review

Transforming Knowledge Management in the Construction Industry through Information and Communications Technology: a 15-year Review

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Abstract

Information and Communications Technologies (ICTs) play a vital role in the knowledge management (KM) of the Architecture, Engineering and Construction (AEC) industry, which is knowledge intensive and yet faces unique challenges in managing knowledge due to its complex and dynamic nature. In order to show the state-of-the-art of ICTs for knowledge management in the AEC industry, this paper conducts a fifteen-year review of 89 related papers and reports from the industry. A clear line of key technologies evolving from ontology, semantic network to knowledge graph has been revealed from the collected literature. The interactions between different ICTs, as well as their advantages and disadvantages for different knowledge management process are discussed. The study also finds certain imbalance in the development of the industry and academia, as well as cognitive barriers and lack of evaluation standards. Suggestions for future development are also proposed to benefit the research community and relevant practitioners.

Keywords

ICT; Knowledge management; Construction management; Review; Knowledge graph; Semantic network

1. Introduction

As the main driving force of social and economic development and competitive strength of an enterprise, knowledge management (KM) is one of the important ways for improving the management performance of organizations, which is widely used in many fields such as biopharmaceutical (Kruesi et al., 2020), innovation management (Quan et al., 2020) and venture capital (Rossi et al., 2020). The application of knowledge management in the AEC industry is necessary and important due to the following reasons. First, the instability of teams and labor forces (Garcia et al., 2020) makes knowledge sharing and dissemination difficult. Second, considering the large project volume, long construction period, and various procedures involved, it is hard and complex to manage knowledge in the AEC industry (Tong 2019). Third, the complex and dynamic nature of the construction industry makes it impossible to simply migrate KM methods from the manufacturing industry (Zhang et al., 2014). Fourth, the unstructured data collected in the construction industry is difficult to be recognized and processed by computers, which increases the difficulty to share knowledge among different projects and enterprises (Yao 2019). Therefore, the characteristics of the AEC industry clearly prove the importance and the necessity of the application and development of knowledge management.

Knowledge has been managed since the organizations have existed, even without the KM label (Anumba et al., 2008). Malhotra (1998) pointed out that knowledge management is an important response method in terms of an organization's adaptability, survival, and competitiveness when it faces increasing non-continuous environmental changes. In essence, it involves the development process of the organization and seeks to combine the data process and information collection with the ability of invention and creativity of human beings (Malhotra 1998). With advantages of information and communications technology (ICT), it is much effective to promote the creation, access and reuse of knowledge (O'Leary 1998).

The unique challenges for knowledge management faced in the AEC industry promote the developments and applications of advanced ICT-assisted knowledge management tools, which in turn contribute to the evolution of knowledge management in general. This paper conducts a comprehensive review of the recent applications of ICT-assisted knowledge management in the AEC industry based on the following considerations.

(1) ICT provides a more convenient means of acquiring, processing and sharing knowledge in the AEC industry.

Distinctive features of the AEC industry make the task of managing construction projects particularly appropriate for applications of ICT tools (Ahmad et al., 1999). Most documents in the AEC industry are represented in a single format (Rasmussen et al., 2019), including video information, 3D models, cost, schedule, and other multi-modal information. ICT-assisted knowledge management in the AEC industry helps to deal with the miscellaneous information of various project activities and enhances communications among involved project organizations (Ahuja et al., 2010; Martínez -Rojas et al., 2016). In addition, with the help of Building Information Modeling (Inyim et al., 2015), multi-modal knowledge can be organized and managed. Different from traditional knowledge management tools, ICT-assisted knowledge management tools have advantages in the temporary, unstable, fluid and dynamic nature of data.

(2) ICT has undergone qualitative changes in recent years, but the role of ICTs in knowledge management is often neglected.

In recent years, ICTs have undergone tremendous changes. The AEC industry has benefited from ICT technology, such as semantic network simulation of green building (El-Diraby, 2017) and building fault detection through ontology (Previtali, 2020). The application of new technology itself can promote the development of knowledge management. For example, the development of semantic network technology can promote the expansion of knowledge databases. However, many scholars do not regard it as a part of knowledge management when they study a certain ICT technology, and some scholars only use some management methods and organizational behaviors when studying knowledge management. As Spender points out, it makes little sense to introduce such a complex concept as knowledge into the management domain if we do not take seriously the properties of "knowledge", specializing it and distinguishing it from "information" (Spender 1996). Therefore, the importance of ICTs in knowledge management, particularly in the AEC industry, is often neglected.

(3) ICT and knowledge management are mutually reinforcing.

Knowledge is a combination of information and experience that is predictable and leads to effective behaviour. In the AEC industry, due to the large amount of information, the complex processing process and the temporary single project, management of information is not enough. There has been an increasing awareness that information systems do not capture the knowledge or even the information that managers use in their daily lives (Anumba et al., 2008). Therefore, the concept of knowledge and knowledge management can promote the development of ICT.

In a knowledge intensive industry such as the AEC industry, the ICT applications to assist knowledge management will be required to respond to more demands from the user, which will therefore guide the application of ICT to a higher level. On the other hand, ICT itself is a way and tool to realize knowledge management, which is necessary for the success of knowledge management. The intervention of ICT can popularize the application of knowledge management, where practitioners do not need to understand the meaning of knowledge management but only need to learn to use relevant ICT software, which can lower the threshold of knowledge management. Therefore, knowledge management and ICT are mutually beneficial.

In light of the importance of ICT in knowledge management in the AEC industry, a review of recent advancements of ICT that assists knowledge management is needed from time to time. However, as shown in Table 1, most of the existing review papers on the relevant topic focus on a certain technology of ICT in the context of the AEC industry (Dinis et al., 2021, Khallaf, 2021, Liu et al., 2020, Wagner et al., 2020, Tang et al., 2019, Senaratne et al., 2021) or on a specific engineering management field (Zamarrón-Mieza et al., 2017). There are limited review papers on the development of ICT in the AEC industry from the perspective of knowledge management.

Table 1. Comparative study of similar theme review

Reference	Adopted methods	Year range	KM		ICT
Lu et al., 2015	Bibliographic review	1998~2012	——		Classification and integration
Hu et al., 2021	Bibliographic review, visual presentation	2009~2019	Organization	√	——
			Acquire	√	
			Share	√	
			Store	√	
			Evaluation		
Cerovsek, 2010	Bibliographic review	1995~2010	——		——
Castro et al., 2012	Bibliographic review	1981~2012	Organization	√	——
			Acquire		
			Share	√	
			Store		
			Evaluation		
Yepes et al., 2021	Bibliographic review, classified discussion	2012~2020	Organization	√	Data security
			Acquire	√	

			Share	√	
			Store		
			Evaluation		

According to the above analysis, the following research gaps can be identified:

- As applications of knowledge management in the AEC industry evolve, ICT and knowledge management promote and complement each other. However, most papers study ICT and knowledge management separately, and lack the analysis of the combination of the two. Most of the existing reviews focus on research process of a specific tool, such as discussions on the development of a specific ICTs in the AEC industry, or the application of a certain knowledge management process in the AEC industry.
- There are also some excellent reviews from a macro perspective. Lu et al (2015) studied the application progress of ICT in the AEC industry, and Yepes et al (2021) revealed the development and prospect of knowledge management in the construction industry. However, they did not combine knowledge management with ICTs.
- AEC is an industry with strong practicability, which requires that technological innovation should not be separated from practices. However, few academics have compared technology applications in industry with research in academia, especially in the field of knowledge management in the AEC industry.

Therefore, through a rigorous review of both the academia and industrial efforts of the ICT applications to assist knowledge management in the AEC industry, this paper intends to review the existing widely-used techniques, analyze the trend of research, and analyze and compare several typical applications from the perspectives of processes in knowledge management and the evolution of ICTs. This paper aims to fill in the above research gaps and provide a comprehensive review for the upgrading and transformation of ICTs for knowledge management in the AEC industry.

2. Research methodology

The main research method of this paper is combining bibliometric statistics with manual system analysis. In general, the applications of ICT-assisted knowledge management are divided into academic and industrial, and then summarized through bibliometric analysis. The methodology of this literature review is as follows, which explain how the literature for review was selected how the contents analysis was performed.

- Time frame: *Knowledge Management in Construction* written by Chimay J. Anumba is a landmark book on the application of knowledge management in the AEC industry, which clearly states that it is important that the implementation of knowledge management initiatives is not simply based on a desire to 'join the bandwagon' but on a deep-seated conviction of the positive impact that effective knowledge management can benefit construction business processes (Anumba et al., 2008). Therefore, this paper will set the year 2008 as the watershed and focus on the study of ICT-assisted knowledge management applications after it.
- Selection of 3 typical technologies: Based on the review of the literature on knowledge management and ICT, it can be concluded that "Ontology", "Semantic Network" and "Knowledge Graph" are three milestone technologies.
- Keyword determination: The combination of keywords is "AEC or Construction" and "Ontology or Semantic Network or Knowledge Graph".
- Determination of the dimension of academic analysis: The collected literature is analyzed in terms of evolution of ICTs and their roles in the typical knowledge management processes.
- Determination of the dimension of industry analysis: Public reports regarding knowledge management in the AEC industry are collected and interviews and research into 4 typical real estate companies are carried out. The results are then compared with findings from the academic research.

The specific steps of this review are as follows (Figure 1): The first step is to search by keywords in Web of Science. Based on the above preliminary review of the literature on knowledge management and ICT, it can be concluded that "Ontology", "Semantic Network" and "Knowledge Graph" are three milestone technologies. After the arrangement and combination of the keywords "AEC", "Construction" and "Ontology", "Semantic Network" and "Knowledge Graph", a total of 109 papers were collected, and a total of 89 valid papers were selected after removing unrelated papers. Among the selected papers, there are 55 papers related to ontology, 38 papers related to semantic network, and 14 papers related to knowledge graph. A comprehensive analysis was then carried out according to all the collected literature, including countries, publishing journals, contributing authors. After that, the number of published papers, the relationship between the year of publication and technology, and the

relationship between the year of publication and the application field are analyzed. Due to the scarcity of papers on knowledge graph, this paper focuses on its concept, advantages and relationship with other technologies.

The second step is aimed at the knowledge management practices in the AEC industry. The research reports of Kerry Research Center and Guosen Securities Economics Research Institute as well as the information technology brochures from typical real estate enterprises are used to study the degree of cognition and innovation of ICT-assisted knowledge management applications in the industry.

The third step is to summarize the existing problems, prospects and suggestions of ICT-assisted knowledge management.

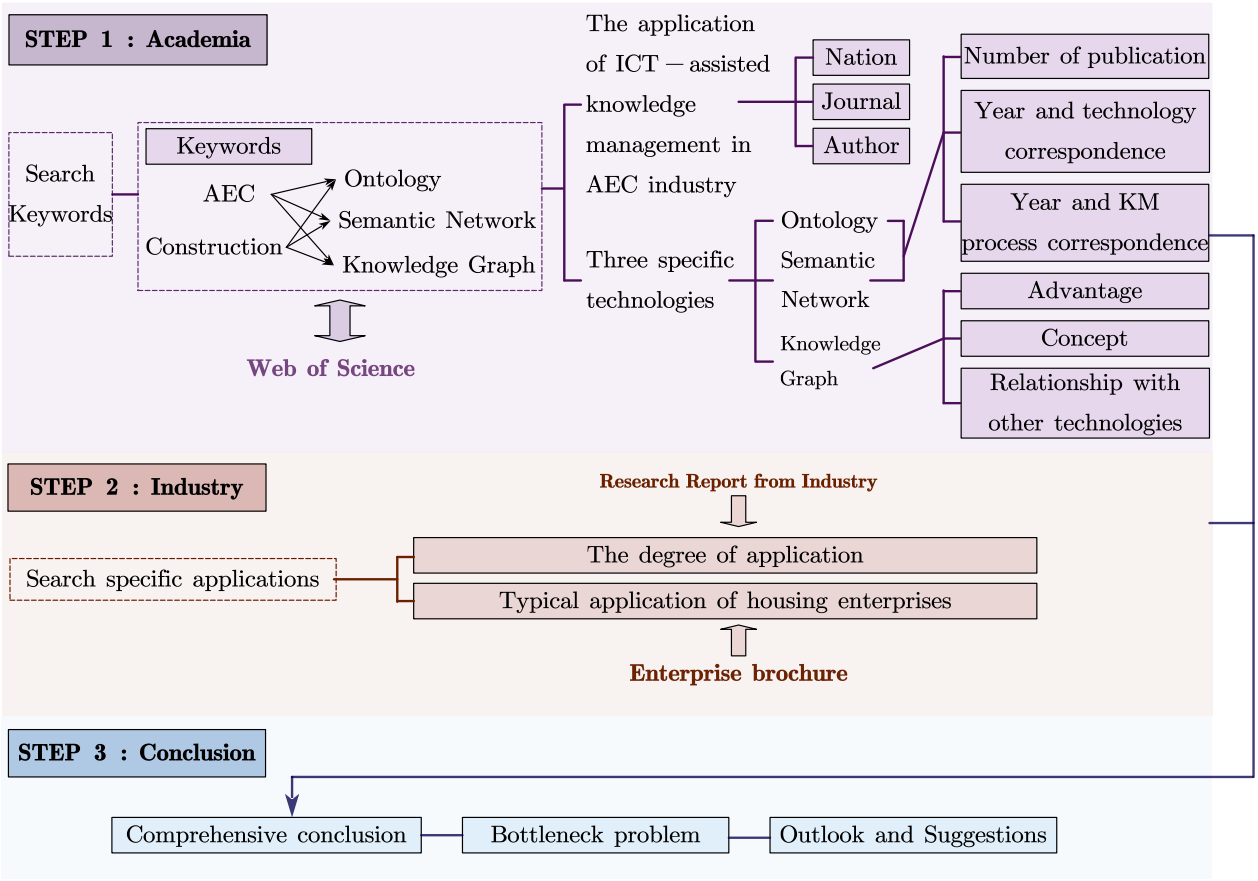

Figure 1. Overview of the proposed research methodology

Through the review of 89 articles, this paper analyzes the application of ICT in knowledge management in the AEC industry from the aspects of academia and industry. The major contributions of this paper are as follows:

- A medium and long-term review report was formed through literature research across 15 years. Specifically, it includes the development history of literature related to ontology,

semantic network, knowledge graph and related knowledge management tools, as well as typical representative technology applications in the industry.

- The concepts and applications of ICT and KM in the AEC industry are expounded respectively, and the two are combined for the first time to analyze the relationship between ICT and KM. This study identifies the key concepts of ICT assisted knowledge management and their complementary relationships to fill the research gap.
- We summarize knowledge management and corresponding ICT applications in the AEC industry, analyze the advantages and disadvantages of them, and carry out critical discussion. Based on literature statistics and analysis, the challenges and problems of ICT-assisted knowledge management in the AEC industry are obtained, and future development directions are suggested.

3. Overview

3.1 History of knowledge management and applications

The development of knowledge and knowledge management has a long history (Figure 2). From the ancient Greeks to Adam Smith and Alfred Marshall, knowledge was discussed and studied by many brilliant people. In the mid-1990s, the management of knowledge received more attention with the development of modern enterprises. It was not until the last five years of the 1990s that the concept of "knowledge management" was clearly defined and widely used (Anumba et al., 2008). The year 1995 can therefore be used as the unlabeled demarcation line for knowledge management. However, the development of knowledge management in the AEC industry is not comprehensive and deeply investigated. In addition, the wide range of opposing definitions of knowledge management and different approaches adopted by companies adds to confusion within companies with conflicting interpretations of knowledge management and a lack of distinction from information management systems (Carrillo and Chinowsky, 2006).

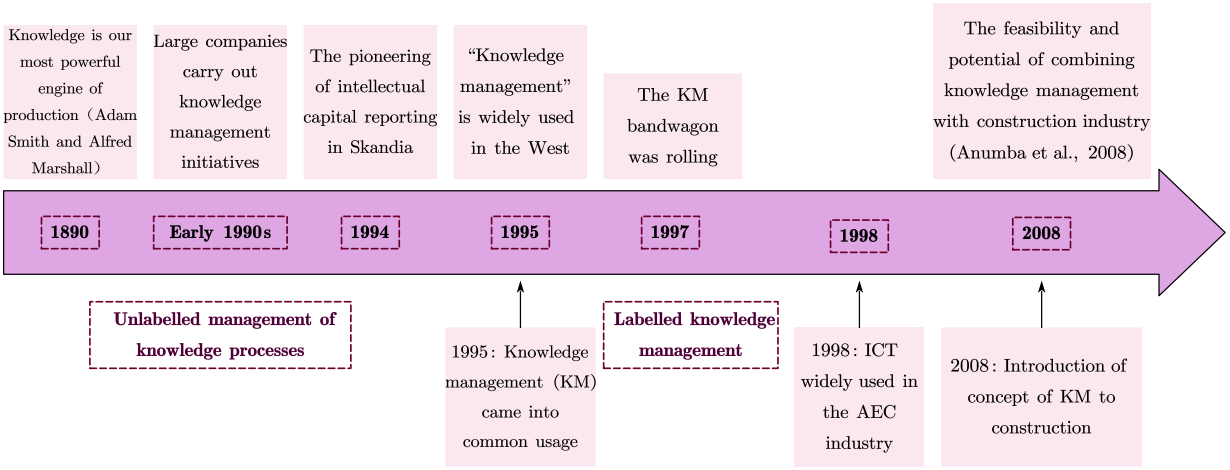

Figure 2. Roadmap of knowledge management

Knowledge management is the activity of planning and managing knowledge. As outlined by Figure 3, in the 1960s, Peter F. Drucker first introduced the concept of knowledge workers. Then, the Fifth International Conference on Artificial Intelligence defined the concept of knowledge engineering and knowledge base systems. Soon afterward, the concept of knowledge management began to be introduced in the AEC industry, among which expert systems, ontology technology and semantic network technology were the most widely used forms of KM. In the 1980s, represented by expert systems, knowledge-based systems began to be used in the construction industry. Then, in 1991, the ontology technology was applied to the monitoring of building façades. Since 2002, represented by the ifcOWL, semantic network began to be widely applied in the construction industry. In 2008, Chimay Anumba published *The Knowledge Management in Construction*. In 2012, Google proposed the concept of knowledge graphs. In addition to the three major categories of ontology, semantic network and knowledge graph, there are scholars who combine deep learning with the fusion of multi-source heterogeneous data. For example, Bai et al., 2021 combine knowledge management with Bayesian network to develop a knowledge driven project safety assessment model.

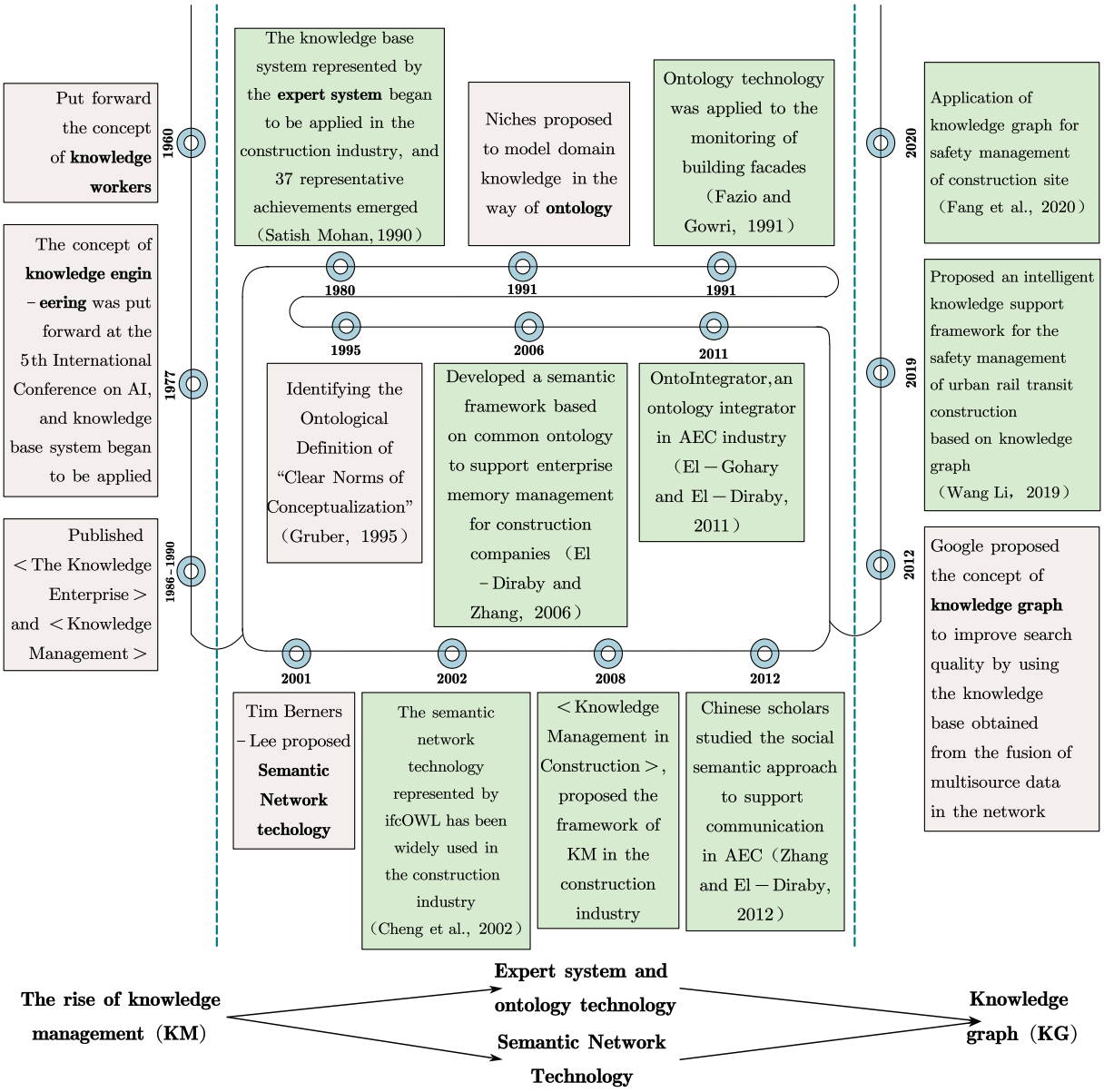

Figure 3. Evolution of knowledge management applications

3.2 Suitability of ICT-assisted knowledge management and AEC industry

AEC is a special industry, that unlike factory-like assembly line manufacturing, has characteristics such as temporary, instability, liquidity (Garcia et al. 2020), complex (Tong 2019), and dynamic (Zhang et al. 2014). Figure 4 presents a mind map of the suitability of ICT-assisted knowledge management and AEC industry. Moreover, data in the AEC industry is usually unstructured and difficult to be recognized by machine language (Yao 2019). This requires industry staff to organize and manage data through various software or management means with the help of proper knowledge management. However, at present, the development of knowledge management in the AEC industry is not sufficient, mainly due to the uneven knowledge level of practitioners, conflicting interpretations of knowledge management

(Carrillo and Chinowsky 2006), and the poor ability of multimodal information management. In view of the dilemma of knowledge management in the AEC industry, the benefits of combining ICT with knowledge management are obvious. ICT helps to lower the entry barriers in practice, establish a unified collaborative communication format, facilitate overall planning, deal with the miscellaneous information of various project activities and enhance communications among project organizations (Ahuja et al., 2010; Martínez-Rojas et al., 2015).

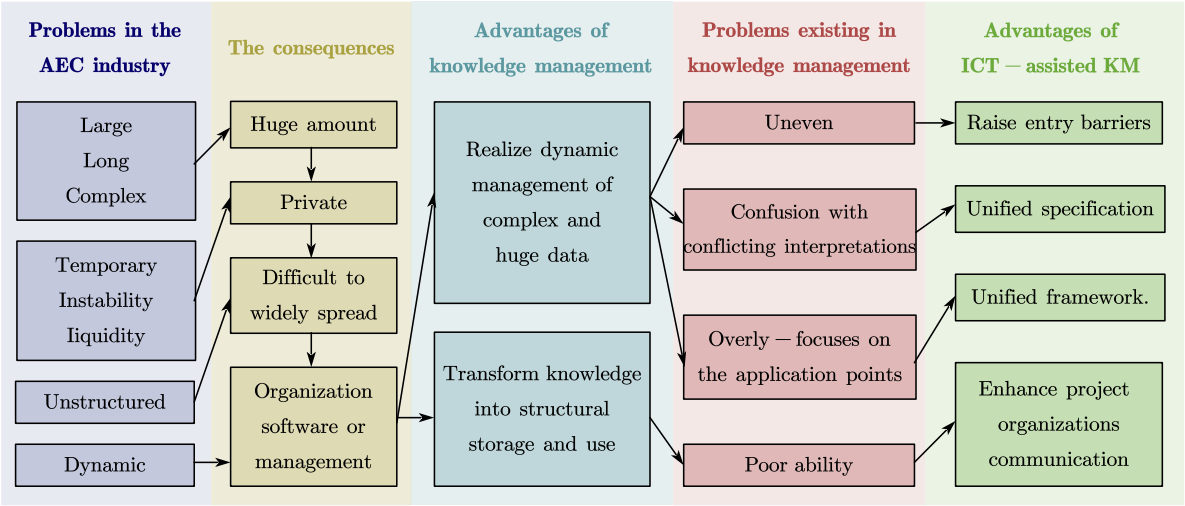

Figure 4. Relationship between AEC industry, knowledge management and ICT

3.3 Classification of selected literature

The collected literature are listed in Table 2, aiming to comprehensively analyze the relationship between ICT and knowledge management as well as the existing research gaps. The horizontal coordinates are the 5 main processes of knowledge management (Jashapara 2016), and the vertical coordinates are the main ICT with the highest frequency after the statistics of collected literature.

Table 2. ICT used in the literature and their correspondence to the five processes of knowledge management

	Organization	Acquire	Share	Store	Evaluation
Linked Building Data (LBD)	(Rasmussen et al., 2019) (El-Diraby et al., 2019) (Wagner et al., 2020)	(Pauwels et al., 2017)	(Rasmussen et al., 2019) (Dinis et al., 2021) (Pauwels et al., 2017) (Hu et al., 2016) (Pauwels et al., 2017)	(Roxin et al., 2019) (Tchouanguem et al., 2021) (Corry et al., 2014)	(Tchouanguem et al., 2021) (Zhang et al., 2021)
Semantic Network	(Rasmussen et al., 2019) (Tibaut et al., 2017) (El-Diraby et al., 2017) (Costa et al., 2020) (El-Diraby et al., 2019) (Jiang et al., 2020) (Wagner et al., 2020) (Svetel et al., 2020)	(Werbrouck et al., 2020) (Boje et al., 2020) (Huang et al., 2021) (Perez-Perez et al., 2020) (Pauwels et al., 2017) (Zhang et al., 2020) (Jiang et al., 2020) (Zhou er al., 2019) (Antwi-Afari et al., 2019) (Wu et al., 2021) (Mutis and Issa, 2012) (Finat et al., 2009)	(Valluru et al., 2020) (Tang et al., 2019) (Boje et al., 2020) (El-Diraby et al., 2017) (Niknam and Karshenas , 2017) (Zhao et al., 2020) (Tang et al., 2019) (Zhang et al., 2020) (Dinis et al., 2021) (Venugopal et al., 2015) (Pauwels et al., 2011)	(Churacharit et al., 2022) (Senaratne et al., 2021) (Zhang et al., 2020) (Roxin et al., 2019) (Tang et al., 2019) (Tchouanguem et al., 2021) (Raghavi et al., 2019) (Previtali et al., 2020) (Costa et al., 2020) (Rasmussen et al., 2021) (Corry et al., 2014) (Finat et al., 2009) (Kofler and Kastner, 2010)	(Maureira et al., 2021) (Tchouanguem et al., 2021) (Ren and Li, 2017) (Liu et al., 2020) (Zhao et al., 2020) (Rasmussen et al., 2021) (Antwi-Afari et al., 2019)
SPARQL	(Ma and Liu, 2018) (Costa and Sicilia, 2020)		(Farias et al., 2015) (Pauwels et al., 2014)		(Zhang et al., 2021)
IFC	(El-Diraby et al., 2017) (Costa and Sicilia, 2020) (Ma and Liu, 2018) (Chen and Luo, 2016) (Svetel et al., 2020) (Venugopal et al., 2012)	(Pauwels et al., 2017) (Nepal et al., 2013)	(Chen et al., 2018) (El-Diraby et al., 2017) (Farias et al., 2015) (Pauwels et al., 2017) (Kusy, 2013) (Venugopal et al., 2015) (Zeb and Froese, 2012)	(Raghavi et al., 2019) (Roxin et al., 2019) (Kusy, 2013)	
Ontology	(Kukkonen et al., 2022) (Costa and Sicilia, 2020) (Rahmawati et al., 2019)(Leon, 2020) (Ma and Liu, 2018) (Zhang et al., 2020) (Xu er al., 2018) (Tibaut et al., 2017) (Bonino and Russis, 2018) (Fiorani and Acierno, 2017) (Chen and Luo, 2016) (Venugopal et al., 2012) (Nepal and Staub, 2016) (El-Diraby et al., 2014) (Cerovsek, 2011) (El-Gohary et al., 2011) (Fioravanti and Trento, 2011) (Zhu et al., 2010) (Nawari, 2010) (Anumba et al., 2008)	(Nepal et al., 2013) (Mutis and Issa, 2012) (Park et al., 2013) (Lin and Hsieh, 2012) (Zhu et al., 2010)	(Niknam and Karshenas , 2017) (Jiang et al., 2019) (Rasmussen et al., 2019) (Dinis et al., 2021) (Boje et al., 2020) (Chen et al., 2018) (Bonino and Russis, 2018) (Ren et al., 2019) (Pauwels et al., 2017) (Farias et al., 2015) (Pauwels et al., 2014) (Kusy, 2013) (Hu et al., 2016) (Venugopal et al., 2015) (Costa and Madrazo, 2015) (Zeb and Froese, 2012) (Lee and Y, 2012) (Zhang and El-Diraby, 2012) (Zeb et al., 2012)(El-Gohary et al., 2011) (Fioravanti and Trento, 2011) (Nawari, 2010) (Anumba et al., 2008)	(González et al., 2021) (Rasmussen et al., 2021) (Previtali et al., 2020) (Kusy, 2013) (Kamsu-Foguem and Abanda, 2015) (Kofler and Kastner, 2010)	(Amorocho et al., 2021) (Acharya and Chakrabarti, 2020) (Rasmussen et al., 2021) (Tchouanguem et al., 2021) (Ren and Li, 2017) (Zhao et al., 2020) (Kovács and Micsik, 2015) (Zhao et al., 2018) (Oti and Tizani, 2015) (Zeb and Froese, 2012)
DT	(Zhang et al., 2020)	(Boje et al., 2020)	(Boje et al., 2020)	(Roxin et al., 2019)	
IoT			(Boje et al., 2020) (Tang et al., 2019)	(Tang et al., 2019)	
AI		(Finat et al., 2009)	(Boje et al., 2020) (Dinis et al., 2021)	(Finat et al., 2009)	(Khallaf, 2021)
Big Data			(Boje et al., 2020)		
Database		(Zhang et al., 2020)	(Zhang et al., 2020) (Hu et al., 2016)	(Previtali et al., 2020) (Zhang et al., 2020) (Piryonesi and El-Diraby, 2021) (Kofler and Kastner, 2010)	
OWL	(Chen and Luo, 2016)	(Pauwels et al., 2017)	(Zhao et al., 2020) (Kusy, 2013)(Pauwels et al., 2014)	(Kusy, 2013)(Kofler and Kastner, 2010)	(Zhao et al., 2020)
KG		(Pan et al., 2022)	(Rasmussen et al., 2019)		
Point Cloud	(Xu et al., 2018)	(Perez-Perez et al., 2019)			(Zhao et al., 2018)
AR		(Park et al., 2013)	(Lin et al., 2019)		
Computer Vision		(Zhong et al., 2019) (Luo et al., 2019) (Wu et al., 2021)			
SWRL	(Ma and Liu, 2018)				
Integrated Digital Delivery (IDD)					(Liu et al., 2020)
Machine Learning		(Luo et al., 2019)		(Piryonesi and El-Diraby, 2021)	(Khallaf, 2021)
VR					(Liu et al., 2020)
NLP		(Leng et al., 2019)			

Legend ■ 2008~2011 ■ 2012~2016 ■ 2017~2022

4. ICTs in the Knowledge Management of the AEC Industry

This session will explain the application of ICT related to knowledge management in the AEC industry from the perspectives of academia and industry. The analysis of the former focus on the ontology, semantic network and knowledge graph, while the latter explains the process of practical application in China with the help of the information platforms of four typical enterprises.

4.1 ICT Applications for Knowledge Management in the Academia

The ICT application of knowledge management in the academia of the AEC industry focuses on expert systems, ontology technology, semantic networks and knowledge graph, and these four applications are interrelated and interdependent. Expert systems have been developed the earliest but have been less studied in recent years. To some extent, it is a gradually obsolete technology. Ontology technology is an important basis for the development of semantic network technology, and semantic networks are the premise of the development of knowledge graphs.

Since these three techniques are complementary and interrelated, there is some duplication in the collection of papers. The published countries, published journals and contributing authors of collected papers were sorted out as shown in Figure 5, Table 3 and Figure 6.

Figure 4 is generated based on a keyword search after removing duplicate documents. There are a total of 31 countries or regions, and the top 9 countries are the United States, China, the United Kingdom, Canada, France, Belgium, Spain, Germany and Ireland. These countries or regions have been proven to lead the knowledge management of the AEC industry to a large extent.

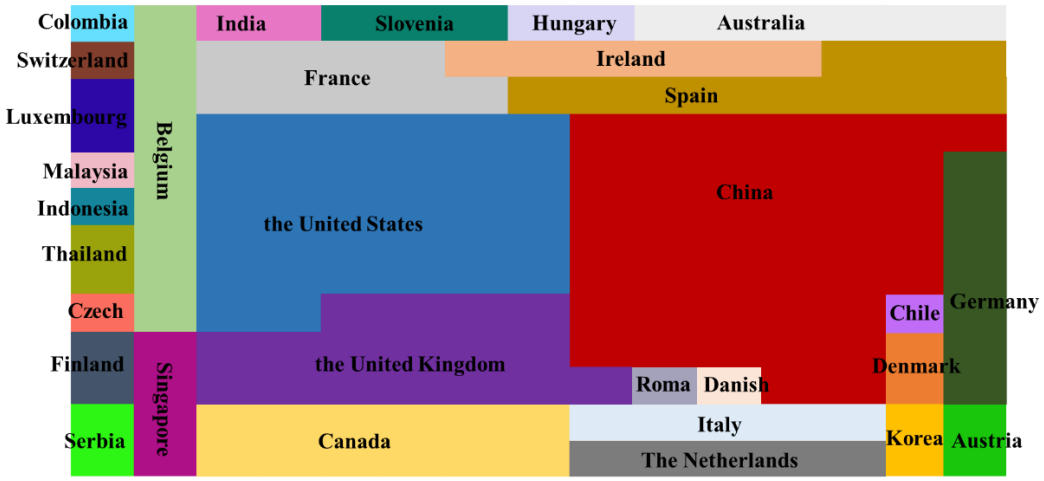

Figure 5. National distribution map of literature

Table 3 presents the journals with more than 1 published articles in the collected literature. Automation in Construction, Advanced Engineering Informatics and Journal of Computing in Civil Engineering, are more frequent and theme-related, accounting for 28.21%, 10.26% and 7.69%, respectively. These three journals are deeply rooted in the AEC industry, which shows that knowledge management and related ICTs are an important research area in the development of the AEC industry.

Table 3. Distribution of literature in the publishing journals

Journal name	Number of papers
Automation in Construction	22
Advanced Engineering Informatics	8
Journal of Computing in Civil Engineering	6
Applied Sciences	3
Journal of Information Technology in Construction	3
Computer-Aided Civil and Infrastructure Engineering	3
Engineering, Construction and Architectural Management	2
Archives of Computational Methods in Engineering	2
Journal of Building Engineering	2

In terms of the authors, 200 authors were contributing to the literature. After the elimination of authors who had only published a paper once, a two-dimensional bar chart was drawn as shown in Figure 5. Pieter Pauwels, Tamer El-Diraby, Gonçal Costa, Charles M. Eastman, Guoqian Ren, Haijiang Li, Ivan Mutis, Edward Corry, Lieyun Ding, Jiarui Lin, Zhenzhong Hu, Jianping Zhang, Heng Li and James O'Donnell have published many studies and are scholars deeply engaged in knowledge management of the AEC industry. It is also discovered that active authors continue to conduct in-depth research in the field, which also proves that ICT-assisted knowledge management has research prospects.

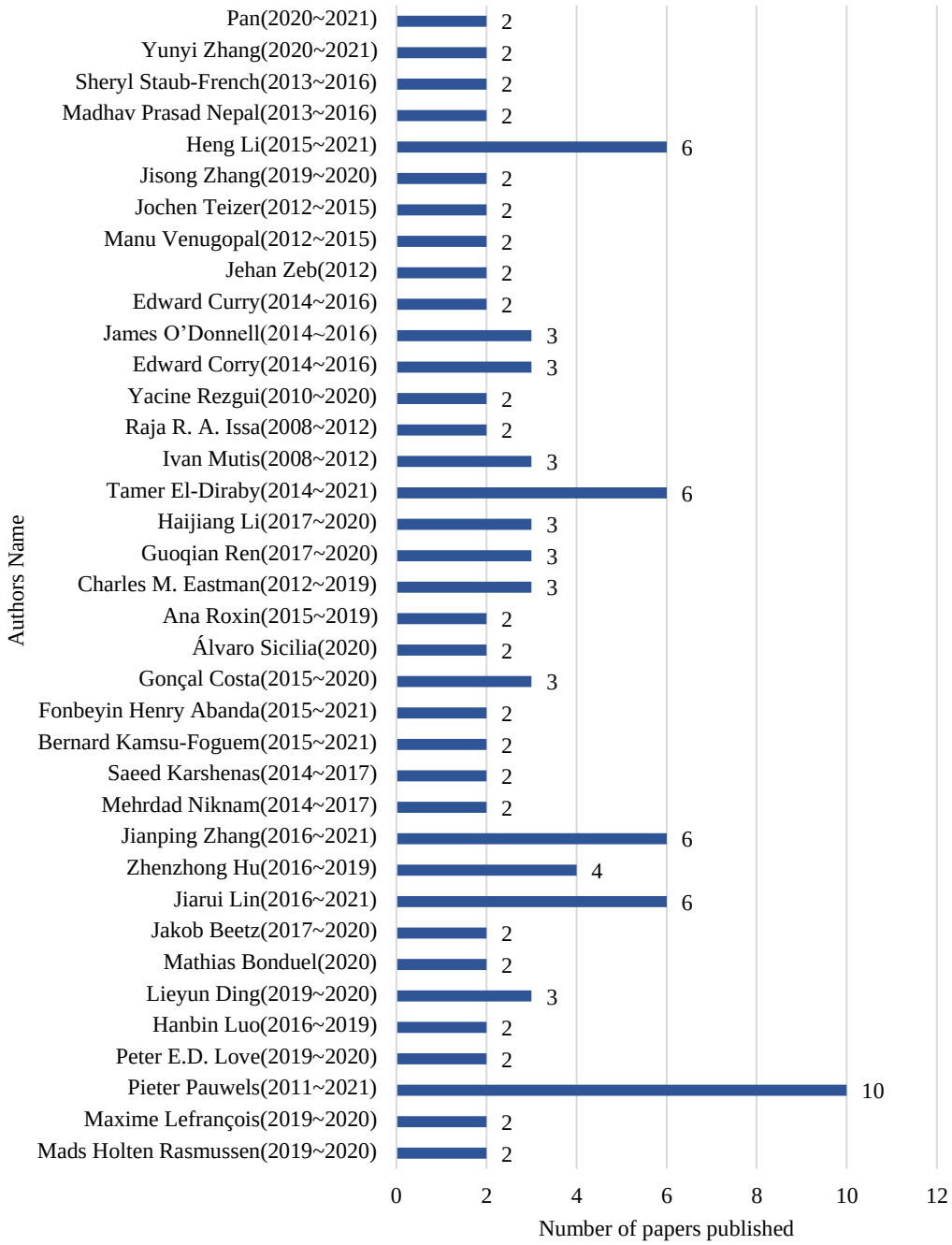

Figure 6. Author statistical chart of publications

4.1.1 Ontology applications reported by academia

Figure 7 is obtained by calculating the number of papers published in different years. Ontology technology has an early adoption with an increasing number of papers after 2010. The trend line (dashed line) also shows that the development of ontology technology in the AEC industry is still increasing. With the development of other related ontology-based technologies, its application in the AEC industry is still in the booming stage.

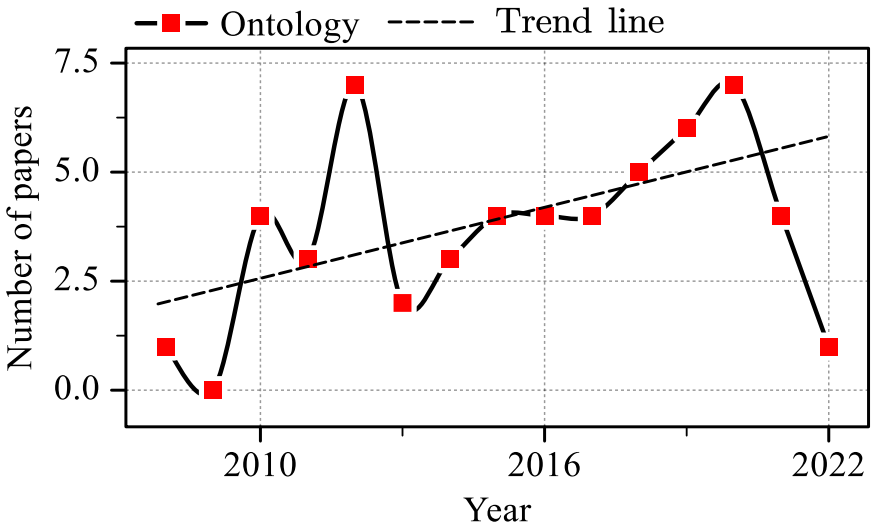

Figure 7. Statistics on the year of publication of ontology technology related papers in academic circles

Figure 8 shows the technologies presented in the papers and their published years. ICTs related to ontology are divided into 3 parts: knowledge acquisition and evaluation, knowledge share and store, and knowledge organization. Before 2016, the results showed that ontology-related ICTs were concentrated on Domain Ontology, Concept Maps, Feature-Based Modelling, COBie and Information Extraction. In 2017 and beyond, Decision-Making and Linked Building Data (LBD) technology continued to emerge. In addition, some ICTs have always played an important role, such as Collaborative Networks, Ontology-Web-Language (OWL), Industry Foundation Classes (IFC), Interoperability, Inference and Databases. From the perspective of knowledge acquisition and evaluation, ICTs have changed from Information Extraction to Decision-Making, during which IFC has always been an important role of acquiring building information. From the perspective of knowledge share and storage, Collaborative Networks has always been an important ICT that appear with high-frequency in research, while Information Delivery has been weakened continuously, and Query Languages has gradually become prosperous after 2018. This shows that knowledge management is not only about storing and calling multi-source heterogeneous data, but also to establish relationships and realize the functions of reasoning and prediction.

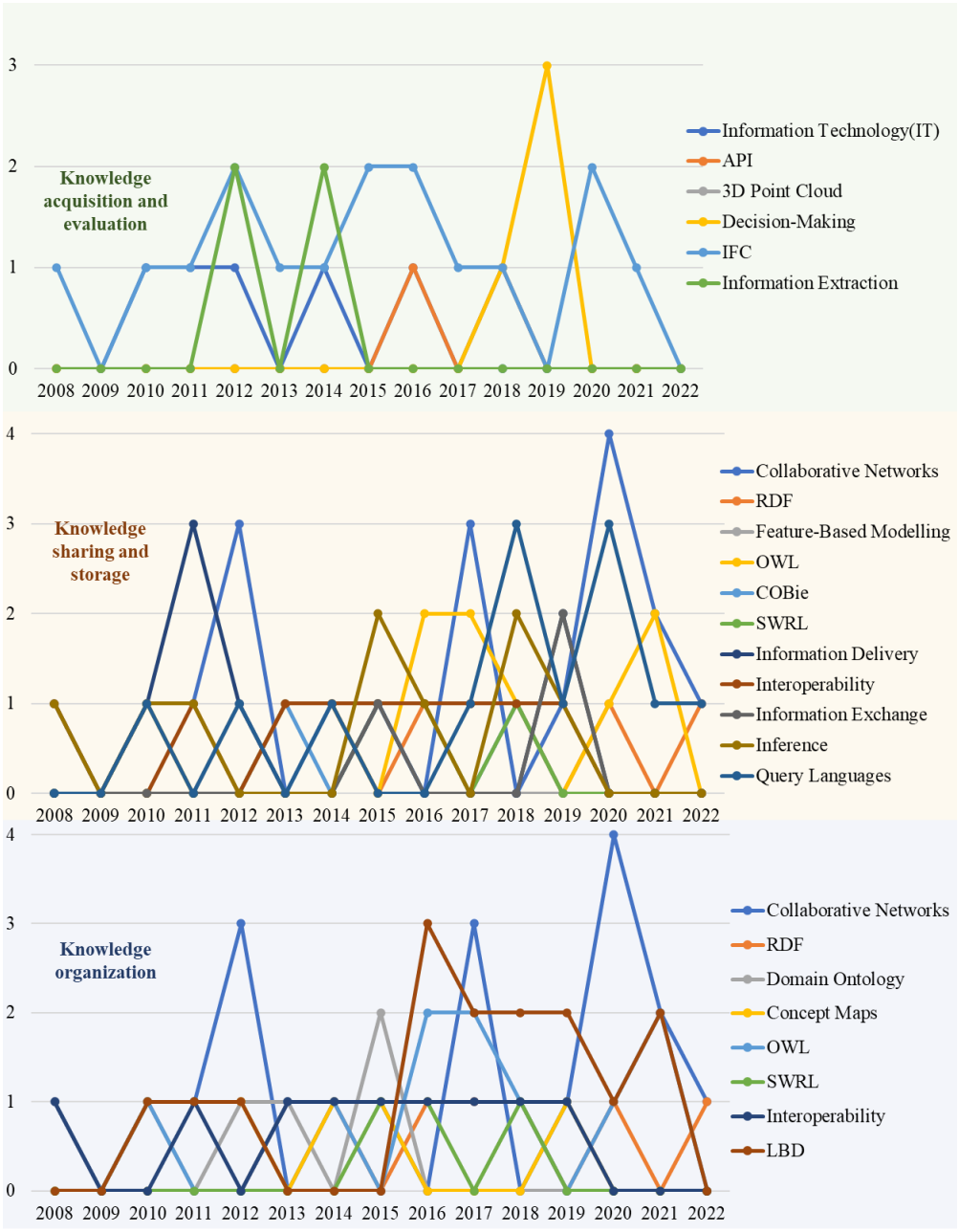

Figure 8. An analysis of the year of publication and the corresponding application of ontology technology in academia

Ontology is the foundation of semantic network and knowledge graph, and has the most abundant literature and the most extensive application fields, as shown in Figure 9. In the past three years, the application of ontology in the AEC industry has been widely investigated. Acharya and Chakrabarti proposed a "conceptual tool for environmentally benign design" (Acharya and Chakrabarti, 2020). Zhang developed sustainable structural design (SSD) with the help of ontology technology and digital twinning (Zhang et al., 2020). Djuedja proposed a tool that can be used to make environmental data available in the early phases of the building lifecycle (Djuedja et al., 2021). Information exchange and sharing have gained the most interest in all literature and made great achievements in the past three years. Costa and Sicilia analyzed

the potential of semantic network query languages to facilitate the data transformation of building data through different alternatives (Costa and Sicilia 2020). Jiang carried out research on engineering information interoperability in information representation, information query, information exchange, information extension, and information integration (Jiang et al., 2019). Ren developed a novel schema with the help of an information delivery manual (IDM), which specifies the required information exchanges (Ren et al., 2019). The fields of city districts, geographic, enterprise and negotiation and decision-making, which appeared in the literature for the first time in several years, represent the new trend of industry development to some extent. Rahmawati introduced BIM and e-negotiation practices in the AEC consulting businesses (Rahmawati et al., 2019). Kovács and Micsik provide a decision method that can monitor the status and performance of the BIM model from different aspects at each project milestone (Kovács and Micsik, 2019). The above two papers describe recent developments from the perspective of negotiation and decision-making. In the field of enterprises and geography, Girón proposed an ontology integration model with the help of enterprise architecture (AE) and geospatial enterprise architecture (AE-GEO) to describe the architecture. By subdividing knowledge acquire and evaluation, as shown in Figure 10, it is found that in recent years ontology has been continuously applied to building operation and maintenance management (Amorocho et al., 2021, González et al., 2021), reflecting the gradual transition of the AEC industry from “well-constructed” to “well- experienced”.

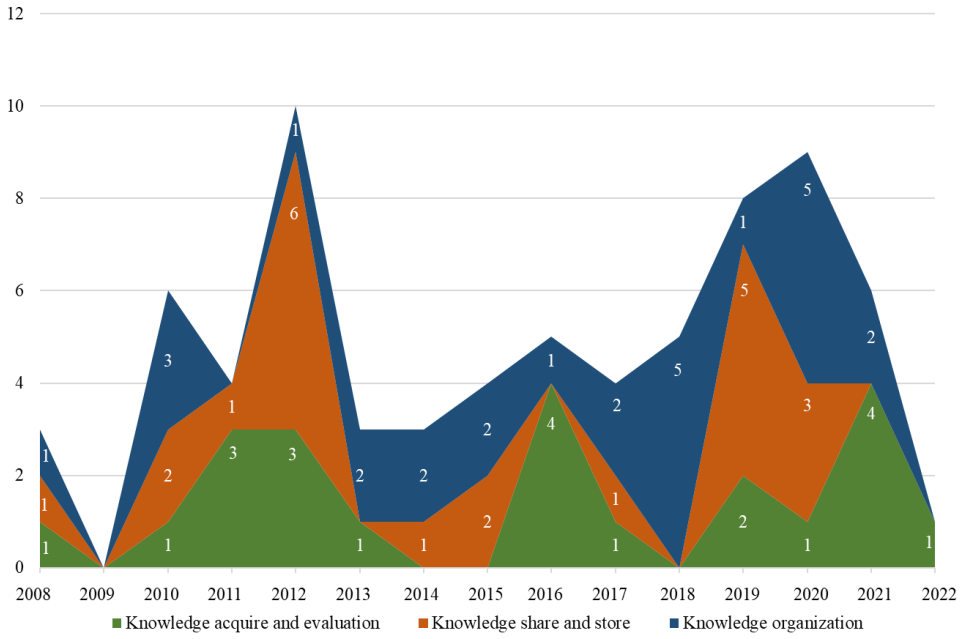

Figure 9. Analysis of the application of ontology technology in the AEC industry

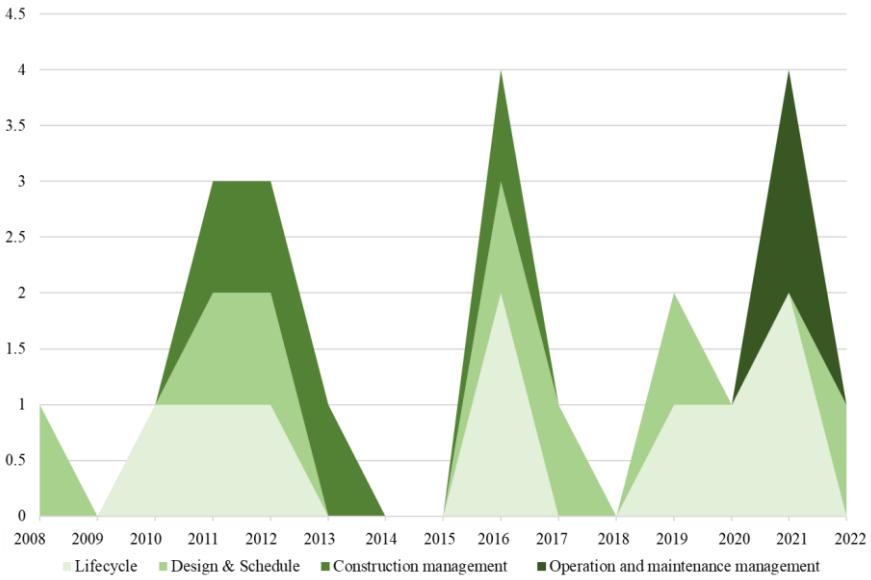

Figure 10. Analysis of the application of ontology technology in knowledge acquire and evaluation

Based on the analysis in this section, we can make the following findings about ontology:

- From the perspective of ICTs, the upgrading of technology is obvious, but there are also some classic technologies which are continuously applied and studied.
- The ICTs used in different knowledge management processes has some emphasis, but Collaborative Networks and OWL are not only commonly seen in the dimension of knowledge management process, but also stay on the ICT timeline for a long time. This shows that they are the basic tools for the application of ontology in the AEC industry, and have great research significance.
- The applications of ontology in different processes of knowledge management are relatively balanced, similar to the overall quantity change.
- From the perspective of the AEC industry, the development of ontology has gradually shifted from the design and construction of buildings to the operation performance and defect detection in the operation and maintenance phase, which means that "making building users more comfortable" is likely to be a future development trend.

4.1.2 Semantic Network applications reported by academia

As shown in Figure 11, according to the trend line (dashed line), an increasing number of research papers have been published since 2008. After 2016, with the development of ontology technology, query language and other related technologies, the application of semantic network technology in the AEC industry began to develop vigorously from sporadic studies.

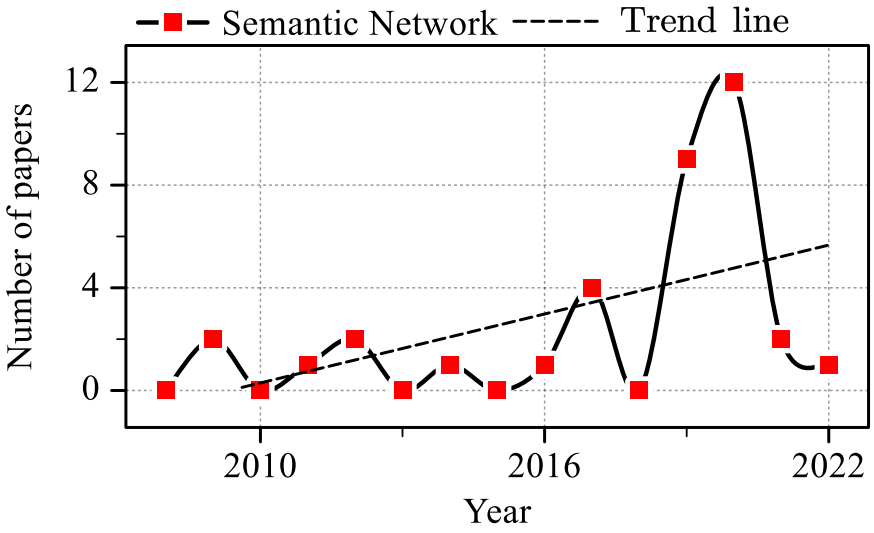

Figure 11. Statistics on the year of publication of semantic network-related papers in academic

Figure 12 shows the techniques presented in the papers and their published years. Conceptual models are related ICTs that appeared in the early stage, and IoT, Information Exchange, LBD, AI and Query language emerged in recent years. In addition, Collaboration Networks, RDF and IFC have long been developed as basic technologies. As far as the knowledge acquire and evaluation process is concerned, AI, IoT and Digital Twin are all new technologies that have developed rapidly after 2017. As far as knowledge store and share are concerned, IFC, OWL, Collaboration Networks and LBD had little attention in the early stage but have been developed rapidly after 2017. In terms of knowledge organization, Collaboration Networks, LBD, OWL and Database have developed relatively well after 2017. Among them, the fusion of deep convolutional neural network and knowledge management is a new trend that has emerged in recent years, and it is expected to be more applied in the AEC industry.

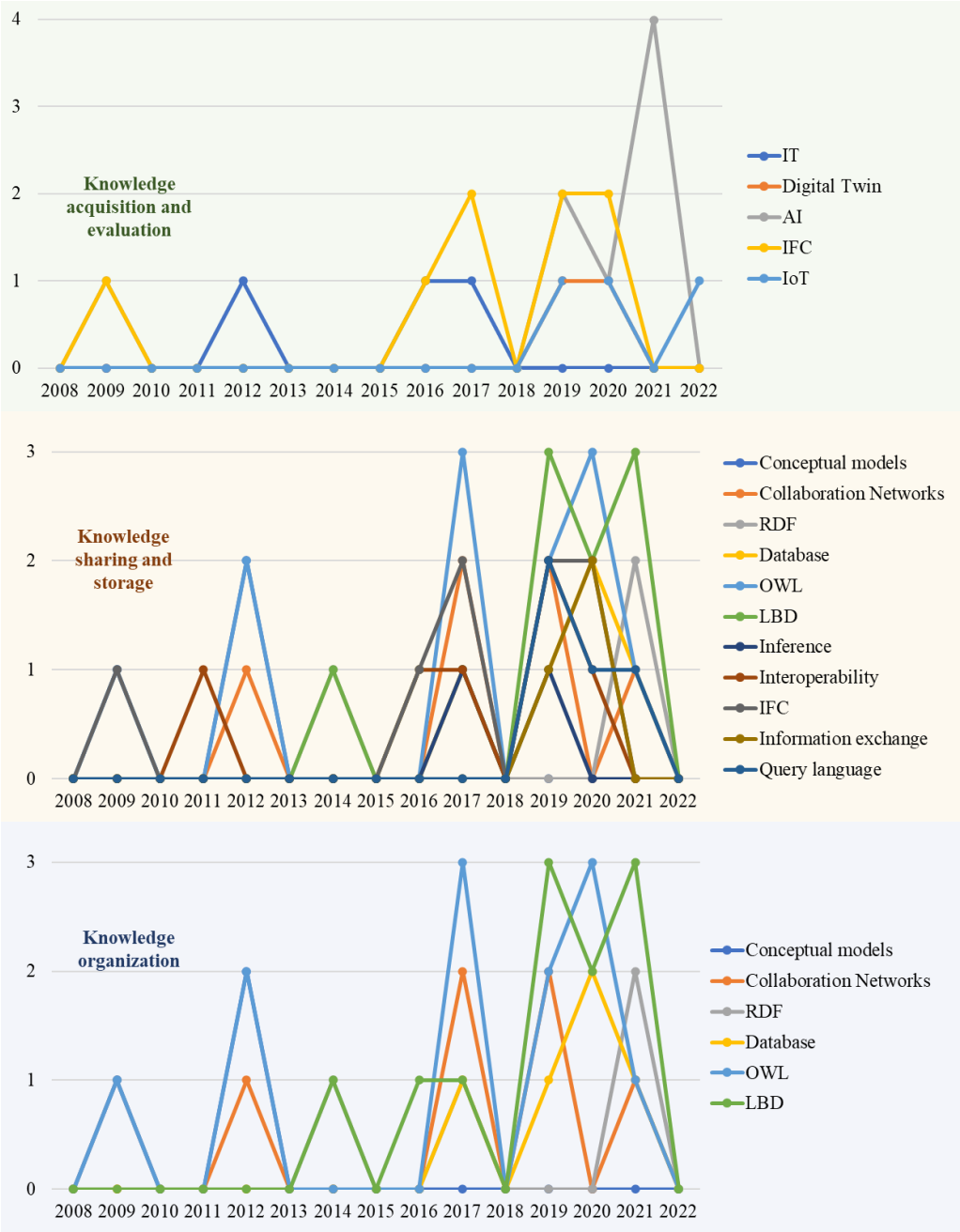

Figure 12. An analysis of the year of publication and the corresponding technology for Semantic network technology in academia

As time goes by, the application of semantic networks and related technologies in academia is increasingly intensive and frequent, and its application fields are also evolving, as shown in Figure 13. Green building and whole-process semantic technology are the most involved fields, belonging to knowledge organization and knowledge acquire and evaluation processes respectively. The combination of these two fields has great development potential, including the green building performance evaluation (BPE), structural thermal performance analysis, green system design and development, sensor data integration, environmental assessment, and building energy performance (BEP) simulation. Zhao integrated ontology with

406 the green building post-occupancy assessment domain to develop a unified semantic model that
407 systematizes the fragmented knowledge (Zhao et al., 2020). Liu generated the project green
408 mark score digitally and developed a BIM platform to enhance the productivity and accuracy
409 as far as Envelope Thermal Transfer Value (ETTV) calculation is concerned (Liu et al., 2020).
410 El-Diraby designed and developed an online system called Green2.0, where social network
411 analysis and semantic modelling tools are used to extract information from interactions (El-
412 Diraby et al., 2017). Finat establishes a semantic framework capable of recognizing patterns,
413 managing models, and exchanging publicly supported information, improving interoperability
414 for sensor data capture, monitoring, and control (Finat 2009). Djuedja built the criteria for the
415 classification of language code identifiers (LCIDs) in the field of environmental assessment,
416 with the help of semantic network technology to enhance interoperability between
417 heterogeneous systems (Djuedja et al., 2021). Costa built the criteria for the technology to
418 integrate data into BEM simulation models automatically (Costa et al., 2020). In addition, the
419 application of Semantic Network technology itself in the construction process is also evolving.
420 In 2009, Svetel summarized the role of the semantic network in knowledge management in the
421 construction industry and pointed out that triples are structures consisting of subjects, predicates
422 and objects (Svetel and Pejanovic 2010). Mutis proposed an approach to semantically reconcile
423 representations through the study of the internal role of representations (Mutis and Issa 2012).
424 Corry found that traditional methods of information capture fail to consider the value of soft
425 information available throughout a building. Therefore, he accessed soft AEC data by using
426 semantic technology (Corry et al., 2014). In 2017, which was the milestone of the significant
427 growth of Semantic Network technology in the AEC industry, Pauwels presented a review of
428 Semantic Network technologies in the AEC industry (Pauwels et al., 2017). In the past three
429 years, semantic network technology has developed more rapidly. For example, Maureira et al.
430 (2021) combines knowledge query with AI, which enriches the semantic network of the AEC
431 industry and lays the foundation for the development of knowledge graphs.

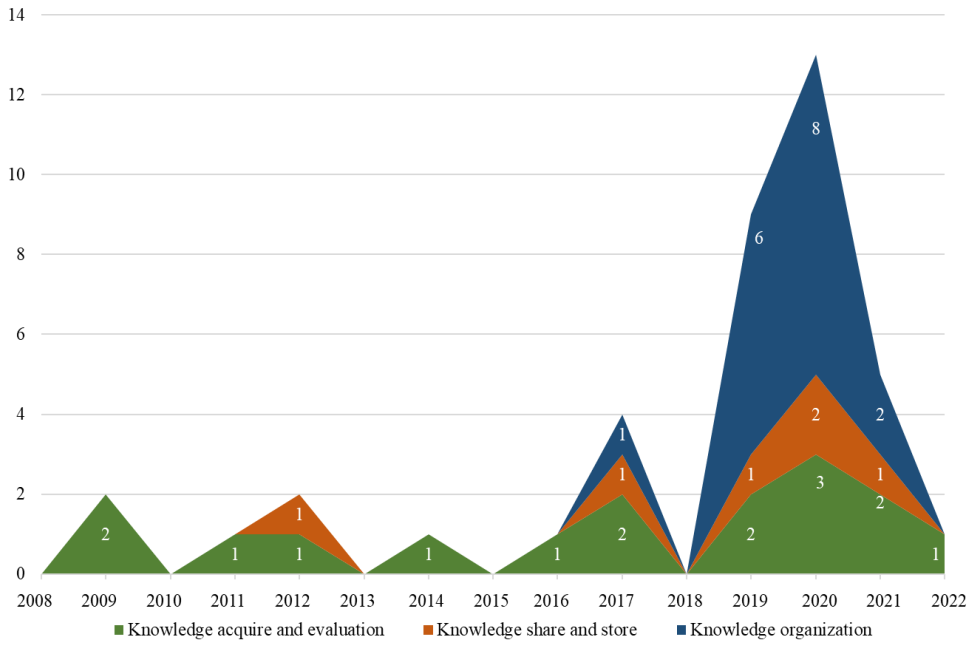

Figure 13. Analysis of the application of semantic network in the AEC industry

Based on the analysis in this section, we can make the following findings about semantic network:

- The development of the semantic network is advancing in an orderly manner. In terms of ICTs related to the semantic network, there is also a certain lag compared with the ontology, which also shows that semantic network is a development of ontology.
- Different from Ontology, Semantic network has developed rapidly in the past three years, especially when combined with advanced ICT such as deep learning and machine learning.
- The development of Semantic network in different process of knowledge management is relatively balanced, similar to the overall quantity change.

4.1.3 Knowledge Graph applications reported by Academia

Knowledge graph is a new concept proposed by Google in 2012 *(White Paper on Knowledge Atlas Standardization)*, but its development in the AEC industry is not rapid, as reflected in the fact that only 13 valid studies were obtained by searching the keywords "AEC and Knowledge graph". However, this does not mean that the knowledge graph is not suitable for the AEC industry or that its application prospect is meaningless. In fact, the development of the knowledge graph is necessary and promising, but there are some bottleneck problems existing today waiting for the resolution and leading to the slow development.

A knowledge graph is essentially a semantic network that expresses concepts, entities and relationships among entities in the objective world in a structured form. As shown in Figure 14, the knowledge graph consists of a data layer which is composed mainly of knowledge networks

of entities, attributes and relationships, and a schema layer which is a combination of a knowledge base and ontology. Knowledge graph has the potential to tackle the issues raised in knowledge management in terms of fragmentation, complexity and low-reuse rate in the AEC industry. One example is reported that realizes the unified integration of multidimensional information from building model information and project progress information for heat loss calculation in the building space (Rasmussen et al., 2019).

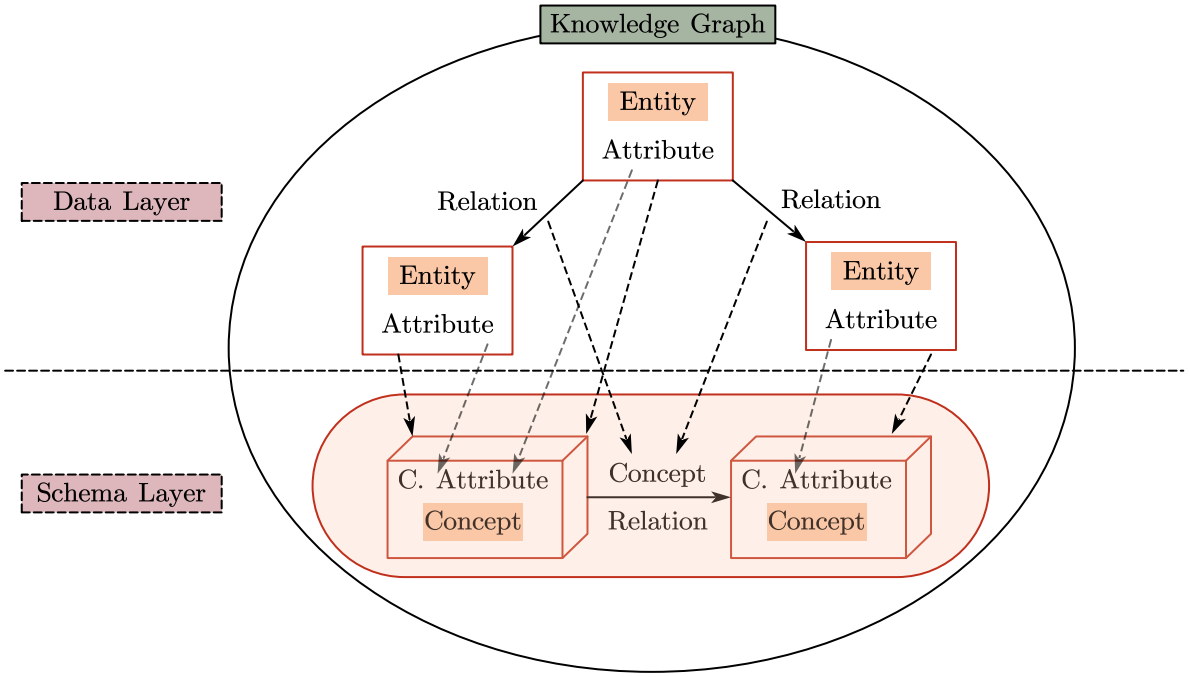

Figure 14. Logical structure of the knowledge graph (Reproduced according to Pan et al. 2021)

As shown in Figure 15, ontology is the conceptual model of knowledge graph. At the same time, the combination of ontology and knowledge base is part of the schema layer. Knowledge graph is composed of entities and relationships between entities. Semantic network is a part of knowledge graph data layer. Data layer and Schema layer are organically combined to form knowledge graph. In addition, knowledge graph, as the foundation of semantic content of the internet, can continuously improve itself. For the AEC industry, the knowledge graph integrates important ICT means in the knowledge management process of the AEC industry, combines ontology and semantic network, and is the most advanced knowledge management technology at present.

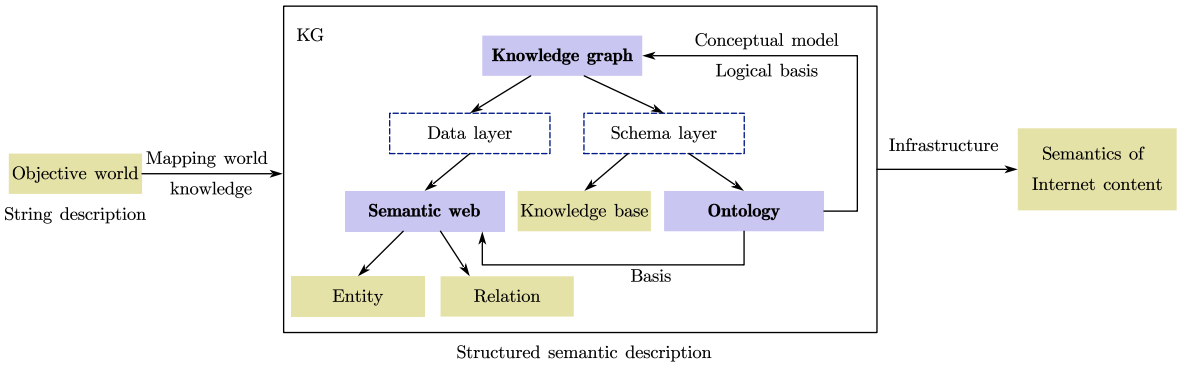

Figure 15. Relationship between the knowledge graph and other related technologies

As shown in Figure 16, knowledge representation, including symbol-based knowledge representation and learning-based knowledge representation, is the basis of other contents of the knowledge graph. The former includes first-order predicate logic representation, production rule representation, frame representation and semantic network representation (Zhang et al., 2020). The knowledge modelling and storage structures are shown in the figure, including complex relationship modelling, presentative modelling, tree structure and diagram structure. Knowledge acquisition includes entity extraction (also known as named entity recognition, NER), attribute extraction, relationship extraction and event learning. Essentially, it forms a knowledge unit extracted from natural language texts and other multimedia documents, such as pictures and videos, by automated, semiautomated or unstructured techniques. Knowledge fusion includes knowledge updating and processing, aiming to integrate different knowledge graphs into a unified and concise form, which is easy to be stored and read. Knowledge graph query reasoning (also known as knowledge computing) carries out reasoning and mining for incomplete or incorrect information based on the completed knowledge graph to realize knowledge updates, queries and links. The knowledge graph inference includes logic-based and chart-based approaches. Knowledge graph applications include visual decisions, intelligent questions, machine reasoning, recommendation systems, prediction events and semantic search. Knowledge graph has been widely applied in the fields of intelligent medical treatment, transportation, retail logistics, justice and public security. However, the development of knowledge graphs in the AEC industry is still not significant.

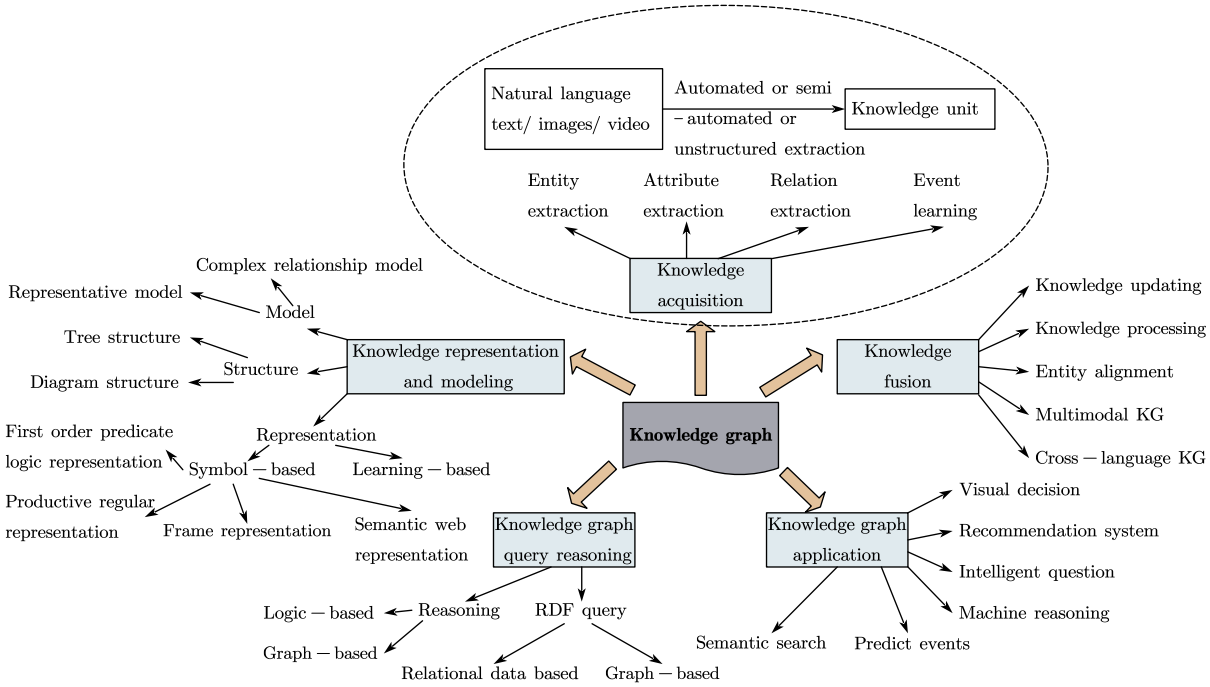

Figure 16. Main content of the knowledge graph

Scholars have carried out the pilot applications of knowledge graphs in the AEC industry. Ren used the Chinese knowledge map CN-DBpedia to realize automatic annotation (Ren et al., 2018). Fang proposed a knowledge graph that can automatically and accurately identify danger considering the dynamic nature of the construction site. (Fang et al., 2020). Pan combined zero-shot human-object interaction detection techniques with general KGs to update the construction activity KG (Pan et al., 2022).

4.2 ICT Applications for Knowledge Management from the Industry's Perspective

Practice is the sole criterion for testing truth (Akinola, 2021). The application of knowledge management and related ICT technologies in academia eventually needs to be tested and implemented in the industry. The Global Most Admired Knowledge Enterprise (MAKE) award is a widely recognized award for knowledge management. Over the years, the companies that have won this award are mostly involved with management consulting, information technology, professional services, automobile, medical care, media. However, limited enterprises are related to the construction industry.

While reviewing the application of knowledge management by Chinese real estate enterprises, results showed that many enterprises have carried out the investigation and application of knowledge management-related technologies, but there is a lack of large-scale research. As shown in Figure 18, UAVs, AI design, building robots and BIM systems are typical intelligent construction applications that represent the level of development of knowledge

management. As shown in Figure 17, the BIM system, as the basic and core part of the ICT application of knowledge management, has been used by 86% of real estate enterprises, while other technologies are hardly used due to the different strategies adopted by the real estate enterprises.

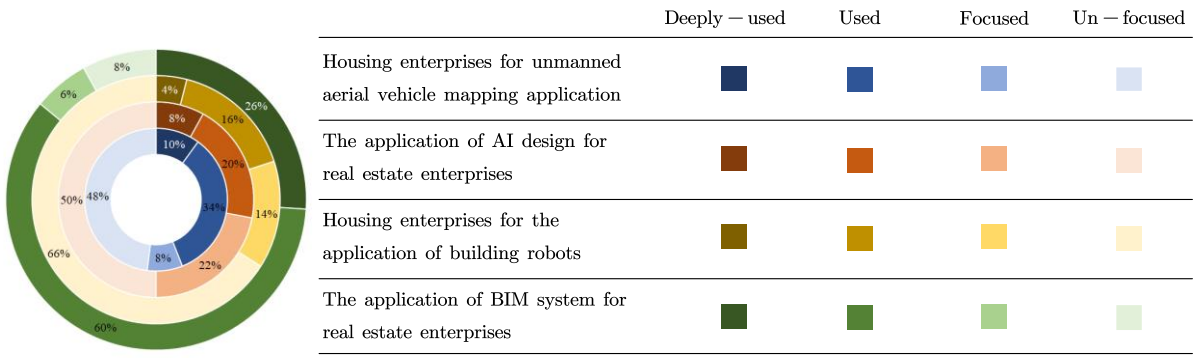

Figure 17. Application of four key ICT technologies for smart building

Note: (source): collated by Kerry Research Center and Guosen Securities Economics Research Institute

After the investigation of the ICT applications of knowledge management used by four typical real estate enterprises, Figure 14 shows that enterprises have widely carried out the application of BIM, AI, VR, AR, information exchange, semantic networks, databases and other technologies in practical applications and have made some significant achievement. However, many ICT applications have not been mentioned in the previous academic literature, such as the application of image recognition and scene interaction in the marketing of Enterprise A which achieved an immersive online display of real housing resources and offline interactive display to offer a good user experience. Enterprise B realizes real-time acquisition and database connection through ERP (Enterprise Resource Planning), making the process clear and professional. With the cases collected from the industry, the differences between the ICT application of knowledge management in academia and the industry are analyzed.

- First, there is a lag between ICT application in the industry and in academia. For example, some advanced technologies such as text sentiment analysis, representation learning and knowledge mapping have not been adopted by enterprises.
- Second, the enterprise focuses on the end-to-end integration and application of different technologies, while academic research focuses on the potential of a certain technology. For example, the “Fertile soil project” of Enterprise B integrated AI, VR,

dynamic management, visualization, management, 3D printing and other ICT technologies based on the BIM platform.

- Third, the research of knowledge management in academia and industry has different preferences, but only by combining both of them can research and practice be mutually reinforced.

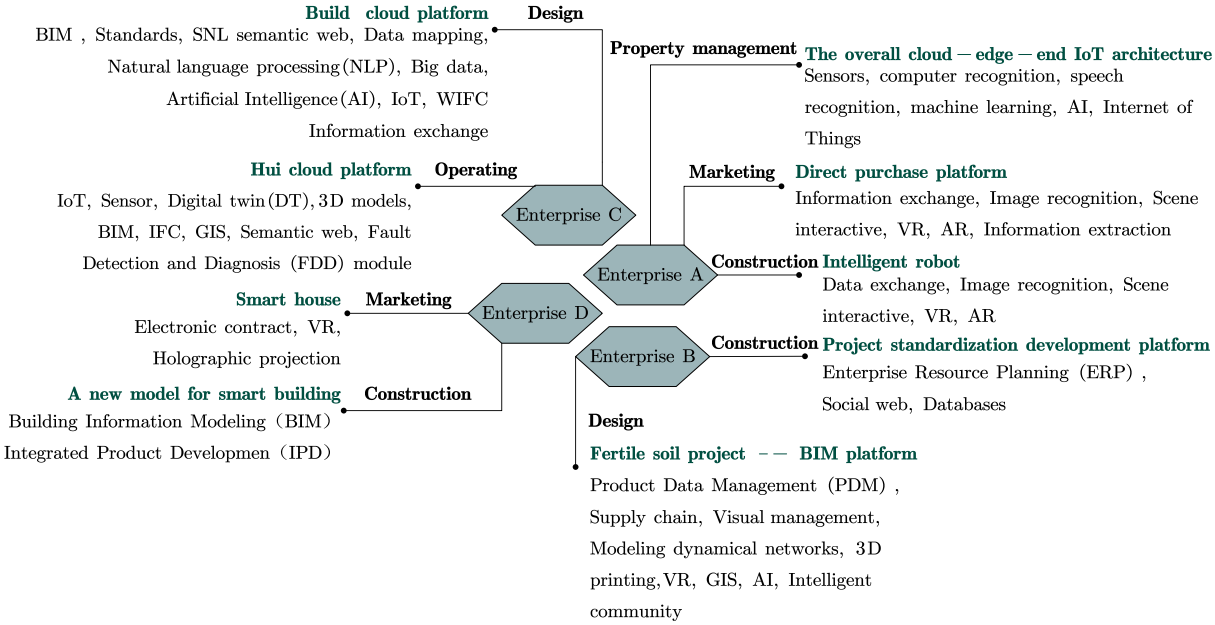

Figure 18. Typical enterprise application of ICT for knowledge management

5. Discussion and Suggestions

In the context of this review, the following findings can be reported.

(1) ICT-assisted knowledge management is highly adaptable to the AEC industry.

AEC industry is characterized by temporary, large volume, dynamic change and unstructured data, which causes the knowledge to be controlled by few people and hard to be spread. Knowledge management can help solve this problem, but there are some problems in the development of knowledge management in the AEC industry, it is not enough to just propose the application of knowledge management in the AEC industry due to the confusion of management, uneven level of practitioners and deviation of research focus. It is ICT that has the ability to solve the dilemma of knowledge management. For example, ICT-related teaching activities can improve the level of professionalism of personnel in the AEC industry, which lifts the threshold of employment; ICT is able to establish unified data transmission patterns and speed up the spread of information through collaborative platforms. In conclusion, ICT-assisted knowledge management is highly adaptable to the AEC industry.

(2) The development of Ontology in turn helps the development of other key technologies of knowledge management in the AEC industry, Ontology, semantic network and knowledge graph interact and promote each other.

In terms of the number of papers, the number of valid studies about ontology technology is twice the number of valid studies about semantic networks. The timeline of papers shows that paper on ontology has exploded in 2012 and the last three years. The first surge in the number of papers is speculated to be related to the formal introduction of semantic network applications in the AEC industry and the formal specification of knowledge graphs. Since these three technologies are composed and complementary to each other, the application of one technology in the AEC industry is closely related to the development of other technologies. The second surge in ontology-related papers was in the last three years that was similar to the surge in semantic network technology, which also demonstrated the interaction between technologies. Second, as far as AEC is concerned, in terms of keywords found in the literature, papers about ontology and Semantic Network had a lot of overlapping. Third, from the point of view of applied technology, we clearly find that the picture of ontology technology involves richer ordinates than semantic technology. Both have similar applications, including digital twins, the Internet of Things (IoT), big data, linked data, inference and information exchange, showing that ontology technology is likely to be the basic technology of semantic networks.

(3) Knowledge graphs will become one of the important means of knowledge management in the future.

Knowledge graph (KG) is an efficient tool for knowledge management that can effectively reuse, retrieve and visualize knowledge in a structured way（Pan et al., 2021). Knowledge graph application is the research aiming at the specific problems in the comprehensive application of many technologies. Basically, both ontology technology and semantic network technology are used in knowledge graphs, which proves that knowledge graphs are composed of various typical technologies, and knowledge graphs have broad research potential.

(4) The application of ICTs for knowledge management in the industry lags behind the research of ICTs in academia.

In the industry, knowledge management is achieved by integrating various ICTs that can form end-to-end solutions. Meanwhile, most of the research on knowledge management in the academia focus on a single point of view that aims to expand the frontiers of ICTs for knowledge

management in the AEC industry. Thus, many innovative technologies have been introduced as a concept in academia, but the practical effectiveness of related technologies has yet to be tested and verified by the industry, which is also a reflection of the lag in the application of ICTs for knowledge management in the AEC industry. Only when academia and industry keep advancing at a similar speed at research and development, can the emergence of knowledge management be healthy and stable.

(5) Knowledge management in the operation and maintenance stage will be important research direction.

In terms of application fields, in the early years, scholars focused more on knowledge management in the design phase or construction phase. In recent years, more and more attention has been paid to the operation and maintenance stage of buildings, which imposes higher requirements for the level of knowledge management.

In the process of the literature review, some problems in the current ICT-assisted knowledge management have been found.

(1) Practitioners are becoming more positive about knowledge management, but there are still large numbers of people who do not understand the ICTs.

Structural design and project company management, as key areas of ICT application, have developed rapidly in recent years (Lu et al., 2014). It is demonstrated that the knowledge management initiatives used by these companies have clearly benefited the business (Carrillo and Chinowsky 2006). The whole industry has realized the prospects and benefits of knowledge management, both in terms of the number of papers, fields involved and the breadth of technologies applied by academia to the AEC industry and in terms of the development of various knowledge management platforms in the industry. However, from the perspective of academia, there are problems applying knowledge management-related technologies to the production process. From the perspective of the industry, there is a lack of understanding from the users who use the knowledge management platform. There is a certain gap between theory and practice.

(2) The application of ICT-assisted knowledge management technology in different parts of the AEC industry is blooming everywhere; however, there is a lack of industry-oriented integration and standardization.

Through the analysis of the literature of ontology technology and semantic network, most of the literature focuses on the specific research field. In addition, there are conflicting interpretations of knowledge management within the company and confusion about the lack of differentiation from information management systems (Carrillo and Chinowsky 2006). Thus, the interoperability problem still is the biggest stumbling block to the development of knowledge management. The interweaving of verbal and nonverbal communication, coordination, and collaboration are important for all phases of the project and for interface management (Lu et al., 2015). There is much literature on "semantic interoperability" and "interoperability" as key technologies, but most of the literature focuses on natural language, images processing and 3D modelling.

(3) Lack of evaluation criteria for knowledge management and corresponding ICT applications.

In the collected literature, there are few evaluation criteria or evaluation systems of ICT for the AEC industry. Among these systems of ICT, Cerovsek argued that the metrics should provide measures for usability, correctness, complexity, and coverage of modelling constructs (Cerovsek 2011), Kovács and Micsik specified milestones, discipline designers, indicator metrics, and topics for evaluation using ontology and aggregation rules (Kovács and Micsik 2019). However, generalizable findings that may be extended across the industry remain somewhat elusive (Franz 2019). Whether it is the whole process of the project or the application of a knowledge management platform for construction enterprises, there is no recognized evaluation system, which may be due to the AEC industry involving a large number of participants, complex information related to the project, performance target diversification, etc. To some extent, the quantitative evaluation of knowledge management in AEC has not been resolved.

5. Conclusions and Future Work

This paper reviews ICTs for knowledge management in the AEC industry. From the time period of valid literature selected, this review covers ICT-assisted knowledge management in the AEC industry from 2008 to 2022. We continue the work of Yepes et al. (2021) and Lu et al. (2012), and summarized the progress of ICTs for knowledge management in the AEC industry. Then, this paper discusses the ICT application technology of knowledge management in the AEC industry from the perspectives of academia and industry. From the academic point of view,

the ICT-assisted knowledge management methods are statistically analyzed from the time dimension and the five processes of knowledge management. From the perspective of the industry, the development in practical applications of the industry is described through the industry reports and the actual applications of 4 typical enterprises. Moreover, based on the above-mentioned statistical analysis of the literature, this paper obtained 5 findings, summed up 3 challenges brought by industries to ICT-assisted knowledge management. In response to the above discussion on the development of knowledge management for the AEC industry, the following suggestions are proposed.

First, in the industry, training should be strengthened to improve the skills and awareness of practitioners. Constant communication and corporation between universities and enterprises can mutually promote the ability to study knowledge. In addition, it is necessary to guide students to fully understand knowledge management and ICT skills in the university to develop a multidisciplinary learning habit.

Second, it is recommended that uniform standards should be established in terms of the interoperability issues. There are 5 papers in the collected literature dealing with interoperability in semantic networks and 10 papers in ontologies. A knowledge graph will be an important means to further tackle this problem. Moreover, the knowledge management technology should be developed synchronously with the evolving ICTs, and the integration of conceptual knowledge management technology reported by academia and ICT applications in AEC should be strengthened. This in term reflect the need for strengthening the awareness and training of practitioners in the industry.

Third, the government is suggested to take the lead in formulating the evaluation system of ICT applications in the industry. With an established standard in the ICTs for knowledge management, the applications of enterprises in the AEC industry will be regulated and easily populated, and market competition will promote the development of ICTs for knowledge management, which will in turn promote the learning and development of new ICTs.

As for the prediction of the future trend of ICT-assisted knowledge management, the continuous emerging new technologies can bring more possibilities to AEC industry. Sensing City, AI for Everybody, proposed by the Massachusetts Institute of Technology Review (2018), can inspire the development of ICT-assisted knowledge management. The sensor has already been studied by scholars and connected with the concept of smart construction, pollution control,

transportation management, energy management to build Sensing City. Brain-like intelligence and brain-computer interface have great potential to be investigated in the AEC industry with the United States launching the “Brain Project” in 2013, the European Union proposing the “Human Brain Project” in 2013, and Japan proposing the “Brain Science Strategic Research Plan” in 2008. The time series correlation of brain-inspired intelligence is more in line with the real world and fits well with the AEC industry. In addition, the brain-like intelligence has strong correlation analysis ability, which is suitable for the complex, huge and dynamic knowledge network characteristics of the AEC industry.

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