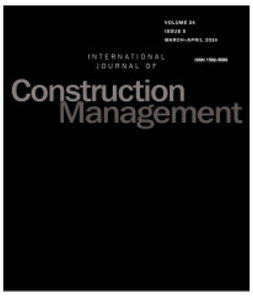

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Xianbo Zhao

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Construction risk management research: intellectual structure and emerging themes

Xianbo Zhao

School of Engineering and Technology, Central Queensland University, Sydney, New South Wales, Australia

ABSTRACT

This study aims to undertake a holistic review of global construction risk management (CRM) research published between 2000 and 2021 and identify the intellectual structure and emerging themes of the CRM research. A total of 2034 primary documents and 68727 secondary documents were collected from Web of Science core collection database. Document co-citation and bibliographic coupling techniques were adopted with qualitative discussion to show the intellectual structure of the CRM knowledge domain and emerging themes. The CRM knowledge domain consists of the key themes relating to CRM steps, RM in construction projects with specified characteristics, RM in international construction and management of particular risk categories. In addition, the emerging themes include advanced risk analysis techniques, information and communication technology-driven CRM, integration of CRM into other management functions, as well as human factors in CRM. This review study is more inclusive than any prior reviews on CRM and provides an in-depth understanding of the CRM research and benefits industry practitioners and researchers.

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Bibliometric analysis; construction; review; risk management

Introduction

According to International Organization for Standardization (ISO 2018), risk refers to 'effect of uncertainty on objectives'. This definition confirmed that risk arises from uncertainty (Hillson and Simon 2007) and is recognized as a double-edged sword causing both threats and opportunities (Loosemore 2006). Risk management (RM) refers to 'coordinated activities to direct and control an organization with regard to risk' (ISO 2018) and has been implemented in various industries, including the construction industry.

The construction industry has been widely recognized as a high-risk industry and requires management of the risks faced by this industry. In most cases, risks are inherent in all the phases of a construction project's life cycle and impact project performance in terms of time, cost, quality, health and safety and environmental sustainability. Also, construction companies, as the entities operating in the construction industry, have to be exposed to the risks that arise outside the projects as well as the risks faced by being a business enterprise (Low et al. 2009).

Construction risk can be seen as the effect of uncertainty on the objectives of an organization in the construction industry, and construction risk management (CRM) can be seen as the coordinated activities to direct and control an organization regarding construction risk. Holding a broad view, CRM encompasses all the RM activities at project, company and industry levels in the context of the construction industry. Researchers have produced increasing publications on CRM since 2000, covering a wide variety of themes. Some studies focussed on identifying and assessing multiple categories of risks in construction projects (Fang et al. 2004; Hwang et al. 2017); some assessed a single category of risks, such as political risk (Chang et al. 2018), safety risk (Sun et al. 2008; Zhang et al. 2014) and schedule risk (Chen et al. 2020; Chen et al. 2021); some attempted to developed novel quantitative risk assessment techniques (Khazaeni et al. 2012; Dehdasht et al. 2017; Islam et al. 2017); and some integrated various information and communication technologies (ICTs) into CRM (Ding et al. 2013; Zhang et al. 2016). The variety of themes is attributed to the fact that risks are diverse and complex and that CRM cannot stand alone and should be integrated into other management functions of an organization. These publications with various focal points have contributed to the CRM knowledge domain in the past decades. However, few studies have holistically reviewed the CRM knowledge domain. Hence, it is worth understanding: (1) *what is the underlying intellectual structure of the CRM knowledge domain?* (2) *what are the emerging themes of CRM research?* To answer the research questions, this study aims to undertake a holistic review of the CRM research published in 2000–2021 through document co-citation and bibliographic coupling analysis to answer the two questions, respectively.

Methodology

This study adopted a bibliometric review method. Figure 1 shows the review process adopted in this study. The key steps of this process are discussed as follows.

Selection of database

The bibliographic data were collected from the Web of Science (WoS) core collection database by Clarivate Analytics. This was because WoS database contains the most important and influential journals (Pouris and Pouris 2011). Scopus is also an

CONTACT Xianbo Zhao b.zhao@cqu.edu.au School of Engineering and Technology, Central Queensland University, Sydney, New South Wales, Australia.

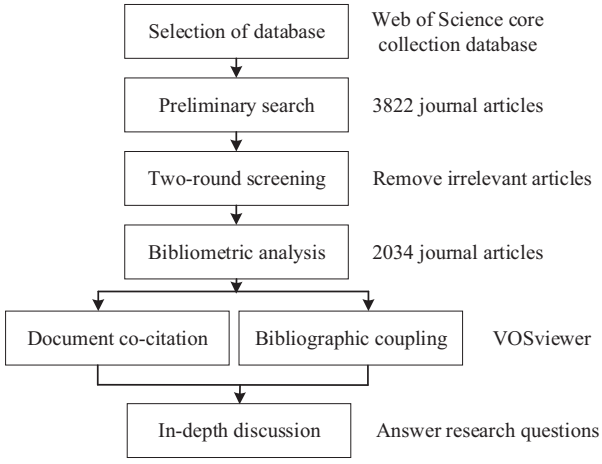

Figure 1. Bibliometric review methodology.

important database for literature review. Most of the journals indexed by WoS are also indexed by Scopus and there are great overlaps between journal articles in these two databases (Gavel and Iselid 2008; Mongeon and Paul-Hus 2016). In addition, the citation information in WoS has been adopted by the Australian Research Council. To ensure the consistency of the citation data, only WoS was used in this study. WoS has also been extensively applied in previous reviews of a similar nature (e.g. Song et al. 2016; Li et al. 2017).

Bibliographic data search and screening

The following search code was used in the WoS advanced search engine:

$$\begin{aligned} &\mathrm{TI} = (\mathrm{risk})\ \mathrm{AND}\ \mathrm{TI} = (\mathrm{construction}\ \mathrm{OR}\ \mathrm{building}\ \mathrm{OR}\ \mathrm{built} \\ &\quad \mathrm{OR}\ \mathrm{engineering}\ \mathrm{OR}\ \mathrm{infrastructure}\ \mathrm{OR}\ \mathrm{architect}*)\ \mathrm{AND}\ \mathrm{TS} \\ &\quad = (\mathrm{manag}*\ \mathrm{OR}\ \mathrm{analy}*\ \mathrm{OR}\ \mathrm{assess}*\ \mathrm{OR}\ \mathrm{mitigat}*\ \mathrm{OR}\ \mathrm{identif}*) \end{aligned}$$

The character '*' denotes a fuzzy search to capture relevant variations of a term. 'TI' and 'TS' represent the title and topic of a publication, respectively. The time span of the search was set as 2000–2021. In addition, only journal articles in English were used in this study, which has been a common practice of most bibliometric reviews (Darko and Chan 2016; Jin et al. 2019).

A preliminary list of 3822 bibliographic records was collected in early January 2022. In the initial screening, the search was refined to the following relevant categories: civil engineering, construction building technology, industrial engineering, management, multidisciplinary engineering, business, architecture, green sustainable science technology, public environmental occupational health, etc. Hence, 2507 bibliographic records were retained. In the second-round screening, the abstracts of the 2507 articles were checked carefully. The articles not relevant to CRM were ruled out. Finally, the search process returned 2034 bibliographic records with 68727 references. It merits attention that the sample of this study was much larger than those in prior reviews, showing the inclusiveness of this review study.

In this study, the term 'document' refers to all types of publications, such as journal articles, books, conference papers and reports. Primary documents are defined as the documents identified from the literature search, namely the 2034 articles retained after two rounds of screening. Secondary documents are the references cited by the primary documents, namely the 68727 documents in the reference lists of the 2034 primary documents.

Bibliometric review

Literature review contributes to an in-depth understanding of a knowledge domain. Many researchers have undertaken informative and diverse reviews of CRM research. Most of the prior CRM reviews were subject to a limited scope. For example, Taroun (2014) reviewed various risk assessment techniques and explained their advantages and drawbacks; Siraj and Fayek (2019) reviewed common construction risks identified by 130 articles published in prestigious journals; and Ganbat et al. (2018) reviewed the use of building information modelling (BIM) for CRM in international projects. Such reviews provided readers with fragmented insights, but not a holistic understanding of the global CRM research in its entirety. Moreover, most of the prior reviews over relied on manual reviews, which were short of producibility and prone to subjective viewpoints (Hammersley 2001). This limitation has been touted by the critics who highlighted the objective evaluation of construction management research (Jin et al. 2019; Zheng et al. 2020). To achieve a holistic understanding of a knowledge domain, it is necessary to review a large sample of bibliographic data. However, manual reviews face difficulty in handling a large sample of articles. The research problem lies in the lack of a holistic understanding of the CRM knowledge domain without over reliance on subjective viewpoints. To overcome this problem, this study undertakes a holistic review of the global CRM research through bibliometric analysis.

Bibliometric reviews uses broad inclusion criteria to assess literature and relies on a wide range of quantitative citation analysis, helping to examine the relative importance of certain publications and visualize their clustering in networks (Vogel et al. 2021). In the field of construction management, bibliometric analysis methods have been used to analyze literatures on various research topics. This study selects the bibliometric review over the traditional review because of the two research questions relating to the knowledge domain and emerging research themes. The two bibliometric analysis techniques, i.e. document co-citation and bibliographic coupling, are the primary tools for detecting the intellectual structure of a knowledge domain and the emerging research themes.

Analysis techniques and software

This study adopted two major bibliometric analysis techniques: document co-citation and bibliographic coupling. The two techniques differ in the analysis of citations between primary and/or secondary documents.

Document co-citation analysis focuses on the secondary documents that are cited together (co-cited) by primary documents (Small 1973). The document co-citation strength is measured by the frequency with which two secondary documents are co-cited by primary documents. More co-citations indicate the content of two secondary documents that are more semantically interrelated and more likely to be aggregated into a cluster. Clusters of co-cited documents reveal the intellectual structure of a knowledge domain (Chen et al. 2010), thus answering the research question – *what is the underlying intellectual structure of the CRM knowledge domain*?

Bibliographic coupling aims at the primary documents that cite the same secondary documents. The document strength indicator is the co-occurrence frequency of secondary documents in the references of two primary documents (Kessler 1963). These two primary documents with at least one reference in common

are seen 'coupled'. Bibliographic coupling explores the emerging topics and future trend in the literatures (Van Raan 2005), thus answering the research question – *what are the emerging themes of CRM research*?

This study used VOSViewer software for document co-citation and bibliographic coupling (van Eck and Waltman 2010). All the 2034 bibliographic records and 68727 references that were output by WoS were input into VOSviewer. This software can analyze the selected records based on certain criteria, such as the strength indicators. The manual by Van Eck and Waltman (2022) shows the detailed operation and data analysis process that has been followed by prior bibliometric reviews in the construction management filed (Hosseini et al. 2018; Jin et al. 2018).

As recommended by Vogel et al. (2021), each bibliometric study focussed on the top 100 documents and their clustering. For an individual bibliometric method, the document strength indicator was used to determine whether a document was among the top 100 or not. In the networks produced by the software tools, each node represents a document. The closeness of nodes indicates the relation between nodes. The document strength is proportional to the node size, whereas the colours of nodes represent the clusters assigned to the documents. In addition to quantitative bibliometric analysis, in-depth qualitative discussion was made to supplement bibliometric analysis and help to answer the research questions. This has been a common practice in all prior reviews as subjective discussion and judgments are inevitably involved in reviews (Jin et al. 2019).

Results

Document co-citation clusters

Document co-citation analysis focuses on semantic similarity in the secondary documents that are co-cited by primary documents, on the assumption that two co-cited secondary documents usually share semantic similarities (Small 1973). As older documents tend to attract more co-citations, co-citation is usually recognized as a dynamic measure that changes over time. This study targeted the 68727 secondary documents (i.e. references) of the 2034 primary documents. The co-citation strength indicator is the frequency with which two secondary documents are co-cited by primary documents. The node size is proportional to the co-citation strength. This study selected the top 100 most co-cited documents, whose co-citation strength ranged from 1001 to 109, with an average strength of 274. Of the top 100 documents, 93 were journal articles while seven were books.

Cluster analysis has been widely used together with document co-citation analysis to show the intellectual structure of a knowledge domain. In VOSviewer, each cluster is represented by an individual colour. The clustering technique was proposed by Waltman et al. (2010) and incorporated a resolution parameter that helped to deal with the resolution limit problem. As shown in Figure 2, the top 100 documents are grouped into four co-citation clusters, represented by different colours. Node size is proportional to co-citation strength of a document. Clusters 1 (red), 2 (green) and 3 (blue) consisted of 29, 29 and 28 documents, respectively, while cluster 4 (yellow) had 14 documents.

Cluster 1 (red) was labelled as 'formal project RM process' because most documents were related to the project RM process or specific steps of this process. The years of publication ranged from 1985 to 2011. The earliest document by Perry and Hayes (1985) presents the basic steps of RM (risk identification, analysis and response) in construction projects. With a more in-depth perspective, some journal articles focussed on a single step of a formal project RM process, such as risk identification (Tang et al. 2007) and risk analysis (Baloi and Price 2003). Most documents in this cluster relied on questionnaire surveys to collect risk data and simply rank risks in terms of their importance or significance (Tang et al. 2007; Hwang et al. 2014) because RM mainly relied on intuition, subjective judgement and experience (Akintoye and MacLeod 1997).

Cluster 2 (green) was interpreted as 'risk analysis methods' because most documents adopted or developed quantitative risk analysis methods. The years of publication ranged from 1965 to 2014. The earliest document by Zadeh (1965) set a foundation for fuzzy set theory (FST) and various fuzzy analysis techniques. FST was developed to represent uncertainty using linguistic variables and membership functions and introduced to deal with subjectivity in construction risk analysis at the end of the 1980s. In addition, analytical hierarchy process (AHP), developed by Saaty (1980), is a widely used multi-criteria decision making (MCDM) method, which can quantify relative priorities of decision alternatives on a ratio scale to support decision making. Despite their shortcomings, AHP and fuzzy approaches became the principle methods for dealing with problems of subjectivity in construction risk analysis (Taroun 2014). Moreover, various MCDM methods have been introduced to construction risk analysis, such as the grey system theory, technique for order of preference by similarity to ideal solution (TOPSIS) (Zavadskas et al. 2010) and consistent fuzzy preference relations (Kuo and Lu 2013).

Cluster 3 (blue) was labelled as 'RM in regional and international market' because most documents were related RM in a single region or country or in international construction projects. The years of publication ranged from 1981 to 2016. The earliest document by Fornell and Larcker (1981) was focussed on structural equation modelling (SEM), which was used as a method for analyzing interdependencies among risks international construction projects (Liu et al. 2016). Some documents presented various frameworks for international CRM (Hastak and Shaked 2000; Wang et al. 2004) that covered a wide range of risks in international construction, whilst others focussed on the key risks that were possibly faced by international contractors in a regional market, such as China (Zou et al. 2007) and India (Ling and Hoi 2006). Moreover, some documents paid special attention to a single type of risk in the international construction market, such as political risk (Deng et al. 2014).

Cluster 4 (yellow) was a small cluster and labelled as 'schedule and cost risks in construction projects' because most of the 14 documents focussed on the factors contributing to time and cost overruns in construction projects. Nearly all the documents targeted the construction projects in developing countries.

Overall, the document co-citation analysis results indicated that the CRM research was heavily informed by research on a formal CRM process, diverse risk analysis techniques and CRM in regional or international market. These themes constituted the intellectual structure of the CRM knowledge domain. However, document co-citation analysis has a temporal focus of the past. Thus, bibliographic coupling is necessary to identify the emerging themes of the CRM research.

Bibliographic coupling clusters

Bibliographic coupling focuses on the primary documents that cite the same secondary documents. Because the primary documents that include citations are more recent than the cited

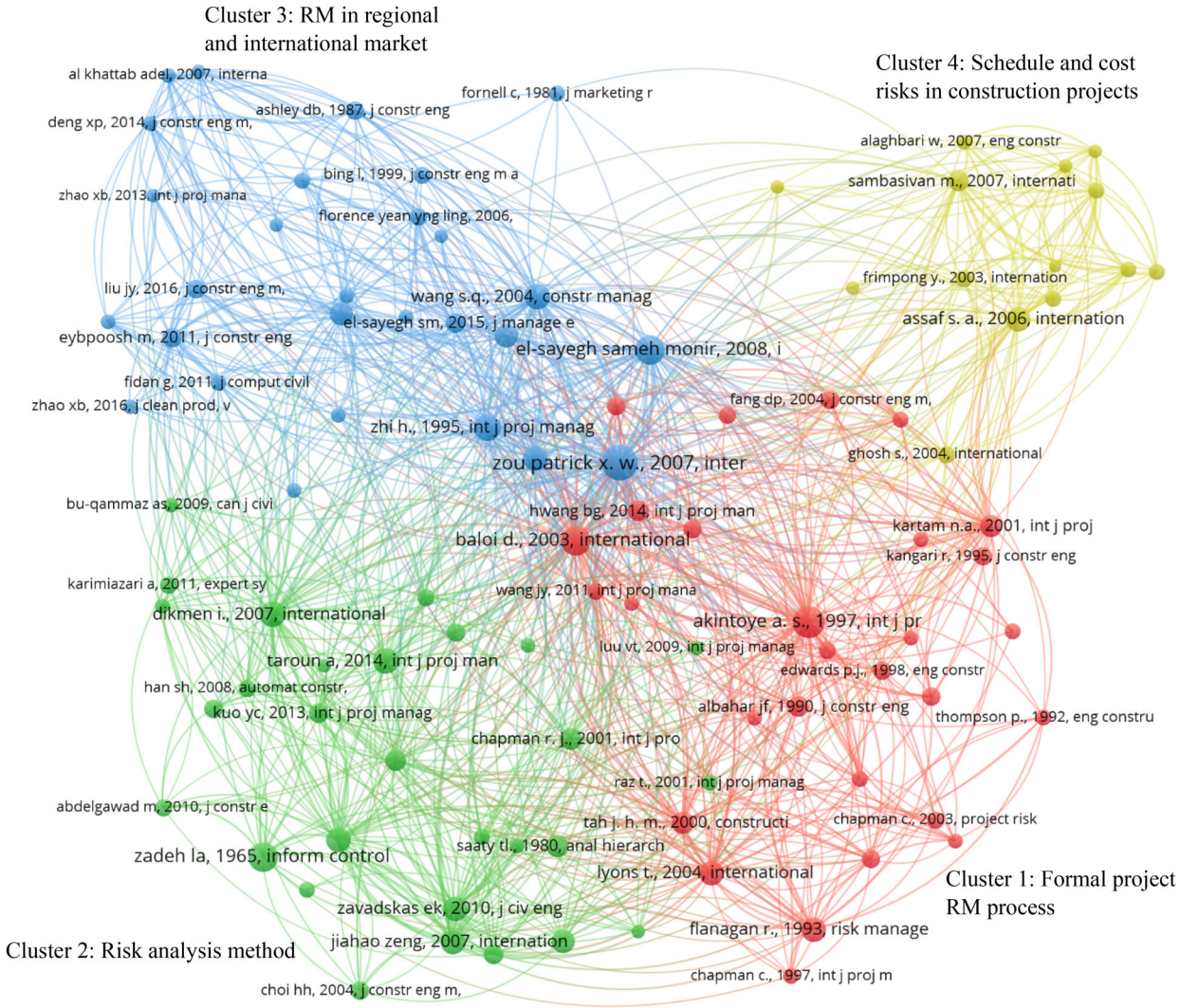

Figure 2. Document co-citation network of CRM research.

secondary documents, bibliographic coupling is situated in the present and helps to identify emerging themes. The more the overlaps in bibliographies of two primary documents, the higher the coupling strength of primary documents. This study selected the top 100 documents in terms of their coupling strength. As shown in Figure 3, the top 100 documents are grouped into three bibliographic coupling clusters, represented by different colours. Node size is proportional to coupling strength of a document. Clusters 1 (red) and 2 (green) consisted of 49 and 45 documents, respectively, while Cluster 3 (blue) had only six documents. Thus, more attention was paid to Clusters 1 and 2 to identify the key emerging themes.

Most of the documents within Cluster 1 received high coupling strength. Most documents were related to RM in construction projects with various specified characteristics, such as prefabrication (Luo et al. 2015) and diverse procurement methods including target cost contracts and guaranteed maximum price contracts (TCC/GMP) (Chan et al. 2010) and public-private partnership (PPP) (Osei-Kyei and Chan 2017). These documents usually addressed the risks specifically to the project characteristics as well as the common risks applicable to all types of construction projects. In the 2010s, RM in PPP projects has attracted increasing attention from researchers as PPP has been seen as an effective way to finance infrastructure projects in both developing and developed countries. The documents on RM in PPP intertwined with those in Cluster 3, which were closely related to risk allocation in PPP projects, including decision-making models (Jin 2010) and risk allocation preferences in PPP projects (Ke et al. 2010). In addition, several documents were related to management of a particular type of risk, such as safety risk (Zhang et al. 2016), environmental risk (Lucchi 2020) and disaster risk (Bosher et al. 2007).

Cluster 2 (green) can be divided into two research themes. The first theme was RM in international construction. Political risks have been considered significant in the international construction market and the ability to address political risks contributed towards competitive advantages of international contractors (Deng et al. 2014). The documents relating to this theme covered the causes of political risks (Deng and Low 2014; Deng et al. 2018) and strategies to mitigate political risks (Chang et al. 2018) in international construction. In addition, after global financial crisis, construction companies started to hold a top-down perspective of risks. Thus, enterprise risk management (ERM), as a holistic approach to RM, has been advocated and investigated in international construction companies (Zhao et al. 2014, 2015).

The second theme was regarding various risk assessment and allocation methods. Fuzzy analytical network process (ANP) and fuzzy Bayesian belief network (BBN) have been increasingly used

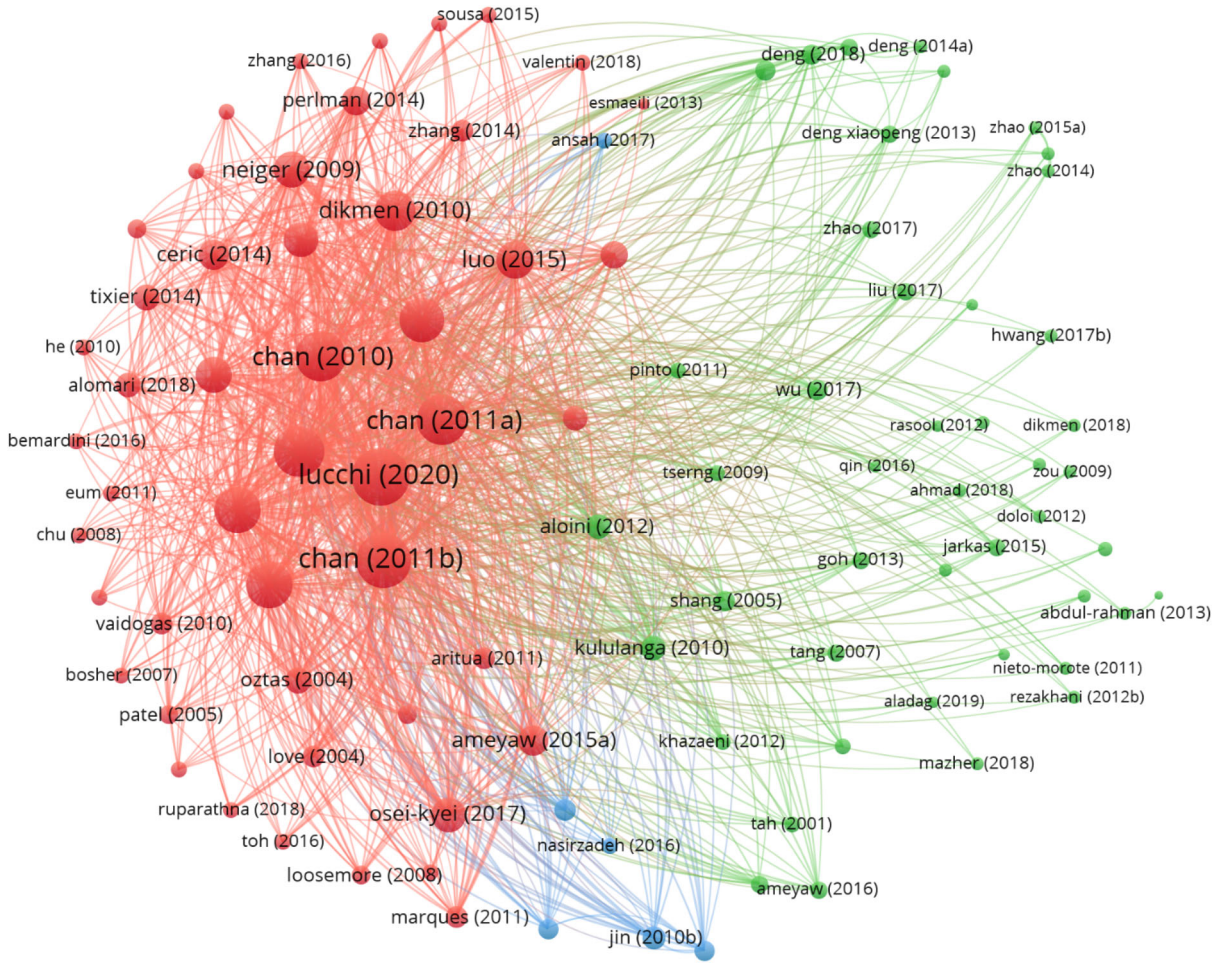

Figure 3. Bibliographic coupling network of CRM research.

to analyze complex risks (Islam et al. 2017) whilst fuzzy TOPSIS was used to allocate risks between project players (Khazaeni et al. 2012). In addition, decision making trial and evaluation laboratory (DEMATEL) and ANP was integrated as a DEMATEL-ANP approach that was adopted to assess interdependencies among risks (Dehdasht et al. 2017). SEM was also used to analyze interactions among risks in the form of a risk network (Eybpoosh et al. 2011). Additionally, BIM has potential to transform CRM and a dedicated BIM plugin for RM was highly recommended (Ahmad et al. 2018)

Discussion

Qualitative discussion was made to supplement bibliometric analysis and rearranged the clusters *via* merging the themes of a similar nature under the clusters. This has been a common practice as subjective discussions are inevitably involved in all reviews (Jin et al. 2019).

Intellectual structure of the CRM knowledge domain

Clusters of co-cited documents demonstrate the intellectual structure of the CRM knowledge domain and helped answer the first research question. The following major research themes under these clusters comprised the intellectual structure of the CRM knowledge domain. Each research themes consists of relevant documents.

Risk identification, analysis and response

An important observation was that the knowledge relating to a formal CRM process had been well established through the documents focussed on either generic RM processes or specific steps of a typical RM process. A formal RM process has been recognized as an effective way to handle risks in organizations. ISO31000:2018 provides a generic RM framework and process (ISO 2018). At the project level, the Project Management Institute (PMI 2017) develops a framework and process for project RM, which is applicable to construction projects.

As an essential step of a typical RM process, risk identification has been well researched in CRM documents. This involves finding, recognizing and describing risks that might impact organizations' achievement of the objectives and exploring their sources and consequences. Risk identification is currently not only limited to identification of risk events but also extended to identification of risk sources and vulnerability (Zhang 2007). CRM documents usually started with identifying a list of risks to develop a risk breakdown structure or risk categorization and then adopt diverse risk analysis methods to prioritize risks (Shen et al. 2001; Fang et al. 2004; Zou et al. 2007). In practice, a risk register or risk checklist may be used to identify risks. However, as new risks emerge, previous identification of risk events or sources may not be exhaustive. Hence, more recent articles have been still summarizing previous identified risks (Siraj and Fayek 2019) and focussing on emerging risks (Risbeck et al. 2021).

Risk analysis is another essential step that has been highlighted in the past decades. Probability and impact have been

widely recognized as two dominant dimensions of risk (Taroun 2014), whilst more dimensions have been taken into account, such as manageability (Dikmen et al. 2007), controllability (Cagno et al. 2007), discrimination (Cervone 2006), vulnerability (Zhang 2007) and exposure (Jannadi and Almishari 2003). In addition, a wide variety of risk analysis methods have been presented in a large number of CRM documents. Monte Carlo simulation and other probabilistic methods dominated risk analysis in the 1980s. Then, FST and MCDM methods, including hybrid methods (e.g. fuzzy AHP and fuzzy TOPSIS), started to attract research attention and have become the principal methods for handling subjectivity in risk analysis. More recently, BBN, system dynamics, FTA, ANP and SEM have been used to examine the interdependencies among risks (Nasirzadeh et al. 2008; Eybpoosh et al. 2011; Islam et al. 2017), providing opportunities of holding a network view of risks, while various neural network models have been used to predict or model risks (Shan et al. 2018; Li and Wang 2021). All these risk analysis methods have constituted the CRM knowledge domain.

Risk response or treatment involves formulating and selecting risk response strategies, assessing the effectiveness of these strategies and deciding whether the remaining risk is acceptable. CRM documents adopted qualitative methods or simple statistical analysis to prioritize risk response strategies (Hwang et al. 2017; Do et al. 2021). Indeed, the selection of risk response can be impacted by many factors and is therefore seen as a multi-objective optimization problem (Zhang and Fan 2014). Risk response is faced with resource constraints and tends to minimize the expected losses of risks and total costs of risk response strategies with consideration into risk preferences of decision makers (Yan et al. 2022).

Rm in construction projects with specified characteristics

RM in construction projects varies according to projects characteristics. Hence, researchers focussed on RM in a specific type of construction projects in a region, achieving a more in-depth view of risks in these projects.

Many documents discussed RM in projects with various procurement methods (e.g. TCC/GMP, design-build, design-bid-build and PPP) because procurement methods can impact the roles of project players in contracts. RM in PPP projects have been a hot theme in the 2010s, and many documents investigated risk identification (Li and Zou 2008), analysis (Chan et al. 2018), mitigation (Xiong et al. 2017) and allocation (Ke et al. 2010) in PPP projects.

In addition, building projects using different methods of construction tend to face different risks associated with these methods. Documents have targeted RM in green buildings (Hwang et al. 2017) and prefabricated buildings (Li et al. 2017) because these types of buildings bring about diverse potential benefits.

Moreover, infrastructure projects tend to face more risks than building projects and attracted more attention from researchers. Some of the documents relating to RM in infrastructure projects indeed focussed on the risks related to PPP delivery of infrastructure projects, whilst other documents focussed on common risks, such as investment risk (Ye and Tiong 2000), safety risk (Ding et al. 2012), geological risk (Chen et al. 2021) and social risk (Yuan et al. 2018), but not the risks peculiar to procurement methods.

Rm in international construction

RM in international construction was another important theme comprising the CRM knowledge domain. Since 2000, with the globalization of the construction market, an increasing number of contractors have ventured into the international construction market to expand their business (Liu et al. 2022). Contracting overseas faces not only the typical risks at home, but also the risks closely relevant to overseas business (Han and Diekmann 2001). Hence, RM in international construction has been a hot research theme since 2000. Researchers divided the risks into various levels for further analysis and mitigation (Hastak and Shaked 2000). International construction joint ventures (ICJVs) have been a popular way for international contractors to compete for overseas projects. Previous studies have investigated critical risks and risk allocation within ICJVs in different regions, such as China and Singapore (Shen et al. 2001; Hwang et al. 2016; Hwang et al. 2017). Some documents focussed on an individual type of risk, such as social risk (Li et al. 2021), legal risk (Ling and Low 2007) and political risk (Deng et al. 2018). These risks are closely relevant to the host countries, with which international contractors may be unfamiliar. Hence, the capability of handing these risks can contribute to the competitive advantages of international contractors (Deng et al. 2014). Moreover, the studies regarding RM in a single country or region (Fang et al. 2004; Zou et al. 2007) also provided valuable information for the international contractors that intended to expand business to the country or region.

Management of particular risk categories

The research on the management of a particular risk category also comprised the CRM knowledge domain. As relevant to construction project objectives, schedule and cost risks have been a popular research theme, especially in developing countries (Doloi et al. 2012). Health and safety RM was another important theme that incorporated knowledge of other disciplines, such as ICT (Ding and Zhou 2013) and medicine (Wang et al. 2015). Environmental RM became a focus of the documents relating to infrastructure construction (Fang et al. 2011) and indoor environment of buildings (Lucchi 2020). In addition, disaster RM was another important theme regarding construction and operation & maintenance phases of construction projects. Specifically, geological disasters (e.g. collapse) threatens mountain tunnel construction (Chen et al. 2021), while fire disaster (Vaidogas and Sakenaite 2010) threaten the operation and maintenance phase of construction projects.

Emerging themes of CRM research

The temporal focus of bibliographic coupling analysis is present and future, enabling identification of research fronts and emerging themes (Van Raan 2005). Hence, the bibliographic coupling clusters based on the top documents, to some extent, revealed the emerging themes. More recent documents may not be ranked within the top documents but still shed light on emerging themes. Thus, the following emerging themes were identified based on both bibliographic coupling and qualitative analysis of recent documents.

Advanced risk analysis techniques

Risk analysis methods have been and will be a key part of the CRM knowledge domain. New and complex quantitative risk

analysis methods have emerged. The new methods are usually hybrid methods that combine existing individual risk analysis methods and overcome the shortcomings of an individual method. Recently, a hybrid method, which integrated best-worst method (BWM) and measurement of alternatives and ranking to compromise solution (MARCOS) under the context of interval type-2 fuzzy sets, was proposed by Celik and Gul (2021) to analyze safety risks in dam construction. BWM was used to weight severity and probability of risk and MARCOS was used to rank hazards. In addition, another hybrid method combining fuzzy TOPSIS, fuzzy FTA, Fine-Kinney method and fuzzy inference system was proposed by Alipour-Bashary et al. (2021) to classify and prioritize risks in building demolition. Moreover, a novel Bayesian Monte Carlo simulation-driven technique was developed by Chen et al. (2021) for construction schedule risk inference of infrastructures. This technique does not require observation data to develop Bayesian network model, constructing the directed acyclic graph based on the topological structure of key risk network using deep-first search and adapted maximum-weight spanning tree algorithms and developing the conditional probability tables using the leaky-MAX model. All these advanced risk analysis techniques have been tested and validated in real-world case projects.

In recent years, the concept of emerging risk has attracted great attention, especially the relation between emerging risk and black swan events (Flage and Aven 2015). Construction projects tend to face emerging risks that do not follow a unified probability distribution and increasingly complex interactions among risks with considerations into diverse stakeholders. When the background knowledge is limited, a pure probabilistic approach would not be feasible (Aven 2016). Hence, future CRM research is expected to propose new risk analysis methods that can be incorporated into ICTs to support the decision-making process.

ICT-driven CRM

The advancements of ICTs have driven CRM practice. ICT-driven CRM is expected to transform CRM practice in the future and thus becomes a future research direction of CRM. It merits attention that ICT-driven CRM also relies on the development of risk analysis methods. In the future, more complex risk analysis methods will be developed to handle the emerging risks with increasing complexity.

Artificial intelligence (AI) is a broad term to describe how to make machines do things, which at the moment, people do better, whose subfields include machine learning, knowledge-based systems (KBS), computer vision, robotics, natural language processing (NLP), optimization and automated planning and scheduling (Abioye et al. 2021). The existing risk analysis methods, such as fuzzy hybrids methods and MCDM methods, are under the umbrella of AI. Machine learning has been used to predict and assess risk. Gondia et al. (2020) developed machine learning models to predict construction delay risk sources, whilst Shan et al. (2018) adopted artificial neural network (ANN), as one of machine learning models, to assess collusion risk in construction projects. In addition, computer vision, NLP, KBS and optimization have also been used for CRM in recent studies. Piao et al. (2021) combined computer vision and dynamic Bayesian network to assess fall risk of construction workers; Zhao et al. (2016) developed a KBS for enterprise RM in construction companies; and Zou et al. (2017) presented a risk case retrieval system using NLP and case-based reasoning. Hence, AI can monitor, recognize, analyze and predict potential risk (Afzal et al. 2019) and effectively address the inherent limitations of traditional CRM, such as the vagueness and vulnerability from specialist experience and subjective judgement (Pan and Zhang 2021) and thus enable professionals to quickly assess risks and propose proactive risk response measures, finally preventing risks from impacting the achievement of objectives. In dangerous environments, robotics can to some extent replace humans to handle the tasks with hazards.

Other ICTs, such as radio frequency identification (RFID), Internet of Things (IoT), BIM, big data and virtual reality (VR), have been applied for CRM. For example, Li et al. (2017) developed a RFID-enable BIM platform to handle schedule risks in prefabricated building projects; Ding et al. (2013) presented a real-time safety risk early warning system for metro construction based on IoT and RFID; Ma and Wu (2019) relied on big data analytics and ANN to develop a quality and schedule risk correlation model for Shanghai apartment projects; and Shi et al. (2019) adopted a multi-user VR system to examine how learning methods influenced fall risk behaviour of construction workers.

It merits attention that diffusion of new ICTs for CRM would bring about additional risks, such as data security and ownership issues, technology acceptance and technical risk (Zhao et al. 2017). However, the negative effects of these risks can be offset by the benefits from new ICTs. Future research would develop more efficient and accurate models and systems to intelligently identify or detect construction risks, analyze risk importance and interrelationships and select relevant risk response strategies. Such ICT-driven CRM systems should be customized according to the characteristics of organizations.

Integration of CRM and other management functions

Management functions of an organization aim to achieve objectives; however, the objectives may be impacted by risks. Hence, RM should be integrated into other management functions of an organization (Hwang et al. 2015). In large-sized construction companies, a senior executive may be appointed to take care of ERM and coordinate the RM issues relating to different functional departments and projects (Zhao et al. 2013). In construction projects, project RM should be integrated into other management functions. As most risks finally impacts project schedule and cost objectives, project RM has been integrated into project schedule and cost management. Many documents have discussed schedule and cost overruns, which supplemented schedule and cost management (Dikmen et al. 2007). RM has also been integrated into project procurement management (Li and Zou 2008; Chan et al. 2010), quality management (Zhou et al. 2020), value management (Hwang et al. 2015), site management (Ahn et al. 2020), environment management (Lucchi 2020) and human resource management (Kifokeris and Xenidis 2021).

Additionally, RM should also be undertaken with stakeholder management because different stakeholders may hold different perceptions of a risk. The role of project stakeholder management has been highlighted by PMI (2017). In construction projects, a risk needs to be allocated to the responsible stakeholder that is best capable of managing this risk at least costs. Risk allocation could be dynamic across phases within a project life cycle or under different scenarios. Hence, previous studies have examined stakeholder-associated risks. For instance, Yang and Zou (2014) and Yang et al. (2016) examined the stakeholder-associated risks of green building projects using SNA, whilst Xia et al. (2018) recommended integrating a dynamic perspective into

stakeholder analysis to understand the stakeholder-associated risks in different scenarios.

Moreover, RM should also be related to supply chain management. Supply chain risk has been significant because of the global pandemic and resulted in a series of problems, such as shortage of materials and delays. Koc and Gurgun (2021) categorized 135 construction supply chain risks into 10 phases of a life cycle and mapped the risks to relevant stakeholders in the supply chain, whilst and Luo et al. (2019) analyzed stakeholder-related supply chain risks and their interrelationships in a prefabricated building project.

Future CRM research would examine how CRM is integrated into other management functions and how organizational characteristics will influence the integration.

Human factors in CRM

CRM inevitably involves the participation of decision makers, stakeholders and those who could be impacted by risks. Human factors, such as risk attitude, risk tolerance and personality traits, may influence individual's decision making and behaviour relating to CRM. Risk attitude refers to an individual's response to uncertainty that matters, influenced by knowledge and experience, personal characters, risk perception and external environment (Lee and Foo 2022) and influence decision making and risk rating behaviour (Dikmen et al. 2018). Risk tolerance refers to an individual's readiness to bear the risks after risk treatment in order to achieve its objectives (ISO 2018).

Construction safety RM has been a field, where human factors have been frequently discussed in recent years. The safety risk tolerance of construction workers is influenced by their subjective perception, work knowledge and experiences, work characteristics and on-site safety management (Wang et al. 2016), as well as individual and sociocultural determinants, such as affective associations, control beliefs, safety culture and risk attitudes (Salas et al. 2020). In addition, risk tolerance could be divided into personal risk tolerance and work-related risk tolerance. The former is the comfort or discomfort with risks in everyday life, and the latter refers to the comfort or discomfort with hazards or safety risks in workplaces. Personal risk tolerance was found to be positively associated with both work-related risk tolerance and risk-taking behaviour of construction workers (Bhandari et al. 2021). Moreover, safety risk-taking behaviour was found to be influenced by construction workers' outcome expectancy, risk perception, risk attitude and safety training and promotion policy.

In addition, CRM researchers usually rely on various management or psychological theories or models to investigate the effects of human factors on behaviours, such as the big five inventory (Lee and Foo 2022), reinforcement theory and goal setting theory (Guo et al. 2018) and social identity theory (Andersen et al. 2018). Most of these theories or models set a basis for a better understanding of the complex interactions among the factors influencing behaviours in CRM. Although human factors have been examined in safety RM research, RM professionals' human factors and decision-making behaviour relating to the management process of other risk categories are also worth further investigation. Future CRM research would investigate human factors and decision-making behaviour related to diverse risk categories, extending the knowledge body relating to CRM, management and psychological theories.

Conclusions

All the organizations in the construction industry are faced with diverse risks and thus CRM plays a key role to assure achieving the objectives of organizations, no matter they are at the project or company levels. Since 2000, there have been many journal articles on CRM, but few have attempted to holistically review these publications. This study aims to undertake a bibliometric analysis of global CRM research in 2000–2021. A total of 2034 bibliographic records of primary documents were collected from WoS core collection database, with 68727 secondary documents in the references. Document co-citation and bibliographic coupling were adopted to answer the research questions relating to the intellectual structure and emerging themes of the CRM knowledge domain, respectively.

Document co-citation clusters showed the intellectual structure of the CRM knowledge domain. The key themes included the research relating to the steps of a formal CRM process (i.e. risk identification, analysis and response), RM in construction projects with specified characteristics, RM in international construction and management of particular risk categories. It merits attention that these four themes interacted with each other to form the intellectual structure of the CRM knowledge domain. The key steps of a formal CRM process, namely, risk identification, analysis and response, have consistently been a key research theme and intertwined with the other three themes.

Through bibliographic coupling analysis and qualitative analysis, four emerging themes of CRM research were identified, including more advanced risk analysis techniques, ICT-driven CRM, integration of CRM and other management functions, as well as human factors in CRM. More advanced risk analysis techniques enable handling of emerging and complex risks in the future. Such methods would be incorporated into ICTs to advance CRM practices and support decision making. As RM cannot be separated from other management practices, CRM should be integrated with other management functions within an organization. Hence, it is worth examining the effects of organizational factors on the integration. CRM practices cannot be completed without human's input. Thus, human factors and behaviour under various situations would be a focal point in the future CRM research.

As with all research, this review study has some limitations. First, this study focussed on the journal articles in English in WoS core collection database, thus ignoring the publications in other languages, not indexed by WoS and conference proceedings. Second, given the number of bibliographic records, this study focussed on the top documents in terms of document strength but ignored the role of the documents whose strengths were a little lower than the threshold. Third, bibliometric analysis relies on citation analysis but do not capture why authors cite other documents (Vogel et al. 2021), which is a common problem of bibliometric analysis. Hence, additional qualitative discussion was undertaken to supplement quantitative bibliometric analysis results.

Nonetheless, this review study still expands the body of CRM knowledge through identifying the intellectual structure of the CRM knowledge domain and the emerging research themes. This study covers 2034 bibliographic records in 2000–2021, with more inclusiveness than prior reviews of CRM. This study uses quantitative bibliometric analysis and qualitative discussion, overcoming the shortcomings of mere reliance on either subjective opinions or bibliometric analysis results.

Revealing the intellectual structure and emerging themes, this study provides researchers with an in-depth understanding of the

CRM knowledge domain. The research themes identified for the intellectual structure of the CRM knowledge domain disclose what have been done for CRM research and what constitute the CRM knowledge domain. The emerging themes identified in this study show where CRM research goes and shed light on the future directions of CRM research. In addition, this study enables industry practitioners to know the necessity to refresh their CRM knowledge and improve the CRM skills, thus helping them to achieve the objectives set by construction projects and organizations and assure better performance.

Disclosure statement

No potential conflict of interest was reported by the author.

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