use of SDM with other methods

Research has looked at ways to solve the complicated challenges by combining SDM with other methodologies such networks, fuzzy logic, agent-based simulation, and discrete event simulation (DES) (Rodrigues & Williams, 1998).

According to Moonseo and Peña-Mora (2003), one way to make conventional planning tools more versatile and practical is to integrate the core ideas and principles of network-based tools like CPM, PDM, and PERT into the SDM. Among the network-based methods, there are BP neural networks, cognitive mapping, Bayesian belief networks, and the dynamic planning and control technique [Zhang, Schmidt, Xie, & Li, 2016a; Love, Edwards, & Smith, 2016; Wang et al., 2016; Park, 2005; Lee, Peña-Mora, & Park, 2005]. With these technologies, CM's

complicated difficulties may be efficiently solved. Simulation methods, including agent simulation, which may be integrated with SDM, are used to produce the SDM outcome (Peña-Mora et al., 2008; Lee et al., 2009). Other simulation approaches may assist SDM in solving complicated issues using professional software like Vensim. Among these simulation tools, you can find discrete event simulation (DES) (Peña-Mora et al., 2008; Lee et al., 2009; Alvanchi, Lee, & AbouRizk, 2011; Alvanchi, Lee, & AbouRizk, 2012; Moradi et al., 2015; Hwang, Park, H. S. Lee, & S. Lee, 2016), multi-agent decision-making components (Ozcan-Deniz & Zhu, 2016), and agent-based computational economics (ACE) (Yan, 2015).

According to many studies (Nasirzadeh et al., 2008a; Nasirzadeh, Afshar, Khanzadi, & Howick, 2008b; Nasirzadeh et al., 2013, 2014), the conventional deterministic SDM may not be the best choice when trying to represent CM factors due to their imprecision and uncertainty. To make room for the uncertainties, fuzzy logic is sometimes included into the SDM framework, creating a fuzzy-SDM model (Nasirzadeh et al., 2013). In order for the SDM to account for input variable uncertainties, it has been suggested to use interval arithmetic and Za-deh's extension principle (Na-sirzadeh et al., 2014). Given the inherent uncertainty and imprecision of hazards, the fuzzy-SDM model has found extensive use in risk management (Nasirzadeh et al., 2008a, 2008b). Due to the impracticality of directly using acquired data, data processing technologies are often integrated with SDM. Factor analysis (Zhang et al., 2016a), time-series forecasting models, regression approaches, judgement techniques (Sing et al., 2016), and AHP (Perng, Hsia, & Lu, 2007) are some of the methodologies that have been used to construct the raw data needed for the SDM.

Table 3. Categories of research design in SDM-based papers

Topic	Level of analysis		
	Activity	Project	Industry
Sustainability	13	6	7
Project Planning and Control	20	2	0
Performance and Effectiveness	7	6	6
Strategic Management	2	4	7
Site and Resource Management	9	1	0
Risk Analysis and Management	7	0	0
Knowledge Management	4	0	0
Organization and Stakeholder Management	2	0	0
Total	64	19	20

2.4. Categories of research designs of the SDM papers

Identifying complexity factor and its constructs is the basis of SDM applications in CM research. Meanwhile, research process objectives and it's the level of analysis is another research design factor. CM research using SDM faces the following dilemma (Sterman, 1992): if a simple model is built, then it is criticized for ignoring real-world complex relationships; if a complex model is built instead, then it is criticized for being a 'black box' that no one can un-derstand or check it's working. Thus, the model building process, especially research process objectives, depends on the necessity and practicality of the research (Richardson, 1986). Therefore, balancing complex factors (complexity) and practicality (suitable level of analysis) is significant for SDM applications in CM. An in-depth analysis was conducted to evaluate the design of the identified SDM papers in Table 3. This finding shows that most selected SDM papers focus on the activity (62%) and project levels (18.5%).The industry-level papers only involve three top-ics*: sustainability, performance and effectiveness, and stra-tegic management*. These topics do not only need SDM to explore micro-level but also emphasize its macro research objectives. Of the eight topics involved, only *strategic man-agement* is more focused on the industry-level.

Although SDM is a quantitative method for dealing with complex problems in CM, it can also be used to pro-vide an analysis and explanatory framework to explore the complex CM relationships. SDM is used as a qualitative method to explain behavioral logic in CM for 16 of the selected papers (e.g., Park et al., 2012).

Computer simulation is an indispensable part in SDM research and can overcome the limitations of mental mod-els as it: (i) is explicit and their assumptions are open to review; (ii) is able to interrelate many factors simultane-ously; and (iii) can be carried out under controlled con-ditions, allowing analysts to conduct experiments that are not feasible or ethical in the real system (Love et al., 2000). The early computer languages for SDM were SIMPLE and DYNAMO from the 1950s. These languages were trans-formed into software owing to the development of the *Windows* operating system, the most famous software still being *STELLA/iThink, Vensim, Powersim,* and *AnyLogic* from the 1990s. *Vensim* (52 papers, 50.49%) and *iThink* (30 papers, 29.13%) are the most popular in our sample, with *Vensim* being especially widely used because of its friendly interface and ease of use (Wang et al., 2015).

3. Evaluation of current research and future directions

On the basis of the earlier discussions, a dual-dimensional framework involving the types of complexity and unit of analysis is proposed to assess previous SDM research and identify future directions in CM. SDM is commonly used to tackle internal complexity issues in CM at the activity and project levels (Boxes I and III), which are evidenced by the majority of the papers (68/103) as shown in Fig-ure 5. Early SDM applications were in the area of project rework and then spread to other topics, such as project planning and control, site and resource management, risk analysis and management, and knowledge management.

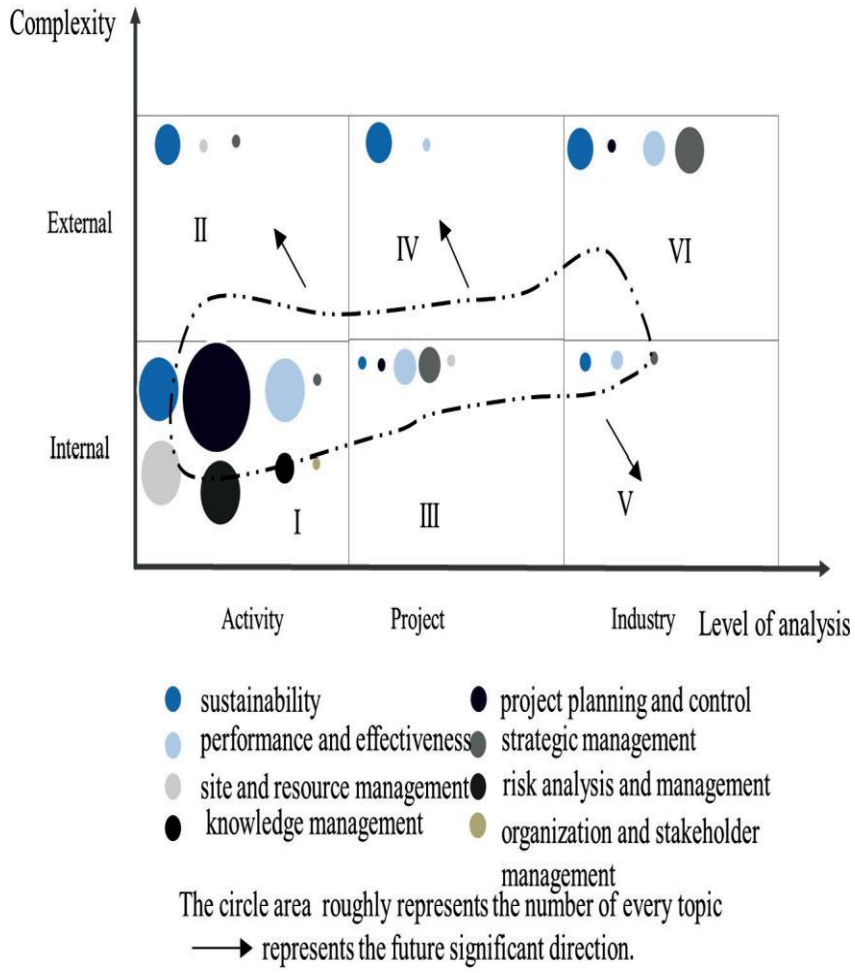
Exploring internal complexity issues at the activity level does not only involves traditional topics (e.g., project planning and control, and performance and effectiveness), but also several emerging topics, such as sustainability, as shown in Box (I). These applications indicate the strong ability of SDM in ascertaining the complicated causal rela-tionships of activities at the micro level.

Boxes (II) and (IV) indicate that another major ap-plication of SDM, as evidenced by 14 papers involved, is in uncovering the impact of contextual complexity (e.g. policy changes, industrial norms, and law requirements) on project activities and arrangements, especially with the topics on project sustainability, performance, and ef-fectiveness (e.g., Onat, Egilmez, & Tatari, 2014; Tam, Li, & Cai, 2014). In particular, SDM has been regarded as a leading method for investigating the impact of external policies on sustainability issues (9/14) (Levitt, 2007). Rec-ognizing the dynamic and changeable nature of built envi-ronments faced by current CM practice, SDM will have a significant potential to make more contributions in these areas.

Box (III) refers to SDM applications exploring internal complexities at the project level, especially those different project types involved, such as infrastructure (Sing et al., 2016), construction (Lee et al., 2009), and power (Ford, 2001). Although the number of papers (13/103) in this do-main is not large, these studies are quite dispersed with five topics involved. This number revealed the ability of SDM to conduct cross-type analysis

Box (VI) refers to the 16 SDM papers that explored ex-ternal complexities at the industry level. Compared with the SDM studies in Box (I), these papers mainly focus on the influence of external factors (e.g., new policies and technology) on the industry (e.g., Zhang et al., 2016a; J. Sim & J. Sim, 2016; X. Guo & X. Guo, 2016; Tang & Ogunlana, 2003a). The number of papers is small. However it can be an important direction due to such rapid changes at the

Figure 5. A dual-dimensional framework for evaluating SDM-based research in CM



at the industrial level, including new technologies (public-private partnerships), procurement regulations, and AI (building information modelling). There are five papers that make up Direction (V), which is all about using SDM to handle internal complexity at the industry level. In particular, these articles examine how environmental regulations affect waste reduction management (Ding, Yi, Tam, & Huang, 2016), the design-build model's effect on strategies (Park et al., 2009), and sustainable building developments (Yan, 2015) as examples of micro construction activities. These results show that SDM can detect the connections and interactions between micro construction activities and environmental factors. In light of the above, SDM has gained widespread acceptance as a tool for simplifying complex casual relationships at the activity, project, and industry levels, as well as for discovering how complex contextual conditions affect project planning and control, performance and effectiveness, strategic management, and sustainability. Future SDM applications will likely focus on these areas because to the growing complexity of the social, economic, and environmental factors affecting building projects, as well as the restricted scope of SDM's current uses.

Conclusions

According to this comprehensive study, SDM has been more and more promoted by scholars over the last 20 years as a means to investigate CM's nonlinear and dynamic complexity problems. Sustainability, project planning and control, performance and effectiveness, strategic management, site and resource management, risk analysis and management, knowledge management, and organization and stakeholder management are the eight themes that emerged from the 103 papers that made up the sample. A mixed-method approach integrating network analysis, fuzzy logics analysis, discrete event simulation, and agent-based simulation is also shown by the review outcomes in various SDM applications. SDM is recognised as a valuable approach for simplifying complex causal relationships across activities, projects, and industries. It also has the potential to reveal how contextual factors impact project planning and control, performance and effectiveness, strategic management, and sustainability. Not only do the results provide a comprehensive overview of SDM's uses in CM, but they also shed light on potential prospects and provide helpful references for researchers interested in exploring SDM's potential future applications in CM.

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