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Review

A Review of Ontology-Based Safety Management in Construction

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Abstract: The construction industry is one of the most dangerous industries in terms of safety performance, with practitioners and experts actively developing various solutions to reduce accident frequency and severity. However, accident information is collected in a wide range of formats by various elements in the construction industry, leading to interoperability issues and poor productivity due to the difficulties of sharing and reusing information. To improve the management of various types of safety management (SM) records in the construction industry, practitioners and researchers have adopted ontological methods. This paper summarizes the SM trends in construction management, along with gaps and opportunities for future work. A data processing framework is developed with a phase research for objective and subjective topic analysis from a collection of articles from 2012–2022 on topics relevant to the use of ontology in SM. The analysis focuses on the ontological life cycle (development, integration, and application), revealing an increasing trend of ontology-based SM (ObSM) research in the SM maintenance phase. Increasing case size and system automation is needed for future ontology-based SM optimization. The findings of the study will help to gain a thorough knowledge of ObSM, which will increase interest in effectiveness and the use of engineering and analytical techniques in SM.

Keywords: safety management; construction industry; ontology; life cycle

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1. Introduction

Construction project management covers all related project aspects such as work location, worksite conditions or temperature, work space, and the correct arrangement of safety facilities [1]. The construction environment imposes dynamic temporal and spatial conditions that impact worker activity [2]. For example, workers operating at elevations must be protected from falls, while those at ground level must be protected from moving vehicles or falling objects.

Increased construction industry activity has been accompanied by an increase in the number of occupational accidents and fatalities (OSHA and NIOSH 2018) [3,4], thus requiring an enhanced consideration of workers' safety, particularly through increased safety awareness and proactive accident prevention [5]. Construction work entails labor-intensive work by many individual workers and heavy equipment in confined areas, leading to an increased risk of serious injuries or death. An industry-wide survey by Fang et al. [6] found that the rate of construction industry deaths remains high and steady. In 2020, construction accidents in the United States claimed 1034 fatal occupational injuries [7], while China sustained 3843 fatal occupational injuries in 2018 [8].

Lu et al. [9] noted the key role of safety management (SM) in construction management (CM), particularly in relation to the deployment of complex construction processes and dynamic work environments. The core process of SM is safety checks involving the active identification of potential worksite hazards [1]. To maximize worksite safety, Fang et al. (2012) [10] proposed enhancing communication efficiency in retrieving and sharing construction safety knowledge information, with an emphasis on recording all activities and processes in various media formats. An intensive task in safety risk management (RM), the identification process in achieving a high level of construction safety becomes important [5]. Soft computing techniques can be used to solve problems intelligently by imitating human thinking [11].

Processing and analyzing data in multi-stakeholder construction activities is made difficult by low construction productivity and poor information interoperability [12]. As such, many researchers have resorted to using ontologies to address this problem [13]. Zhang et al. [14] used ontology-based safety investigation techniques to establish automated safety planning for job hazard analysis (JHA), using building information modeling (BIM) to establish site models and security settings. Melzner et al. [15] integrated the identification of automated accident inspection platforms related to falls. Li and Hua [16] adopted an object library approach for the management of safety components, such as safety equipment collected and presented in the safety design. Aziz et al. [17] introduced an ontology-based method to model and measure possible hazard scenarios for different system properties as well as operational and environmental conditions to perform rapid risk estimation using automated procedures for hazard identification. Goh et al. [18] used active fall protective system (AFPS)-ontology knowledge-based systems to structure cases with a cross-validation approach, using fifty cases to individually test retrieval system performance in dealing with risks of falling from a height. Le et al. [19] developed a security system with ontologies, among others, a social network system for knowledge sharing of construction safety and health (SNSS) using a semantic web wiki and an ontology approach. Wang and Boukamp [20] used automated SM, specifically the analysis and management of occupational hazards, to facilitate the identification of potential solutions to hazards. Wang and Yu [21] and Chi et al. [22] used a construction safety domain ontology for unsafe scenarios to reduce the level of human effort required in JHA and to enrich the solution space. Zhang et al. [14] proposed a construction safety ontology to formalize the knowledge of JHA.

Responding to the practical conditions in the field, many studies have applied ontologies in conceptual and methodological flows. Zhong et al. [23] suggested that the use of ontologies will improve structural information sharing and reuse and facilitate efficient cross-platform dissemination without misunderstanding or data loss, noting that ontology-based services have attracted increased research attention in discussing trends, gaps, and information regarding research sustainability. Several studies have focused on ObCM, outputting detailed descriptions of the title equation, the publishing journal, and the author's country of origin using content analysis and scientometric techniques to identify trends and gaps in construction-based management service ontologies [23].

An ontology is an information model that can explicitly represent a given domain by defining concepts and various relationships between concepts. Due to its computer-oriented and logic-based features, ontology engineering has been widely used for information modeling and analysis, such as for the semantic integration of heterogeneous databases and for information retrieval and management [24]. SM is an important part of CM [1]. Over the last 10 years, several groups have studied ObCM, including Zhou et al. [12], who developed a systematic three-phase search method (objective analysis and subjective analysis) based on potential articles related to construction ontology research, aiming to reduce the arbitrariness and subjectivity of research analysis.

Zhong et al. [23] systematically analyzed and visualized trends in ontology research by reviewing ontologies sourced from the Scopus database from 2007 to 2017. A combination of scientific metric analysis and critical review is used to identify research themes and ontology research challenges in the construction industry. Searches using keywords are often combined with "project management" where ontology facilitates knowledge management and information retrieval. Four research themes were identified using a combination of cluster analysis and critical review: ontology domain, industrial base class, automatic compliance check, and building information modeling (BIM). Zhang et al. [25] produced an overview and analysis of the use of ontology in the construction industry, finding several important gaps, including a lack of automatic or semi-automatic methods to generate a comprehensive ontology, weak methodologies for designing construction approaches, and poorly grounded foundations for existing ontologies. They concluded that the use of ontologies in the construction industry is still under development and far from mature.

Related studies using and combing various ontology-based analytical methods indicate that ontology plays a very important role in the world of CM. A literature review from 2017 to 2019 was conducted of Scopus journals, leaving considerable review opportunities for ontology-based safety analytical trends using certain keywords up to the current time. The literature review reveals a lack of detailed examination of the role of ontology-based work in SM, and the present study seeks to address this research gap to further improve workplace safety practices. Many studies from 2012 to 2022 examine ontology-based work SM services, while others have comprehensively studied ObSM, developing various methods and applications. However, no previous study has taken a holistic view of OBSM trends and application models.

It can be concluded that SM is an attempt to increase knowledge in the field of the construction industry with various weaknesses that arise during the process. Dissemination of information from various systems; no standard or general provisions; Heterogeneous information that cannot be shared or reused due to different systems. Ontology as an essential semantic technique that provides a more precise way of presenting knowledge with semantics that supports reasoning and more efficient querying of a knowledge domain. These advantages make ontology a solid foundation in methods and applications that are planned and engineered to get the best results in SM. In the process, there is no definite information regarding various breakthroughs in ObSM to provide a thorough understanding so that ontology remains a popular technique and worth maintaining in the future. Various studies that continue to emerge with the topic of ObSM raise questions regarding effectiveness and sustainability in supporting better SM services. In the world of engineering, certainty in applying techniques and calculation methods is important when used in analysis and engineering processes, in order to achieve better results in the future.

Using a literature review on a collection of various ObSM journals with topic analysis based on the ontology lifecycle will pinpoint trends, gaps, future breakthroughs, and suggestions for improving occupational SM. Belonging to the literature review type of paper, the study demonstrates knowledge and understanding of the academic literature on a particular topic placed in context. This study proposes a thorough review of the results of 57 papers that are in line with the ObSM topic by using topic analysis.

The next section describes the research methodology with eight steps based on the ontology life cycle, the impact of the cycle, and the trends and gaps in the construction industry. The issues of the data collection process that is based on secondary data are also presented. The third section overviews the 57 papers collected to determine the number of publications by year, number, place of research, organizational level, project phase, application innovation, and methodology used in building ontologies. The fourth section addresses the results' analysis focusing on the ontology development cycle, information integration, and applications built to support ontology-based safety services. The last section concludes the research. Future research directions regarding the ObSM applications are also proposed.

2. Research Methodology

2.1. Objectives and Procedure

This review provides an in-depth overview of existing ontology research and demonstrates emerging trends in this research domain. An overview of the role of various ontology-based analytical concepts and combinations from 2016 to 2019 shows the development of a high degree of research interest in supporting construction industry activities.

Zhou et al. (2014) and Zhong et al. (2019) investigated ontology research to explore emerging trends in the research domains. Several gaps existing in the construction industry have been identified, including (1) lack of automatic or semi-automatic methods in ontology generation, (2) weak methodology, and (3) lack of philosophical foundations and forms of ontology. However, related research is limited to the Scopus journal, so there is still an opportunity to study trends in ontology-based safety analytics, and the results of these studies do not review in more detail the role of ontology-based occupational safety management, both trends and in-depth descriptions, therefore, in the research, the main focus is on improving work safety services in the future.

This study seeks to (1) review ObSM research and leverage the ontology development life cycle, (2) measure the impact of life cycles and gaps on ObSM research and efforts to overcome them, and (3) examine ObSM trends in the construction industry. A systematic content analysis is conducted to review the literature related to the research objectives through the following steps (see Figure 1):

1. Delineating clear research boundaries to ensure consistent and systematic review results.
2. Collecting data from various publishers and authors based on appropriate and relevant keywords and keyword combinations, including "construction management", "risk management", "safety management", and "ontology".
3. The collected sources (from articles, journals, and conferences) were analyzed and screened for ObSM studies in the construction industry around a decade (2012 to 2022).
4. The filtered document set was sorted and categorized to facilitate analysis based on criteria including the year of publication, publisher, title, country of origin, organization level, project stages, project type, tools used in ontology development, and stage of the ontology-based methodology.
5. Developing an overview of ObSM by organizing data based on the number of publications per year, specific journal sources, research country or region, organizational level, project phase, ontology development, and ontology application.
6. To increase specificity and accuracy, further subjective and objective topic analysis is carried out on the contents of each document, where subjective analysis includes gathering information about the ontology development cycle as well as important information on research gaps and suggestions as recommendations for future work.
7. Discussion: based on content analysis results, the ontology life cycle is discussed in detail, starting from ontology development, through information integration, to the resulting application to serve as the basis for recommendations for future ontology research.
8. Results: we summarize the analysis results to provide a clear picture of the role of ObSM and a useful reference for future research.

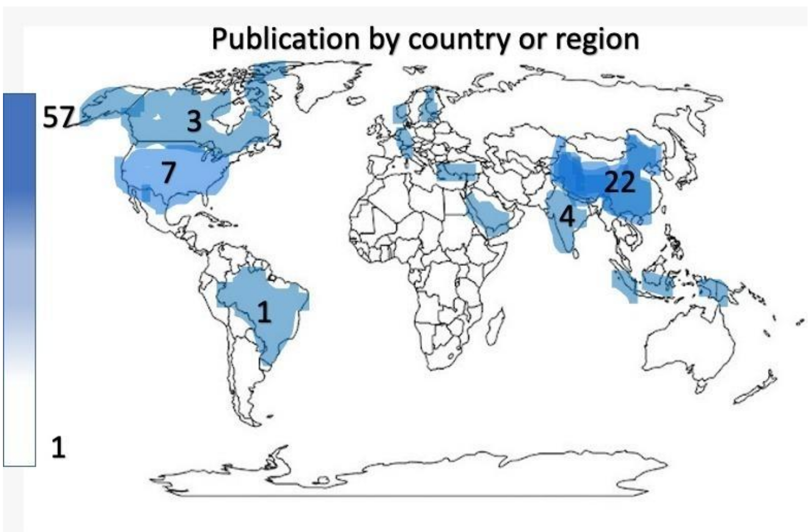

Figure 1. Research publication by country or region.

2.2. Data Collection

Secondary data from various official sources were collected as the primary reference for analyzing the use of ontology in SM. A keyword search was used to identify data specific to SM. To maximize the suitability of the collected data, search limitations were established as follows:

9. Search keywords were specific to the research topic, including management, construction management, safety management, ontological work safety, ontology, semantic web, and semantic networks.
10. The search period is limited from 2012 to 2022.
11. To improve data retrieval, keywords were combined as follows: (“management” * “construction”) or (“construction management” * “ontology”) or (“safety management” * “ontology”) and (“safety management” * “semantic web”).
12. Certain punctuation symbols, such as double quotes at the beginning and end of keyword arrangements, facilitate information identification and retrieval.
13. To facilitate data collection, search results were limited to papers published in English.
14. All data searches were keyword-based, and were collected as a document related to the search topic, thereby increasing the size of the search results.

The search strategy outlined above was applied to journal databases, including DOAJ, JSTOR, Google Scholar, Microsoft Academic, Sage Journals, Research Gate, academia.edu, Free ScienceDirect, the International Journal of Education and Research (IJERN), Oxford Academic Journals, and others.

Table 1 summarizes the search results in the CM domain based on ontology using the data retrieval codes TITLE-ABS-KEY ((“construction management”) OR (construction safety management) OR (work safety) OR (work accidents) OR (construction management) OR (ontology) OR (ontologies) OR (semantic web) OR (semantic technology) OR (semantic) OR (linked data))). Fuzzy search was conducted using the search sign “*”. “TITLE-ABS-KEY” groups search results by title, abstract, and keywords to optimize search results. Keyword-based data collection techniques can increase document retrieval but may obtain results not related to ObSM. This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Table 1. Keyword search results.

No.	Key Words	Time Period	Web Page/Result *			
			Google Scholar	Sciencedirect	Scopus	Web of Science
1	Ontology and safety management	2011–2022	36,000	1879	43,132	1148

* a numerical value indicating the number of titles that are like keywords based on the similarities in the order of letters and the arrangement of keywords used in the initial search and data collection process.

Search results with a combination of important keywords such as ontology, safety management, construction industry, and life cycle obtained a high number of searches. Based on the similarity of titles, the number of searches on journal data provider websites with 1148 search results for science websites, 1879 sciencedirect websites, 36,000 (Google Scholar), and the highest search results on the Scopus website with 43,132 titles. The large amount of linked data based on keywords needs further research to collect topics that contain ObSM. The next step will be a challenge for researchers to be able to exclude and eliminate by highlighting each search result based on predetermined criteria based on boundaries with the ultimate goal of getting papers from journals that review ObSM, as in the main data in this study.

2.3. Data Analysis

The study period was set as 2012 to 2022 and limited to studies within the domain of construction management. The results were further filtered for English-language studies, followed by selection for relevance to ObSM in engineering domains. This process resulted in 57 studies relevant to the research topic.

According to Hemmler et al. [26], coding provides researchers with a factual overview for qualitative data analysis. The coding process will facilitate the analysis of large amounts of data to maximize the credibility of data analysis. We conduct coding using the following steps:

15. Prepare initial data. The final set of 57 papers was coded based on the inclusion of specific terms or symbols used to simplify the document coding process. This "verbatim" approach is used to determine the results of qualitative data analysis through coding.
16. Analysis accuracy with fact-finding. A fact-compacting process is carried out to isolate factual data from reviews and statements, thereby facilitating accurate capture of the meaning of the sentence for conversion into standard words, phrases, or sentences. Fact condensation increases analysis accuracy because it reflects facts, rather than subjective conclusions, thus clarifying topical results for the discussion of trends, processes, and gaps for future work.
17. Probing process. Probing is used to further clarify remaining incomplete information by collecting information relevant to a collection of papers, such as researcher discussions and conclusions. Probing results are used to strengthen the results of data analysis and facilitate the extraction of topical data to enhance analysis objectivity.
18. Collecting similar factual data. This step finds and determines the quality of facts based on the paper content to help researchers systematically categorize key themes as material to develop a data narrative. Collecting similar facts also helps researchers to determine and assess data credibility or whether further confirmation is required.
19. Categorization. Data for this study were divided into categories based on: (a) the year of publication providing an indication of the aggregate amount of research interest in ObSM; (b) the categorization of journals by the publisher to help in assessing paper quality; and (c) geographic distribution of research subjects; (d) inclusion of organizational levels in paper reviews such as industry, project level, sub-project to task level; (e) inclusion of project phases such as planning, design, construction, and maintenance; (f) use of innovative tools and applications to improve ontology-based work safety; and (g) inclusion of the ontology development process in SM.
20. Concept and narrative. Following data categorization to facilitate systematic analysis based on the research topic, we group data by category to facilitate review and analysis of data collected to meet the research objectives.

3. Results

3.1. Number of Publications per Year

Studies from various leading publishers of SM ontologies were collected and analyzed to reveal cases, trends, and issues contained in the research discussion results. The number of publications is a real number used to measure various aspects of disciplines to assess the rigor and potential impact of the research. Over time, reports on the application ObSM in the construction industry have increased in terms of sharing knowledge about safety information. The research year was taken from 1999–2011 to illustrate interest in studying ObSM and continued to increase until the study year from 2012 to 2022, but has not yet reviewed trends, issues, and input in the future. Table 1 shows publication trends for ObSM papers from 1999 to 2022.

The use of SM in the construction industry for the sharing of safety information has increased in recent years. Paltrinier et al. [27] analyzed this development using a time variation system with an information knowledge mechanism that is continuously updated to identify dynamic hazards. Nakayama et al. [28] provided another analysis in the field of construction SM using the bow tie method for hazard identification. Chi et al. [22] used ontology-based text classification (TC) to match safety measures based on unsafe scenarios to provide a safety reference for risk anticipation.

In measuring research trends, the year of publication has been used to derive trends and developments [12,21,23]. Table 2 shows that the number of publications ranges from 1 in 2018 (1.75% of total) to 10 in 2014 (17.54%), and on average, in 10 years of monitoring there were 5.7 or 6 papers published per year, and between 1999 and 2011 an average of 1.8 or 2 papers. The overall trend indicates persistent and increasing research interest over time.

Table 2. Publications up to 2022.

No.	Year of Journal	Number
1	2022	6
2	2021	5
3	2020	7
4	2019	7
5	2018	1
6	2017	5
7	2016	4
8	2015	5
9	2014	9
10	2013	5
11	2012	3
12	2011	3
13	2010	3
14	2009	6
15	2008	1
16	2007	2
17	2006	0
18	2005	0
19	2004	0
20	2003	1
22	2001	1
23	1999	1

3.2. Number of Publications by Journal

A total of 57 papers related to ObSM were published by 29 journals during 2012–2022 and screened, as shown in Table 3. This broad research distribution indicates a significant degree of research interest in the use of ontology in SM. Construction engineering journals generally focus on topics related to applied engineering.

Table 3. Publications by journal.

No.	Distribution of Research by Journal	Number
1	*Automation in Construction*	8
2	*Safety Science*	7
3	*Computing in Civil and Building Engineering*	6

Table 3. *Cont.*

No.	Distribution of Research by Journal	Number
4	*Advanced Engineering Informatics*	5
5	*Procedia Engineering*	3
6	*Buildings*	2
7	*Computers and Security*	2
8	*International Journal of Environmental Research and Public Health (IJERPH)*	2
9	*Process Safety and Environmental Protection*	2
10	*Arabian Journal for Science and Engineering*	1
11	*Applied Sciences*	1
12	*CET-A Journal of AIDIC*	1
13	*Computer Communications*	1
14	*Computers in Industry*	1
15	*Construction Innovation*	1
16	*Construction Management and Economics*	1
17	*Electronic Journal of Information Technology in Construction*	1
18	*Engineering, Construction and Architectural Management*	1
19	*Engineering Science and Technology*	1
20	*Environmental Software Systems*	1
21	*Expert Systems with Applications*	1
22	*Future Generation Computer Systems*	1
23	*IEEE Xplore*	1
24	*IFAC-PapersOnLine*	1
25	*Journal of Applied Logic*	1
26	*Journal of Green Engineering (JGE)*	1
27	*Journal of Intelligent and Robotic Systems*	1
28	*Journal of Loss Prevention in the Process Industries*	1
29	*Journal of Networks*	1
	Totals	57

3.3. Geographical Distribution of Publications

Several comparative studies have categorized research by country or region [12,29]. As shown in Figure 1, the 57 papers reviewed originated from 21 different countries and regions, with China accounting for 38.60% of the total, followed by the US (12.28%), India (7.02%), Canada and South Korea (5.26% each), and Europe (3.51%) Some of the discussion topics related to the use of ontologies in detecting imminent danger through initial image capture [30], integrating BIM with natural language processing (NLP) [31], and decision-making models with CBR and NLP [32], and others.

Papers from China were concentrated in journals focused on safety science (4 journals), advanced engineering informatics (3), and automation in construction (3 journals), the remainder being published in journals focused on MDPI and ASCE. The number of papers published in China increased over time from 2012 to 2022, except for 2018, when no ObSM papers appeared. This shows consistent research interest in ObSM from China. Among papers originating in the United States, the largest concentration is in 6 advanced informing engineering journals, while papers originating in Canada and South Korea wre concentrated in the *Journal of Automation in Construction*.

3.4. Publications by Organizational Level

Studies were classified according to the organizational level used as the focus of the research, including industry level, company level, and the project or sub-project level. Of the three levels, the majority 63.16% were at the company level, appearing in 36 journals that review decision-making with case-based reasoning (CBR) and NLP with ontology, combining CBR and rule-based reasoning (RBR) [32] and security checks with construction safety checking (CSC) ontology [9]. This was followed by industry-level studies (21.05%) and task-level studies (15.79%).

This result of the analysis shows that the lack of task-level research was because the research carried out was specific to direct solutions for individual core problems, such as using ontologies to improve integrated urban pipelines, minimizing falls from a height, and using BIM in information management. At the industrial level, safety diagnostics were related to the use of construction equipment. The United States, South Korea, and Canada all contributed task-level research; this area is still dominated by researchers from China, raising opportunities to increase research interest for assignment-level research in ObSM in construction. There needs to be a concentration on ObSM research at the task level in order to resolve issues, trends, and inputs for SM services.

3.5. Distribution of Project Phase

Construction projects go through a series of stages, including design and planning, construction, maintenance, and supervision, with each stage subject to different SM conditions and requirements. Of the reviewed papers, 35 (61.40%) focused on the planning stage, with 13 focused on China. The construction phase contributed 15 papers (26.31%), followed by maintenance (8.78%) and maintenance and supervision (3.51%). Given that each of these stages is crucial to the success of a construction project, this distribution suggests that further research is needed in the maintenance and supervision stage. The disproportionate research focus on the planning stage was likely due to SM concerns about accident prevention with ontologies in sharing information to establish understanding and consensus between various stakeholders. Zhong et al. [30] determined decision-making and information sharing in the SM maintenance and supervision phase, while Wu et al. [32] discussed the retrieval of case data using CBR and NLP.

3.6. Publication Based on Ontology-Based Application Innovation

The use of ontologies based on levels and needs can be adjusted based on the research objectives, allowing for quick and easy analysis. In the process of calculating and dividing data based on classes and hierarchies as well as relationships between data, the ontology is manipulated using auxiliary applications to obtain reliable results. The tool in question is most known as Protégé [33] and UnBBAYES [17] but is also known as TODE, WebODE, OILED, KAON, and DISCIPLE. Of the 57 papers reviewed, 19% of the papers contain reviews that use or create tools to build and manipulate ontologies, with China contributing the largest number of sources. Most studies use open-source tools due to their ease of use, the wide availability of plug-in extensions, and the use of Java-based programming interfaces in ontology implementations.

3.7. Publications Based on Ontology Building Methodology

Ontology-based data management is a linked data approach mostly used to publish ontologies for construction SM, to ensure terms and concepts developed are machine-readable [34,35]. In the development process, the ontology uses linked data in which several statements are considered reasonable and are joined by applying the logical "AND" operator. This produces a resource description framework (RDF) graph where individual statements are called a triple RDF [36]. This method improves semantics by using a collection of words from a particular language to form sentences (vocabulary). Ontology languages using web ontology language (OWL) can be used to build complex RDF statements through vocabulary selection, thereby enabling semantic interoperability. According to Ding et al. [33], the use of ontology offers three main benefits in knowledge management and modeling: (1) increased model flexibility and extensibility, (2) stronger semantic representation, and (3) increased demand for concept-level retrieval to improve knowledge retrieval.

Ontology building involves establishing an ontological life cycle, subject to certain advantages and limitations. Figure 2 provides examples of formal methods for ontology building, illustrating the various stages and rules in different steps that significantly overlap. The key ontology development processes are as follows:

21. Establish a list of competency questions [12].
22. Use a simple knowledge-engineering methodology (SKEM) [37], SRIonto [5], and AFPS Onto [18] to review existing ontologies, taxonomies, and other sources within ontologies for reuse.
23. Implement the MOTONOLOGY middle-out strategy, focusing on commonly used classes or concepts to solve problems in ontology development.
24. Use the SKEM guidelines to iteratively compile a series of concepts by defining classes, attributes, instances, and their interrelationships.
25. Evaluate the ontology using the METONTOLOGY guidelines to ensure conformity with external stakeholders (Figure 2) in a two-stage process, namely examining the competency questions and the end-user survey approach.

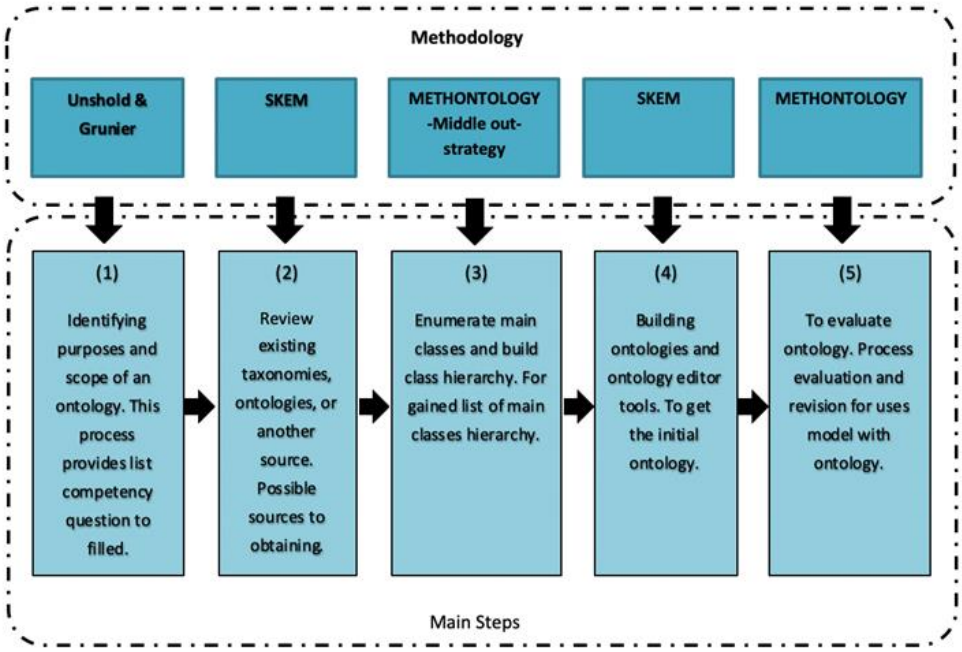

Figure 2. Framework for ontology building.

4. Discussions

The research topics of the 57 papers reviewed were analyzed to assess the ontology development life cycle starting from ontology building, ontological information integration, and application [12]. This analysis links the project phases based on overview results. Design/planning is the dominant project phase, thus focusing additional attention on further review of its relationship with the ontological life cycle in SM and the analysis results reveal research gaps for future work.

4.1. Impact of Building SM Ontology

Ontology development starts from determining methods and stages as well as the tools to be used in determining domains and important ontological terms, the use of existing ontologies, defining classes, hierarchies, class properties, and slots, and then creating instances. These stages can be divided according to the needs of ontology development. Xing et al. [5] used three stages: (1) pre-development to define the meta-ontology model; (2) ontology definition to define classes, properties, and relations, and; (3) ontology coding to process code using the Protégé tool. This model adopts the standard model of ontological development using SRIonto. There are three types of ontologies used in the construction industry: (1) large-scale ontologies, (2) multifunctional ontologies, and (3) special function ontologies.

26. Large-scale ontology development

Large-scale ontology development is labor and time-intensive. For example, the European Commission e-COGNOS project, seeking to improve ontology-based knowledge management, has a 50-year time frame to develop a mature construction domain ontology. El-Dirabay [38] developed DOCK1.0 as a knowledge management domain, seeking to incorporate a comprehensive list of construction, but development is still in the design stage of safety management and has yet to scale up. In the past decade, no ontology development project has achieved large scale with functional stability.

27. Multifunctional ontology

This type of multifunctional ontology is generally developed to manage enterprise institutional memory data. Several of the reviewed papers use this type of multifunctional ontology. Companies use ontologies to support job hazard analysis (JHA) using NIOSH FACE to design text content (TC) for identifying safe approaches from existing resources based on unsafe scenarios [22]. Safety is used to model across domains, promoting the effective management of knowledge and information from areas such as engineering, chemistry, control, automation, and more. This model is applied to a concept related to security and design analysis, enabling the reuse of information to improve process efficiency [24,39–47]. EWOnto was developed to help define formal knowledge structures for industrial safety in various domains, aiming to integrate knowledge related to earthwork safety. Case study evaluations have revealed gaps between high-level safety regulations and well-connected task instructions [48]. Based on this, the focus on ObSM, especially from the design stage, still accommodates reviews of the development of multifunctional ontologies, with 7% of papers reviewed focused on the design stage in ontology development [18,48–53]. Ontology development is time and resource-intensive, and efficient use requires frequent reuse. Ontologies also require constant updating, thus further adding to resource requirements. In addition, ontologies must be publicly accessible and easy to use to encourage public participation.

28. Special function ontology

Problem-solving ontologies or function-specific ontologies are used on a much smaller scale and are focused on specific cases. Several studies applied such ontologies for the development of knowledge-based tools for industry, hazard screening and risk estimation with probabilistic PR-OWL using open-source Portege and UnBBAYES [17]. Zhong et al. [30] used Hownet and a special taxonomy to measure image similarity for proactive hazard identification. The multi-algorithmic approach automatically converts accident case data into an RDF and a SPARQL protocol for cross-querying in the information-sharing process [49]. Shen et al. [31] created an automated inspection mechanism by integrating BIM and safety rules with result detection using NLP for safety rule checks. Wu et al. [32] combined CBR and NLP to facilitate knowledge integration and reasoning for improved decision-making in metro accident response.

Wu et al. [32] built an ontology-based model with CBR with four layers (information acquisition, ontology development, semantic processing, and application services). The model includes different classes, properties, and individuals. By class, individual metro accident taxonomies are created based on the relationships between concepts. The ontology process with CBR is effective in helping decision-making based on metro accident cases, with decision precision results of up to 91%. The same approach was also successfully used in a case-based improvement method with CBR to support subway construction using SRIonto to develop an ontology domain to formalize safety risk knowledge to support the identification of metro security risks [46]. Implemented in a five-step process, SRIonto was used to organize safety risk knowledge across seven integrated classes to effectively address metro construction safety issues [5]. Goh et al. [18] used AFPS with CBR and RBR as a design solution to assess safety equipment quality to prevent falls from a height.

These breakthroughs show that greater importance has been attached to the development of special function ontologies than the other two types. This condition is caused by the emphasis on task completion and the direct impact obtained by the researcher. The primary limitation is that expert knowledge and general logic remain the benchmark for the success of this type of ontology, plus the availability of probabilistic and historical data determines the accuracy of the results. Many models fail to consider secondary hazards that can potentially become primary hazards. Material specifications are not input as a reference, and the resulting information insufficiency requires system updates to recognize potential future hazards. Additional challenges are the need for significant manual effort in updating the special ontology for metro accidents and the limited availability of case data for decision-making, thus impacting search results [32]. Further research is needed with additional cases, thereby increasing prediction accuracy. Interface updating is another obstacle to effective decision-making, requiring the development of suitable and easy-to-operate applications to allow end users to easily build ontology models.

4.2. Successful Ontological Development for Information Integration

Construction industry operations produce various types of information, including technical documents, location data, and project specifications. The challenge in effectively converting the contents of such documents into a machine-readable format involves the efforts of multiple stakeholders, and the information integration challenge increases with information volume. Effective and efficient use of ontologies facilitates information integration from various heterogeneous sources [1]. In the process of sharing perceptions about Safety Management, each stakeholder has different concepts and terms because they are generated by different tools and applications. Meanwhile, decision-making on a construction project must be completed in a short and solid time; therefore, the use of Ontology, in this case, is very helpful.

Information sharing is critical to safety management, and information integration has emerged as an important area of research. Farghaly et al. [35] addressed interoperability issues with a conceptual model for safety management, developing an ontology model linked to ifcOWL in which the SHE Ontology (Safety and Health Exchange Ontology) to identify and manage safety risks in the design and planning stages with eight concepts. The award-winning Open BIM ontology has been shown to be successful in the design phase of information integration. Shen et al. [31] developed an automated risk identification and prevention mechanism for construction processes by integrating an ontology technology-based safety rule library with NLP greatly benefiting safety inspectors and construction managers. Li et al. [54] developed an integration of construction safety to link SM and information models by managing fragmented data.

Ontology with SafeConDM consists of semantics and safety concepts as a solution to embedding the relationships between SM and the information model to overcome interoperability issues between systems in construction implementation. Arogundade et al. [55] built an ontology based on existing accident threat information to improve decision-making capabilities based on the CASE model, thereby improving the management of safety hazard investments. Safety hazard investment is a system that facilitates management decisions in security controls. The HANZOP process identifies and assesses potential hazards from construction activity using the ontology integration model, successfully supporting the identification of potential enterprise hazards [56]. It includes the development of a safety model of ontology with computer vision algorithms to develop knowledge graphs that can recognize hazards and comply with safety rules, even in automated process changes.

The results of this approach can detect fall-from-height hazards in various contexts from images [6] and assist fall protection design and planning in building information models, as suggested by Melzner et al. [15].

An ontology representation framework was proposed to characterize abstract data into four knowledge elements, using NLP to automatically extract ontology instances, thereby facilitating the extraction and integration of heterogeneous data from the ever-increasing literature [44]. Zheng et al. [24] suggest that ontology is important for establishing information interoperability for logistics management and construction workflows. The information integration processes with security ontology mapping with ISO standards and Essential Body of Knowledge (EBK) allow for result reuse, interoperability, integration, and knowledge reasoning. Ontologies also have an important role in information integration in safety management. Various frameworks and working models that have shown considerable promise for improving information sharing, interoperability, and information reuse. Such work is primarily focused in China, the US, and South Korea. Such work primarily originates in China, US, and South Korea, with research results focused on the design and planning process. Of such work, China accounted for 29 (50.88%) of the 57 papers reviewed. These studies reflect the successful progress of ontological development for information integration information in safety management.

4.3. Application of Ontology in SM

SM plays an important role in transmitting knowledge within the construction industry. Due to a general lack of representation, information heterogeneity raises difficulties in information sharing and reuse. Ontologies can be used to bridge such differences using essential semantic techniques through the development of appropriate formal conceptual specifications. In presenting various knowledge information for work safety with ontology, practitioners adapt the model and system development with a level of urgency according to work capacity and conditions. Many tools and applications have been developed to enhance the effectiveness of controlling accident risk (Okudan et al., 2021) [57]. This demonstrates the importance of supporting applications and tools in safety management. In terms of ontology tools and applications, CBRisk is a web-based tool that supports the RM process by using the project similarity feature in the form of fuzzy linguistic variables. CBRisk has been shown to increase the effectiveness of RM in construction projects (Wu et al., 2020) [32]. CBR and NLP methods were developed to formalize metro accident information as a basis for decision-making. The modeling results have been shown to be effective for operational RM and disaster mitigation. AFPS-Ontology, as an AFPS design application, is used to identify the best design in work activities at high altitudes and has been shown to be accurate in trials using existing case data [18]. Optimal model utility depends on properly defining the ontology in terms of its life cycle phase with standardized BIM and the development of appropriate BIM tools [50].

The use of NLP with ontology was also carried out by Shen et al. [31], Wu et al. [32], and Chen et al. [44]. The use of ISO rules by Batres et al. [40] for ontology-based systems engineering have been shown to be easy to read and to facilitate communication between engineers. Communication information technology (CIT) has been shown to effectively promote safety management [58]. Several other applications that are used with ontologies include: SOM (scenario object modeling), NoSQL Cassandra as a database, and SNSS (social network system), where almost 60% of papers use assistive applications in supporting ontology-based safety services. Ontology-based TC was used to match documents with insecure scenarios to assist JHA. SRIonto is used to facilitate knowledge sharing and semantic interoperability, providing formal safety knowledge information for safety risk identification and supporting the development of decision support systems [5]. The use of the How Net structure by including a special taxonomy for the analysis of potential construction hazards by processing construction drawings using semantic annotations and similarity calculations [1].

Several other applications have modified ontologies for automatic security risk identification and prevention by integrating the ontology-based safety rule library and NLP technology [31]. The use of ontological CBR with ontology modification can improve knowledge retrieval performance to support decision-making in metro operations [32]. An ontology knowledge base was developed from unsafe scenarios and secure approaches using TC implementation with a semi-automated procedure to match case reports [22]. Ontology model modification was used to represent potential construction hazards implied in images by combining Hownet and taxonomies to prevent fatal accidents [1]. Wu et al. [32] built a CBR framework using an NLP ontology to create a decision-support model for workplace accidents. With 11 papers covering a wide range of matters relating to semi-automated and automated processes in ObSM, China shows considerable interest in developing tools and applications. The results of the ObSM-related topics analyzed show that the tools are capable of deceiving and modifying the ontology.

In the past decade, there has been an increase in interest in OBSM, which is not only closely related to CM but also a part of safety management. Although there had not been any development of ontology on a large scale until this study, the development of ontology is rapid in terms of information integration. Various breakthroughs have been made in addressing interoperability and knowledge reuse. These breakthroughs have been applied to the design and planning process gradually. As for the approaches used in building ontologies, information integration and application are the limits used in measuring the extent to which trends, issues, and information will be useful in the future. Furthermore, the development of a special ontology is important due to its emphasis on task completion and the immediate impact. For the special function ontology, increasing expert knowledge and general logic, as well as accurate historical probabilistic data, are important in terms of suppressing limitations. Finally, the use of applications in engineering and building ontologies has become important, even though there have not been many additions to the process. It is obvious that there is a need for development in adding supporting applications to speed up the ontology-building process to support safety services. Moreover, the literature in this study is drawn from some specific databases and thus has its limitations. Future studies may expand the number of databases that contain literature written in different languages in order to present a more comprehensive picture of the situation.

5. Conclusions

Research results from a collection of ObSM papers based on the ontology life cycle, information integration, and the resulting application have become important information for safety services. One part of CM is a safety service based on the ObSM, which has been investigated by a number of practitioners and scientists. However, there is no outline of trends, issues, and solutions for the future.

This study aims to present a detailed analysis of 57 collected papers to identify macro research trends focusing on ObSM. Via a literature review, it becomes important to measure how the application of ontology supports work safety services based on the ontology life cycle. Restrictions based on the development life cycle, starting from ontology building, ontological information integration, and application, will find future trends, issues, and solutions for the development of ObSM in accordance with the 57 research results collected.

Nearly 30% of the papers are focused on the planning and design stages, while information integration for subsequent sharing and application accounted for slightly more than half of the paper topics, with China providing the largest number of papers based on geographic origin. Applications and tools accounted for only slightly less than 20% of the papers reviewed. The ontology life cycle in SM has been well developed and forms an area of particular interest, but it is subject to considerable limitations due to a lack of case data and expertise. For the information integration process to support work safety processes, the ontology-based safety model provides many new breakthroughs for collecting fragmented information from various sources and stakeholders.

The important information gathered from topic analysis in ObSM will provide a big picture for improving safety services based on ontology. The conclusions of the analysis results indicate the need to highlight and improve SM applications and supporting tools for better process automation. Overall, ObSM is an important and growing CM domain for improving construction safety. To further improve safety at all stages of the construction process, future work on SM with ontology should focus on, yet it is under-researched supervision and maintenance stages. In the future, it is essential to improve the ability of experts and the probability of data generation for more reliable analysis and to strengthen the application in the ontology development of the construction industry.

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