The Influence of Digital Technologies on Knowledge Management in Engineering: A Systematic Literature Review

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Abstract — Digital technologies are gaining widespread acceptance in engineering and offer opportunities for collating and curating knowledge during and beyond the life cycle of engineering products. Knowledge is central to strategy and operations in most engineering organizations and digital technologies have been employed in attempts to improve current knowledge management practices. A systematic literature review was undertaken to address the question: how do digital technologies influence knowledge management in the engineering sector? Twenty-seven primary studies were identified from 3097 papers on these topics within the engineering literature published between 2010 and 2022. Four knowledge management processes supported by digital technologies were recognized: knowledge creation, storage and retrieval, sharing and application. In supporting knowledge management, digital technologies were found to have been acting in five roles: repositories, transactive memory systems, communication spaces, boundary objects and non-human actors. However, the ability of digital technologies to perform these roles simultaneously had not been considered and similarly knowledge management had not been addressed as a holistic process. Hence, it was concluded that a holistic approach to knowledge management combined with the deployment of digital technologies in multiple roles simultaneously would likely yield significant competitive advantage and organizational value for organizations in the engineering sector.

Index Terms— Engineering, information technology and systems, knowledge and data engineering tools and techniques, knowledge management, social technologies

1 Introduction

KNOWLEDGE is central to strategy and operations in most engineering organizations [1]. In the past twenty years, knowledge has been viewed as one of the most strategically significant organizational resources and a source of competitive advantage [2, 3]. Alongside this, the central role of knowledge as the essence of many organizations has led to an increasing interest in knowledge management [4].

Knowledge management is defined as the process of identifying, capturing, sharing, and utilizing the collective knowledge in an organization to help the organization compete [5]. In highly knowledge intensive industries such as engineering, efficient knowledge management is recognized as the key to success [3].

Digital entities, such as digital twins in the aerospace industry [6] and digital environments in the nuclear power industry [7], are transforming engineering processes throughout the life cycle of products and have the potential to act as persistent sources of information about products for generations of stakeholders. Simultaneously, advances in computer-based technologies have the potential to systematize, enhance and expedite knowledge management [5, 8]. However, organizations sometimes promote changes in technology without considering the need for a commensurate alignment of people, structure, processes and culture [9]. In these situations, it is only after the technology capabilities have been put in place, that many organizations realise that technology on its own is not enough to address knowledge management problems [10]. "People, process, technology" is a popular term in knowledge management studies. Bhatt [11] acknowledged that these three elements collectively influence the effectiveness of knowledge management. Technology is only as good as the processes that wrap around it, while the processes are only as effective as the people that use them [12]. Hence, in the light of the radical changes in engineering practice emerging through the use of digital entities throughout a product's lifecycle, the objective of this study was to conduct a systematic literature review of the relationships between these digital technologies and knowledge management in the engineering sector.

A growing number of review studies have been undertaken which analyze digitally supported knowledge management in knowledge-intensive sectors. For example, Nidhra et al. [13] investigated knowledge transfer challenges and mitigation strategies in global software development; Ahmed et al. [14] studied the current state of research regarding social media used for knowledge sharing; Inkinen [15] reviewed the empirical research on knowledge management practices and firm performance; and Manesh et al. [16] studied the knowledge management changes and future avenues in the fourth industrial revolution, in which digital technology is increasing interconnectivity and

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automation producing rapid changes in both engineering industry and society. However, among these reviews, few have focused on social factors related to knowledge management and almost none conducted their review within engineering. Thus, the aim of this review is to close this gap by considering the social factors related to knowledge management in the context of the engineering sector. Specifically, these gaps are highlighted by interrogating the literature for research outputs associated with the use of digital technology, associated with Industry 4.0, in knowledge management processes in all engineering sectors. The top-level research question established as a basis for this review is: how do digital technologies influence knowledge management in the engineering sector? The answer to this question, derived from this review, is that digital technologies are having some influence on knowledge management in the engineering sector; however, only on individual or isolated processes rather than in a holistic manner, and with little or no impact on social practices.

This review is structured with six sections. Section 2 provides a background of knowledge and knowledge management within engineering. Section 3 describes the methodology through which this review was conducted. Section 4 provides a summary of the content of the papers selected in the systematic review. Section 5 discusses the findings related to the research question above and conclusions are presented in Section 6.

2 Background

2.1 Knowledge

Defining knowledge has occupied the minds of philosophers and researchers since the classical Greek era and has led to various epistemological debates [5]. This study does not discuss the diversity of knowledge definitions. However, it is necessary to make a clear distinction between information and knowledge. Information is defined as structured and understandable data, organized in order to be a useful input to knowledge [17]. Knowledge has many definitions in the literature, each of which is applicable in certain circumstances. One definition provided by Davenport and Prusak [18] is: “Knowledge is information with the most value and is consequently the hardest form to manage. It is valuable precisely because somebody has reflected on the knowledge, added their own wisdom to it, and considered its larger implications.” According to Fahey and Prusak [19], knowledge does not exist independently of a knower: it is shaped by one’s needs as well as one’s initial stock of knowledge. Thus, managing information is by nature different from managing knowledge. The key factor that distinguishes knowledge from information is “people”. As Ruggles [10] said, “if the people issues do not arise, the effort underway is probably not knowledge management. If technology solves your problem, yours was not a knowledge problem.”

2.2 Knowledge Management in Engineering

"Engineering” is defined by the Oxford English Dictionary as “the branch of science and technology concerned with the development and modifications of engines, machines, structures or other complicated systems and processes using specialized knowledge or skills.” [20]. This definition carries the implication that managing specialized knowledge and skills is basic to engineering organizations. Madhavan [21] described engineers as integrators who pull ideas together from multiple streams of knowledge. This indicates that engineers need to work within a wide spectrum of knowledge rather than single strands, which means it is critical to facilitate interactions and connections between entities involved in engineering undertakings.

However, due to the large division of labor across geographical boundaries, between multi-functional business units, multi-tier supply chains and multi-disciplinary projects, the preservation, transfer and inheritance of knowledge presents many challenges [22, 23]. In dispersed organizations, employees often cannot identify what is known by other colleagues as it remains hidden in knowledge silos. Creating a sustainable knowledge sharing culture is therefore a highly complex task [24]. Moreover, breakdowns of communication are often experienced due to the inevitability that involved stakeholders sometimes have various interests and professional backgrounds with different expertise, terminologies, and perspectives [25].

3 Method

A systematic literature review is a means of identifying, evaluating and interpreting all available research relevant to a particular research question, topic area, or phenomenon of interest [26] and is known as a tertiary review when it considers prior systematic reviews. A systematic review differs from traditional narrative reviews in employing a replicable, scientific and transparent process which generates an audit trail of the reviewer's decisions, procedures and conclusions [27]. While a systematic review provides some quantitative information about the available literature, it does not yield detailed statistical data about the relationships between authors and publications provided by a bibliometric review or mapping. In this study, a systematic review was performed because the research relevant to the particular topic area, defined by a research question, was of interest. The guidelines for systematic reviews proposed by Kitchenham and Charters [26] and Tranfield et al. [28] were implemented using the recommended three phases: planning, conducting and reporting, which are explained as follows:

3.1 Planning

A comprehensive review protocol was defined to guide the study and provide a clear plan for the review’s progress. An initial scoping review was first conducted to confirm the need for this systematic literature review. Three main keywords for the search were selected based on the research question and a search was conducted in Web of Science for journal articles only published in the period from 2010 to 2022 in the English language. This search revealed a scarcity of recent review papers on this topic, only 13 reviews were identified. The search string employed was: (“knowledge management” AND “social*” AND “digital*”). Within these 13 reviews, most papers were traditional narrative literature reviews except for two systematic literature reviews. None of the identified reviews focused on digitally supported knowledge management in the engineering sector. Therefore, this confirmed the identified gap and the need to undertake this study.

Synonyms for the three main keywords were added to the search string. The final search string was formed in three parts: "knowledge management" and all the related processes; "social" and its synonyms; "digital" and its synonyms. These three parts were joined with an "AND" operator, and within each part, the synonyms were joined with an "OR" operator. The search string was employed to search the title, abstract and keywords of journal articles available in English and published from 2010 to 2022. The full search string used is shown in Table 1.

Five databases, namely: ACM Digital Library, IEEE explore, ProQuest, Scopus, Web of Science, were selected as the main sources for the research. These databases were selected because they cover a broad range of subject fields and were available to the authors free of charge. All the search results were organized using the EndNote software.

The use of multiple databases with overlapping scopes combined with the inclusion of multiple synonyms for the three main keywords ensured that the probability of omitting a relevant study was low, although it did increase the probability of a large number of duplicates, however this was an acceptable cost to ensure the completeness of the review.

TABLE 1
Search String

Keyword	Synonyms
Knowledge management	"knowledge sharing" OR "knowledge transfer" OR "tacit knowledge" OR "knowledge flow" OR "knowledge capture" OR "knowledge creation" OR "knowledge application" OR "knowledge acquisition" OR "knowledge retention" OR "knowledge exchange"
Digital*	"cyber*" OR "virtual*" OR "digitiz*" OR "digitis*"
Social*	"interact*" OR "communicat*" OR "inter-*" OR "intra-*" OR "collaborat*"
Complete search string	("knowledge management" OR "knowledge sharing" OR "knowledge transfer" OR "tacit knowledge" OR "knowledge flow" OR "knowledge capture" OR "knowledge creation" OR "knowledge application" OR "knowledge acquisition" OR "knowledge retention" OR "knowledge exchange") AND ("digital*" OR "cyber*" OR "virtual*" OR "digitiz*" OR "digitis*") AND ("social*" OR "interact*" OR "communicat*" OR "inter-*" OR "intra-*" OR "collaborat*")

3.2 Conducting

After completing the search process and removing 733 duplicates, 3097 papers remained. The remaining papers were filtered using a set of inclusion and exclusion criteria. The aim of applying inclusion and exclusion criteria was to ensure that the primary studies selected for review were relevant to the research question. The inclusion and exclusion criteria used in this review are shown in Table 2. The inclusion and exclusion criteria were applied to screen the remaining papers by reading the title, abstract and keywords of each paper.

The full text of papers that remained after applying the

TABLE 2

Inclusion Criteria	Exclusion Criteria
Available in full text	Not available in full text
Published in the time period selected	Outside the search timespan
Available in English	Not available in English
Related to the research questions	Not related to the research questions
Published in selected digital databases	Duplicated studies

exclusion and inclusion criteria was read and a quality assessment conducted by appraising the internal consistency and rigor of each study [29]. Based on the generic criteria proposed by Kitchenham and Charters [26], five specific quality assessment criteria were used in this review:

1. Is the topic addressed in the study related to knowledge management processes in a digital environment?
2. Are the knowledge management processes addressed in the study clearly specified?
3. Is the digital technology/framework considered by the study clearly specified?
4. Is the research methodology clearly specified?
5. Are the results of the studies relevant to this systematic review?

Following examples in the literature (e.g., [13, 30]), each criterion was scored from 0 (no compliance), 0.5 (partial compliance) to 1 (full compliance); hence, a study's highest possible score was 5, while its lowest possible score was 0. In this review, the quality of each paper was considered to be high if it scored greater than or equal to 3. A paper that scored between 2 to 3 was considered to be of medium quality. A paper that scored equal to or less than 2 was considered to be low quality and was excluded. No papers scored less than 2.5, and thus no papers were excluded as a result of this assessment. 27 papers were selected as primary studies (i.e., individual studies contributing to the systematic literature review) for further analysis. Fig. 1 shows the selection process of this review.

3.3 Reporting

A data extraction step identified and extracted relevant data from the primary studies. A data extraction form was developed to accurately record the information gathered through the review [26]. This process was conducted by reading the full text of each study and cataloguing the extracted information using Microsoft Excel spreadsheets and EndNote. The extracted elements including study ID (using "S" + "number" to represent each study, e.g., S1 represents [31]), publication year, research field, main knowledge management process(es), technology. The completed data extraction form is shown in Table 3.

TABLE 3
Data Extraction Form

S1	[28]	2010	Not specified	Knowledge creation	Social-tagging systems, pattern-based task-management systems, wikis. (Social media)
S2	[42]	2010	Manufacturing	Knowledge storage and retrieval	a Multi-Agent System on a Virtual Reality platform (Visualization technologies)
S3	[47]	2013	Construction	Knowledge sharing	Building Information Modelling (BIM)
S4	[32]	2013	Not specified	Knowledge storage and retrieval	Big data supported knowledge recorder tool
S5	[35]	2014	Financial	Knowledge sharing	Enterprise social media
S6	[36]	2015	Engineering design	Knowledge sharing	Social media
S7	[29]	2015	Coal mining	Knowledge storage and retrieval	A web-based interactive database (Content management system)
S8	[43]	2015	Nuclear	Knowledge sharing	3D simulation, virtual reality, advanced user interfaces, mobile and wearable devices, geographical information systems. (Visualisation technologies)
S9	[37]	2016	Aerospace	Knowledge sharing	Micro-blogging (Social media)
S10	[44]	2017	Engineering design	Knowledge storage and retrieval	Virtual Aided Design Engineering Review system (Visualisation technologies)
S11	[38]	2017	Multiple industries	Knowledge sharing	Social networking sites (Social media)
S12	[33]	2017	Oil and gas	Knowledge creation	Big data
S13	[21]	2017	Nuclear	Knowledge sharing Knowledge storage and retrieval	Multiple technologies
S14	[49]	2018	Manufacturing	Knowledge sharing	Augmented reality and sensor technology (Cyber physical system)
S15	[22]	2018	Aerospace	Knowledge sharing	Web 2.0: Blogs, Wikis, Forums, social networking sites, etc. (Social media)
S16	[55]	2018	Manufacturing	Knowledge creation Knowledge sharing	Augmented reality, Web 2.0, Data mining (Multiple technologies)
S17	[40]	2018	Multiple industries	Knowledge creation Knowledge sharing	Enterprise social networking system (Social media)
S18	[39]	2018	Manufacturing	Knowledge sharing	Enterprise social media
S19	[30]	2018	Manufacturing	Knowledge storage and retrieval	Content management systems
S20	[54]	2018	Manufacturing	Knowledge creation	Multiple technologies.
S21	[50]	2019	Manufacturing	Knowledge sharing	Cyber-physical systems: Augmented reality, sensor technology
S22	[51]	2019	Manufacturing	Knowledge creation Knowledge sharing	Industry 4.0. Service-oriented Digital Twin. (Cyber-physical systems)
S23	[41]	2020	Software development	Knowledge sharing	Social media
S24	[52]	2020	Manufacturing	Knowledge creation	Industry 4.0. Cyber-physical systems
S25	[23]	2020	Construction	Knowledge sharing	Immersive VR systems and a multitouch table (Visualisation technologies)
S26	[31]	2022	Railway	Knowledge storage and retrieval	Content management system
S27	[45]	2022	Manufacturing	Knowledge sharing	Visualisation technologies

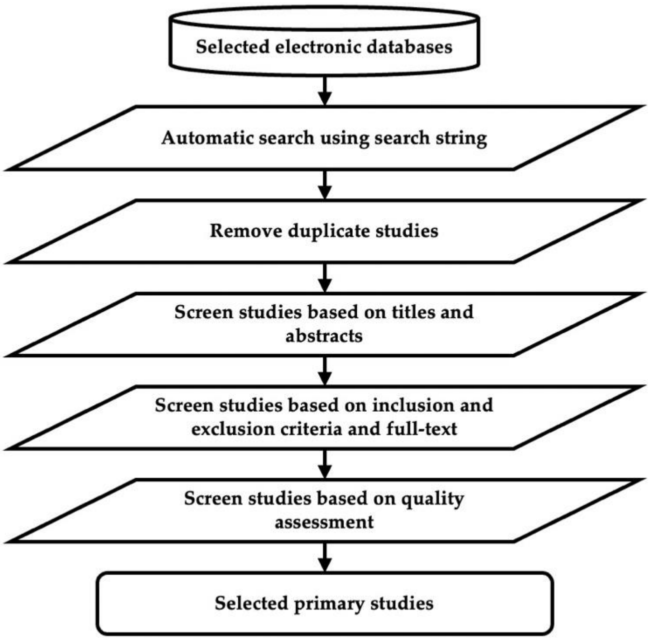

Fig. 1 Study Selection Process

Fig. 2 shows the chronological distribution of the primary studies from 2010 to 2022 and their content in terms of four knowledge processes, namely, knowledge creation, knowledge storage and retrieval, knowledge sharing and knowledge application [5]. Knowledge sharing has been most frequently studied during the last ten years while knowledge creation has been the focus of a number of studies between 2017 to 2020.

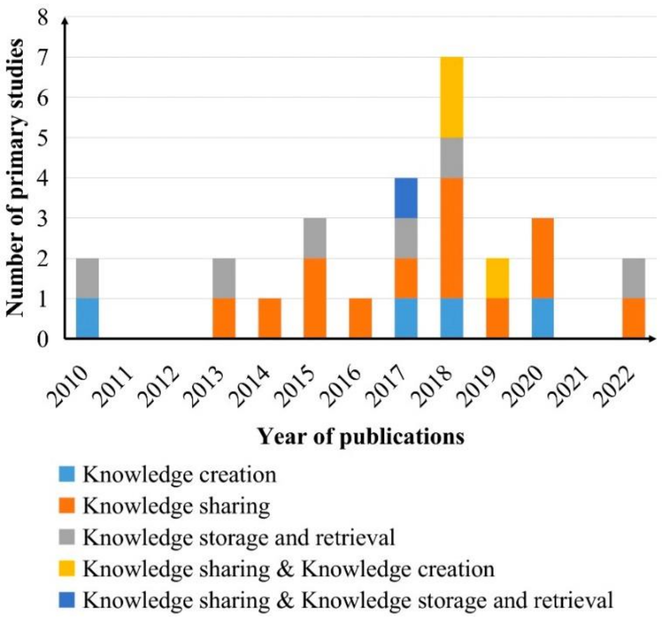

Fig. 2 Chronological Distribution of Primary Studies Showing Frequency of Focus on Four Knowledge Processes

Fig. 3 shows the distribution of research fields described by the primary studies. Manufacturing (10 studies) is the area with the most publications.

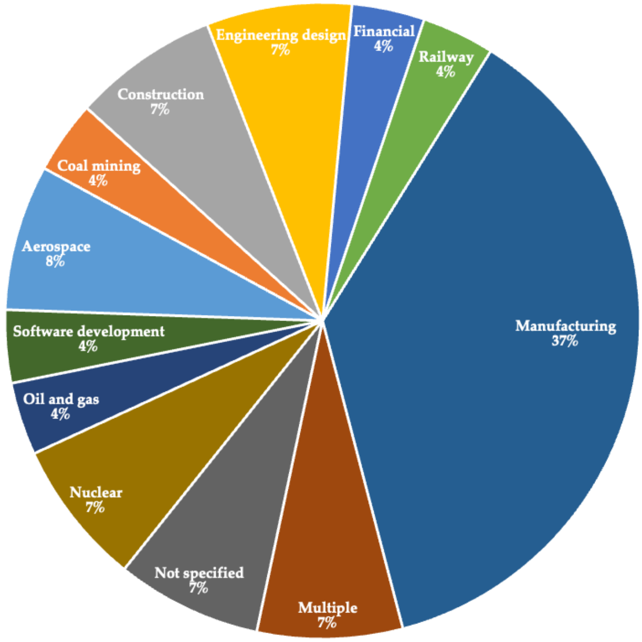

Fig. 3 Distribution of Primary Studies Across Research Fields

4 Content Summary

This section provides a description of how different digital technologies feature within the twenty-seven primary studies. To facilitate this description, the studies have been grouped based on the technology that is their principal focus, into seven technology clusters: Content Management Systems (CMS); big data; social media; visualization technologies; Building Information Modelling (BIM); Cyber-Physical Systems (CPS), and multiple technologies.

4.1 Content Management

Two of the primary studies investigated how content management systems have supported knowledge management. Kirsch et al. [32] introduced an interactive database called RISKGATE to support knowledge sharing between multiple stakeholders in the coal mining industry. The RISKGATE, in the form of a digital web-based tool, supported knowledge management by capturing inter-organizational expert knowledge and facilitating dissemination of the knowledge to field practitioners.

Content management systems (CMS) have been widely used in non-engineering sectors as one of the most important information and communication technologies for managing organizational information and knowledge because it has good capabilities, flexibility and extendibility, but there are few applications of CMS for managing engineering knowledge [33]. Wan et al. [33] proposed a collaborative maintenance planning system based on advanced content management to connect all stakeholders involved in a machine tool's lifecycle. Machine tool manufacturers, users, service providers and parts suppliers would all acquire product knowledge, workflow, maintenance planning and lessons learnt through the same platform. The prototype system was evaluated using a machine tool maintenance case and they showed that the proposed system could potentially enhance the efficiency and effectiveness of knowledge retrieval and reuse.

Abbas et al. [34] conducted a case study at a Dutch railway organization consisting of a group of test laboratories. The case study was based on a content management system, which the authors developed, that supported building collaboration by allowing participants in the laboratories to share knowledge. The system primarily focused on improving the findability and learnability of shared knowledge. They evaluated the performance of the developed system by comparing it to the existing system in terms of file search time and usability of the lessons learned function. They concluded that the proposed knowledge management system facilitated the building of digital collaborations.

4.2 Big Data

Two of the primary studies considered how big data has been applied for knowledge management. In order to study knowledge discovery from diverse data sources, Sukumar and Ferrell [35] introduced an enterprise data discovery and knowledge recorder tool called Schema Exploration and Evolving Knowledge Entity Recorder (SEEKER). The SEEKER software acted as a virtual warehouse of institutional memory within and across enterprise data assets, a repository of the evolution of data elements, queries and schemas as function of time, and a visualization and learning tool for personnel new to the system.

Sumbal et al. [36] explored the relationship between big data and knowledge management by conducting a qualitative study using semi-structured interviews in the oil and gas sector. They found that actionable knowledge was generated through a combination of tacit knowledge of people and explicit knowledge obtained from big data to support decision making in the organization.

4.3 Social Media

Nine of the primary studies focused on using social media to facilitate knowledge management. Enterprise social media is defined as a set of enterprise-wide, internet-based technologies that allow users to easily create, edit, evaluate and link to content and to content creators [37]. The applications of enterprise social media include wikis, blogs, social tagging systems, microblogs, and enterprise social networking systems. Kimmerle et al. [31] described how collaborative knowledge building, aimed at producing new knowledge, occurs in an organization when people interact with each other supported by social media technologies, including social-tagging systems, pattern-based task management systems and wikis. Using micro-blogging as the mechanism, Beck et al. [38] proposed and empirically tested a multilevel model of the characteristics of knowledge seekers, knowledge contributors and their relationships using a dataset of 15,505 messages from microblogging between employees in an enterprise. Gopsill et al. [39] developed a social media tool to support engineering design communication. They went on to validate the requirements that underpin the social media framework and evaluate the impacts of the tool on engineering work, engineering artefacts and engineering project management. The tool was applied to an eleven-week Formula Student race car design project. Evans et al. [40] proposed a conceptual framework to illustrate how organizations in the aerospace industry may improve the capture of employee knowledge to address production development problems through the use of micro-blogging for crowdsourcing ideas and solutions.

Scuotto et al. [41] quantitively analyzed the relationships between social networking sites, innovation performance and absorptive capacity, which was defined as the ability to support enterprises to acquire knowledge from external environments. The partial least squares (PLS) regression results showed that social networking sites have a positive role in affecting both the capacity to absorb knowledge and the innovation performance of small and medium-sized enterprises. Evans et al. [24] used a qualitative research method for a five-year participant-observation study. They developed a framework for virtual knowledge sharing and collaboration in the dispersed development of aerospace products based on a set of social software platforms. The results indicated that social software technologies offered a more openly innovative environment where people shared knowledge more easily and effectively across geographical and functional boundaries. Van Osch and Steinfeld [42] indicated that the visibility of resources on enterprise social media (ESM) could be leveraged strategically to evoke diverse network structures and different boundary-spanning activities across working groups within the organizations.

Qi and Chau [43] also used PLS to investigate the relationship between enterprise social network system (ESNS) usage, organizational learning and knowledge management processes. They found that ESNS usage was an important antecedent of knowledge creation and knowledge sharing, and an important contributor to organizational learning. They also found that the exchange between the organization's social system and an individual's cognitive system supported the development of new knowledge.

Ali et al. [44] applied PLS to analyze the behavior of sixty-one software development teams and tested the influence of social media on absorptive capacity, team innovation performance, and transactive memory, which was described as a socio-cognition system that helps team members benefit from distributed knowledge resources. They recommended that software development teams should consider adopting social media that facilitates the development of capabilities to acquire and integrate knowledge from internal and external resources in order to enhance innovation.

4.4 Visualization Technologies (Virtual Reality and Augmented Reality)

Five of the primary studies examined how visualization technologies were being incorporated for knowledge management. Mahdjoub et al. [45] developed a collaborative design system for mechanical design projects. The system was based on a parametric CAD model, 3D human model simulations, virtual reality tools and a multi-agent system embedded in a product lifecycle management environment. The multi-agent system enabled the localization, classification and extraction of stored knowledge and suggested expert knowledge to designers. A virtual reality platform, data glove and hand tracker enabled engineers to interact in real-time and modify the configuration of the virtual prototype.

Szőke et al. [46] described the utilization of 3D simulations, virtual reality, geographical information systems and an advanced user interface for supporting work in the nuclear industry. They argued that since most data are related to real environments, presenting the data and information to users in the context of their environments enables rapid visual perception and comprehension. The results showed that emerging technologies have huge potential to improve efficiency, safety and transparency in nuclear decommissioning projects.

Sivanathan et al. [47] proposed a virtual-aided design engineering review system (VADER) in which users logged discussions and decisions in real-time using a virtual design environment to promote knowledge capture and facilitate knowledge retrieval. This design engineering review system enabled automatic and unobtrusive logging of multimodal inputs (including audio, video, CAD files, and annotations) and time-phased interactions via an integration and temporal synchronization routine during product design meetings. And the system reformatted the captured content into a readily understandable and accessible format by linking design data with the captured multimodal data from the review meeting.

Roupé et al. [25] proposed a collaborative design system using real-time virtual reality tools to facilitate interactive design work and foster communication. The system enabled different stakeholders to have a first-person perspective and share a common frame of reference for the design environment. They used two collaborative design workshops to evaluate the system in the context of designing new healthcare environments.

Burova et al. [48] described a case study in which asymmetric virtual reality was applied to enable distributed collaboration of geographically dispersed teams working on the development of a series of methods for maintenance and the associated creation of technical documentation. Asymmetry in this study referred to merging the collaboration over two digital platforms: the COVE-VR platform and Microsoft Teams. Based on qualitative evaluation, they demonstrated that distributed asymmetric virtual reality is a low-cost and scalable solution that could be integrated with current industrial practices for remote working and suggested a list of guidelines on how to support the asymmetry between VR and traditional conferencing tools.

4.5 Building Information Modelling

There was one primary study which considered how Building Information Modelling supported knowledge management. Building Information Modelling (BIM) is the process of generating and managing data during the building's lifecycle [49]. Ho et al. [50] developed a way to support project managers and jobsite engineers to effectively acquire, share and reuse experience-based knowledge using the Building Information Modelling (BIM) technology within a 3D CAD environment. The proposed BIM-based knowledge sharing system was applied in a case study to demonstrate the effectiveness of sharing knowledge in a construction project.

4.6 Cyber-Physical System

Three of the primary studies investigated how cyber-physical systems are being incorporated in knowledge management. A Cyber-Physical System (CPS) is defined as the integration of physical and computational processes or assets in a way that both the virtual and physical parts of the system interact effectively [51].

de Carvalho et al. [52] proposed using sensors with augmented reality technology in a cyber-physical system to record movements, haptic information and other types of implicit knowledge embodied in actions during an industrial set-up. They argued that in a complex industrial domain, augmented reality had considerable potential to improve knowledge sharing by offering new ways that expertise and knowledge embedded in actions could be captured, displayed and shared.

Hoffmann et al. [53] presented an empirical study to investigate the potential of CPS technologies to support and advance knowledge and expertise sharing (KES) practices to support machine set-up in a production environment. Based on a one-year ethnographic study, they developed a knowledge and expertise sharing model then matched CPS-based technical possibilities to the practice-oriented knowledge sharing requirements captured within the model. The model served as a bridge between their ethnographic findings and the design of the CPS. They identified the potential for using CPS to support KES in industrial contexts, which was still at an early stage and relatively unexplored.

Longo et al. [54] developed a human-centric manufacturing paradigm where employees, including both managers and shop-floor operators, were empowered with knowledge about the manufacturing processes. They defined a service-oriented digital twin as "the component that offers an advanced and intuitive knowledge fruition through ubiquitously accessible apps and services." The digital twin worked as a link between the cyber-physical production system (CPPS) and the manufacturing employees. In order to achieve intuitive knowledge retrieval and knowledge creation, a close interaction between the manufacturing employees and the CPPS was facilitated using applications and services provided by the digital twin. These were based on its flexible knowledge structure, augmented reality technologies, and an interactive system.

Dragicevic et al. [55] explored the role of the human-in-the-loop in the Industry 4.0 environment. Industry 4.0 refers to the vision of a fourth industrial revolution. It relates to a new paradigm using smart and intelligent systems, automation, and digitalized production [56]. Dragicevic et al. [55] developed a conceptual model for a smart grid that would provide a holistic view of knowledge-based interactions among human, smart objects, and other computational entities as a mechanism for value creation in Industry 4.0. Smart grid in their paper referred to a power network that integrated the behaviors and actions of all stakeholders connected to it. They argued that, in an Industry 4.0 environment, harnessing computation is to enhance human intelligence rather than replace it.

4.7 Multiple Technologies

There were three primary studies that considered more than one of the main digital technologies. Wang et al. [23] proposed a knowledge management framework based on digital systems for the full lifecycle of a nuclear power plant. The technologies used in the proposed framework included an integrated automatic design and analysis platform, a 3D power plant model, a virtual reality building information model and a big data center. Each technology supported different phases of the work and various stakeholders across the lifecycle of a nuclear powerplant.

Wilkesmann and Wilkesmann [57] developed a theoretical framework to analyze the applications of Industry 4.0 using different digital architectures in various organizational environments. They considered organizations structured in different ways across a spectrum from mechanistic to organic environments. They found that mechanistic environments had a top-down structure in which the digital architecture provided a predetermined hierarchy. Whereas in an organic environment, the digital architecture facilitated innovation through a horizontal structure.

Hannola et al. [58] proposed four applications of digital technologies to empower production workers and facilitate knowledge management in knowledge-intensive production environments. These technologies included augmented reality, social networking platforms, and data mining. However, they only provided conceptual proposals for the application of each technology and no practical applications were described.

5 Discussion

This section discusses how the primary studies identified in this systematic review draw on contemporary theories associated with digital technologies and knowledge management and address the top-level research question, i.e., how do digital technologies influence knowledge management in the engineering sector. The use of digital twins with digital frameworks or environments is emerging in a number of industrial sectors to support the design and operation of engineering systems. The prime motivation for this study was to identify the parallel emergence of digital technology in supporting knowledge management associated with these systems which frequently have life cycles that extend beyond the working life of their designers. Hence, the choice of the research question and the positioning of this discussion in knowledge management in the field of engineering. Nevertheless, the discussion attempts to place the outcomes from the systematic review in the broader context of the field of knowledge management by considering the top-level research question using two subsidiary questions. First, from a technical perspective, how digital technologies support the processes of knowledge management in Sub-section 5.1. Second, in sub-section 5.2, how digital technologies influence knowledge management as a social practice, i.e., examining the impact on knowledge, skills and understanding within engineering organizations of digital technology. Existing theories were found to provide a suitable framework for discussion; hence, no attempt has been made to develop a new theory but instead to synthesize the findings of the primary studies within the current paradigm.

5.1 How do digital technologies support knowledge management processes?

One of the most cited knowledge management frameworks was introduced by Alavi and Leidner and has four knowledge processes, namely, knowledge creation, knowledge storage and retrieval, knowledge sharing, and knowledge application [5]. Most of the primary studies considered more than one of these knowledge management processes, and these are discussed below.

5.1.1 Knowledge Creation

Knowledge creation comprises ways to facilitate the development of new knowledge. Nonaka and Toyama [59] conceptualized knowledge creation as a dialectical process, in which various contradictions are synthesized through dynamic interactions among individuals, the organization, and the environment. Digitally supported communication can foster knowledge creation by enabling a space for considering multiple viewpoints, for constructing and sharing beliefs, and for allowing expression of new ideas [5].

Kimmerle et al. [31] discussed the development of new knowledge within an organization when people interact with each other using social media platforms. They argued that the exchange between the social system (collective knowledge enabled by shared digital artefacts) and the individual's cognitive system is the basis for the development of new knowledge. Sumbal et al. [36] investigated facilitating knowledge creation through big data. They demonstrated that knowledge was generated through a combination of predictive knowledge obtained from big data analytics with people's tacit knowledge, including their insights and opinions used in decision-making. According to Longo et al. [54], the role of the industrial Internet of Things (IoT) was to enhance and optimize human work by creating new valuable data and information streams instead of fostering a pure machine-to-machine manufacturing environment. Wilkesmann and Wilkesmann [57] discussed what forms of organizational structures and works supported by digital technologies allow the creation of innovations within Industry 4.0. They proposed using the Internet of Things to gain access to new sources of data and information to promote think tanks for new products and ideas. While recently, Ribeiro et al [60] have considered the influence of knowledge management on Industry 4.0 in the context of knowledge creation and work engagement in the telecommunications industry.

5.1.2 Knowledge Storage and Retrieval

Knowledge storage and retrieval is related to the management of organizational memory [61]. Organizational memory is defined as the means by which knowledge from the past, experience and events influence present organizational activities [62]. Challenges related to knowledge storage and retrieval have been identified in previous literature; for example, organizations do not know what they know and have weak systems for locating and retrieving knowledge according to Huber [63], and lessons learnt are identified and stored in some systems with different formats, yet they are often left behind and are difficult to find and reuse because of their poor organization [33].

Mahdjoub et al. [45] designed a knowledge management system using a multi-agent system to capture, extract and annotate knowledge during mechanical design projects. They used ontology or a semantic knowledge representation to capture knowledge in a generic way, in order to transition information efficiently and integrate it into an environment for reuse and sharing in support of managing the lifecycle of a product. Similarly, Wan et al. [33] used ontology to represent the semantics of maintenance knowledge in a formal way that a computer could interpret and manage in their proposed advanced content management system. Product-service related knowledge was classified, structured and managed to be shared and reused by different stakeholders.

In contrast to contemporary information and knowledge management systems that are separate from the activity that generates knowledge, Sivanathan et al. [47] proposed a new knowledge capture and reuse para-digm by integrating and automating the knowledge cap-ture process within the natural design review activity. The proposed virtual-aided design engineering review (VADER) system enabled the unobtrusive integration of structured and unstructured data via an integration and temporal synchronization routine; and then, systematical-ly organized the captured information for effective retrieval. More recently, de Freitas et al. [64] have considered the benefits and challenges of virtual-reality-based design reviews.

5.1.3 Knowledge Sharing

Knowledge sharing occurs when individuals convey knowledge or acquire knowledge from others [65]. The knowledge can be distributed between organizations or within an organization.

One of the motivational aspects of encouraging knowledge sharing is the generation of social capital [66]. Social capital refers to "the sum of the actual and potential resources embedded within, available through, and derived from the network of relationships possessed by an individual or social unit" [67]. Qi and Chau [43] investigated the impact of the usage of enterprise social networking systems on knowledge management processes. Their results aligned with social capital theory by demonstrating that enterprise social networking systems provided a rich source of social capital by increasing interactivity and individuals began, intentionally or unintentionally, to create and share the knowledge they possessed.

Evans et al. [24] proposed a framework for collaboration and knowledge sharing during the product development process through the utilization of social software platforms. The framework conceptualized the potential of social software, and led to recommended guidelines on which technologies might be most appropriate to enhance collaborative and knowledge sharing practices.

It is hard to share knowledge embedded in practice, such as "know how", in a generic form so that anyone might be able to make sense of it [68]. Conventional computer technologies do not meet the needs of sharing knowledge embedded in actions [52]. According to Nona-ka and Takeuchi [3], "know how" does not necessarily need to be transformed into a propositional form for knowledge sharing to take place. A range of other possibilities have been considered by using video, virtual reality, augmented reality and sensor technology. de Carvalho et al. [52] and Hoffmann et al. [53] proposed recording embodied knowledge and aligning it with propositional content via cyber-physical system technology in the context of an industrial set-up. By capturing the knowledge with adequate and timely information in sufficient detail, knowledge embedded in an individual's routines and practices could be easily understood and shared.

The implementation of a Cyber-Physical Production System (CPPS) calls for not only changes on the technical side, such as processes and systems, but also on the side of human-based skills and organizational competencies [16]. The implementation of a CPPS promotes cultural change by empowering workers to become decision makers rather than simply information handlers [69]. Longo et al. [54] developed a manufacturing paradigm where both managers and shop-floor operators were empowered with ubiquitous knowledge about the manufacturing system and processes. "Ubiquitous" in the paper means manufacturing employees can access the knowledge intuitively and quickly everywhere and at any time. A close interaction between the CPPS and the manufacturing employees enabled communication and full information symmetry within and among all the elements of a smart factory.

Information is often related to real environments, presenting the information to people in the context of the relevant environment enables rapid visual perception and comprehension [46]. Ho et al. [50] proposed using building information modelling (BIM) technology within a 3D CAD environment to support engineers in using their experience to update, share and reuse knowledge in the form of graphical representations. They conducted a case study based on construction project and, using questionnaires to evaluate outcomes, found that the BIM-based knowledge management system was effective. Szőke et al. [46] described the use of 3D simulation, virtual reality and an advanced user interface for knowledge management in nuclear decommissioning projects. Their results were obtained from many years of the authors' experience in research and development on the OECD Halden Reactor Project. They demonstrated the potential of virtual plant models and 3D simulation to plan and monitor working progress, to present dynamic situation information, and to train and support communication between stakeholders. Also in the nuclear industry, Wang et al. [23] proposed using a 3D nuclear power plant model to facilitate communication among various stakeholders during the lifecycle of a nuclear plant. This was a conceptual study that proposed a digitally-supported framework for knowledge management framework but its application was not reported.

5.1.4 Knowledge Application

Knowledge application refers to the use of knowledge for a competitive advantage through improvements in the capability of organizations. There are no primary studies focused only on the knowledge application process. One possible explanation is the nature of the knowledge application process, which is aimed at reusing or integrating existing knowledge for future problem-solving or decision-making. In the primary studies, the knowledge application process is incorporated with other knowledge processes, but not as the main process being investigated. Instead, it is associated with knowledge storage, which can support access to required knowledge, and with knowledge sharing, which can expand an individual's networks and support collaboration thereby enabling organizational knowledge to be applied across time and space.

5.1.5 Summary

The four knowledge processes introduced by Alavi and Leidner [5] have been used as a framework to consider how digital technologies could support knowledge man-agement.

Only five primary studies investigated knowledge creation as their main focus with the most recent being Dragicevic et al. [55]. Hence, this is an area that could benefit from further investigation. Similarly, only five primary studies examined knowledge storage and retrieval as their principal emphasis. All these studies provided detailed information on the preservation of information and knowledge in different forms, while there were fewer details on the performance of knowledge reuse. Since none of these studies mentioned the updating and curation of stored information and knowledge, these topics would appear to an appropriate subject for new studies.

Thirteen primary studies considered knowledge sharing as their main objective. Most of the studies focused on facilitating communication via social media systems. Only two studies mentioned sharing the knowledge and expertise, which are embedded in the actions of individuals, using cyber-physical systems. Incorporating Industry 4.0 technologies in knowledge management is still at an early stage. In order to explore the potential of this type of technology and to identify the issues related to its deployment, more empirical studies are needed across the engineering domain.

Although knowledge management processes are often depicted as sequential in the literature, they are interconnected and interdependent instead of linear [5]. They may never really "start" or "end" and actually run in parallel [70]. If any one of the four processes is weak or fails, the effectiveness and integrity of the overall management of knowledge will suffer [5]. The value of the preserved knowledge depends on its reuse and application, not only recording it [33]. Knowledge creation is strongly related to the knowledge sharing process since social interaction can trigger knowledge creation by enabling individuals to share and develop new ideas [43]. Similar conclusions have been reached recently by González-Tejero et al [71] in the more generic context of small businesses.

To answer the question posed in the title of this section: digital technologies are being to support knowledge management through the coordination and integration of the four knowledge management processes, i.e., knowledge creation, knowledge storage and retrieval, knowledge sharing, and knowledge application. The strongest focus has been on knowledge sharing; however, none of the primary studies considered using digital technologies to combine all four knowledge processes as a holistic activity.

5.2 How do digital technologies influence knowledge management as a social practice?

This question is concerned with the everyday practices or the way in which knowledge management is typically and habitually performed and the impact of digital technologies on these processes. Since there are established theories in social science that provide a suitable framework for this discussion, no attempt has been made to develop a new theory. Social science theory recognizes five topics in which digital technologies can facilitate knowledge management as a social practice: repositories, transactive memory systems, common information environments, boundary objects and non-human actors. Although some of these topics were alluded to in several of the primary studies, almost none were explicitly recognized or analyzed by the authors. Each of these topics is discussed in more detail below.

5.2.1 Repositories

A repository is a system working to preserve explicit knowledge embedded in documents, reports, lessons learnt, best practices, and procedures. Explicit knowledge is knowledge that can be written down or articulated in language or some other symbolic form [5]. Different types of knowledge management systems have been introduced where knowledge is stored for future retrieval so that preserved knowledge can be reused beyond geographic borders and time limits. Repositories normally preserve explicit knowledge to support the process of knowledge storage and reuse.

Sukumar and Ferrell [35] proposed an enterprise data discovery and recorder tool using big data. It served as a digital record of institutional knowledge and as documentation for the evolution of data elements, queries, and schemas over time. Wan et al. [33] used a content management system to manage explicit knowledge including documents, latest maintenance execution procedures, lessons learnt and best practices in the manufacturing domain. While Sivanathan et al. [47] proposed a design engineering review system which captured time-synchronized multimodal inputs including audio, video, CAD files, drawings, and annotations. Hence, it can be concluded that digital technologies can be used effectively as repositories for knowledge.

5.2.2 Transactive Memory Systems

Wegner [72] presented the notion of a transactive memory system that helped group members benefit from distributed knowledge resources. This system developed a group meta-knowledge containing information on who knows what and where the knowledge resides, which enabled individuals to locate the people who possess the needed knowledge [73]. Within a transactive memory system, individuals become sources of external knowledge and rely on each other to pool together complementary knowledge [74].

Enterprise social media not only helps people to solve the specific problem at hand, but also makes locating expertise and connecting knowledge seekers with knowledge contributors more effective [38]. In dispersed organizations with complex structures, it is often difficult to identify and locate individuals who possess highly specific expertise as it can remain hidden and consequently unexploited. Evans et al. [40] proposed using micro-blogging to improve crowdsourcing of knowledge by finding each other, becoming more personally involved, and identifying experts on given subject. Ali et al. [44] developed a model to test the effect of social media on the development of a transactive memory system. According to their results, social media served as an open access meta-knowledge repository by creating individual input footprints and describing who had what type of knowledge.

5.2.3 Communication Spaces

Social networking technologies allow knowledge sharing through an online communal knowledge conversation [37]. People feel free to engage in the knowledge conversations rather than paying for the extra cost of codifying knowledge for input to a formal repository [75]. An individual's knowledge network is extended, with the help of social networking platforms, to reach beyond the beyond the formal communication networks and encourage people to naturally interact with one another in their daily work [43]. Based on primary studies, social networking technologies have great potential to facilitate communication by supporting rapid knowledge flow between people working across geographical boundaries [76]; breaking down knowledge silos in organizations [40]; facilitating collaboration between multi-functional business units and multi-tier supply chains [24]; and identifying the right people with whom to communicate as part of the process of engineering design [39].

5.2.4 Boundary Objects

Star and Griesemer [77] described boundary objects as "...objects which both inhabit several interesting social worlds and satisfy the information requirements of each of them. They are plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites." Boundary objects are critical to knowledge sharing. They serve as translation mechanisms for different ideas, viewpoints and perceptions across otherwise difficult to traverse social boundaries [78] and enable collaboration between different communities of practice or social worlds [79]. However, successful collaboration requires the communities or worlds to have a common understanding and shared interest in the boundary object [80].

The virtual-aided design engineering review (VADER) system proposed by Sivanathan et al. [47] functioned as a boundary object for users involved all phases of the lifecycle of a product while it maintained a common identity as design review system. Distributed users could access, share and reuse knowledge for various tasks via its collaborative 3D interface and auxiliary web interface. Similarly, the framework for knowledge management proposed by Wang et al. [23] for the nuclear industry can also be viewed as a boundary object because it was designed to provide a range of services to different users, including digital R&D, design, verification and validation, manufacture, construction, operation and management.

5.2.5 Non-Human Actors

Actors can be defined as entities that perform knowledge-based activities [55]. Digital technology working as a non-human actor is not merely a passive container for transmitting knowledge, rather it is an actor interacting with people and the environment in doing knowledge work [80]. Sensors, machines and equipment are equipped with embedded local intelligence, which makes them smart objects interwoven over the cloud in order to cooperate with each other [81]. Dragicevic et al. [55] proposed a theory-based knowledge dynamics model in a smart grid scenario that provided a holistic view on knowledge-based interactions among human, smart objects and other actors as a mechanism of value co-creation in Industry 4.0. The deployment of Industry 4.0 had not only a technical but also a human dimension in the interaction of people with technologies [82].

5.2.6 Summary

In summary, to address the question at the start of this section concerning how digital technologies influence knowledge management as a social practice, five roles played by digital technology have been identified, namely as repositories, transactive memory systems, communication spaces, boundary objects and non-human actors.

However, people, processes, and technology need to be incorporated together to support knowledge management [10] because digital technologies acting alone provide little value to an organization [83] since employee competency is crucial in enabling an organization's transformation toward digitalization [84]. Rather than a purely technology-driven approach, there is an evident need for research on people-centered design to properly understand the requirements in social-technical contexts, where such systems or tools for knowledge management will be deployed [52]. The developed tools must be simple to use and embedded into the current systems that people are using, and not developed into "yet another tool" that becomes redundant over a period of time [40], especially given that the costs of digital technologies appear in the immediate or short-term whereas the benefits of knowledge management may only become apparent in the long-term.

6 Conclusions

This paper presents a systematic literature review on how digital environments influence knowledge management in the engineering sector. The following conclusions can be drawn from the analysis presented:

- 3097 results were initially identified, and these were then selected systematically leaving a total of 27 primary studies. These primary studies were then reviewed in more detail (Section 4 and Section 5).

- This analysis has revealed that digital technologies have been employed to support knowledge management in the engineering sector. For the purposes of this study knowledge management was broken down into four sub-processes, i.e., knowledge creation, knowledge storage and retrieval, knowledge sharing, and knowledge application. Among the primary studies, the knowledge sharing process was most prevalent, featuring in (48%) of them, while none of them had knowledge application as their main focus. Furthermore, none of the primary studies investigated knowledge management as a holistic process but instead focused on one or two knowledge processes.
- Almost no studies have investigated the social implications of the adoption of digital technologies in engineering knowledge management. Five people-centric roles played by digital technologies in knowledge management were identified from the primary studies, namely as repositories, transactive memory systems, communication spaces, boundary objects, and non-human actors. It was evident that the ability of digital technologies to perform all of these roles was not considered explicitly within the primary studies and this would therefore be an appropriate area for further investigation.

The top-level question posed at the start of this review was: 'how do digital technologies influence knowledge management in the engineering sector?' The answer can be summarised as knowledge management in the engineering sector is being somewhat influenced by digital technologies but in a limited manner due to piecemeal implementations rather than holistic approaches. As a consequence, there is little or no effect on social practices, i.e., changes in the way knowledge management is habitually performed are not apparent. Therefore, there are significant opportunities for engineering organizations to enhance their competitive advantage and organizational value by improving their speed and efficiency in creating and sharing knowledge through the effective deployment of digital technologies.

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