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LEVERAGING LARGE LANGUAGE MODELS FOR ENHANCED CONSTRUCTION SAFETY REGULATION EXTRACTION

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SUMMARY: *The construction sector has long been known for its complicated safety requirements, which are critical to ensure the well-being of workers on site. However, interpreting these requirements and maintaining compliance can be difficult due to the amount and complexity of the paperwork involved. This leads to difficulty extracting safety information from requirement documents. Besides, information that is presented in a manner similar to human-like responses can improve employee understanding. This study proposed a Construction Safety Query Assistant (CSQA) approach to enhance the extraction and knowledge of construction safety regulations using Large Language Models (LLMs). CSQA comprises of three primary components: (1) the Construction Safety Investigation Module (CSI), which gathers and processes safety regulation documents through text extraction and preprocessing to build a searchable database; (2) the Safety Condition Identification Module (SCI), which utilizes LLMs to interpret user queries and extract relevant information from the CSI database, capitalizing on the models' ability to understand context and subtle textual nuances; and (3) the Safety Information Delivery Module (SID), which presents the retrieved information to users and integrates a feedback loop to refine the accuracy and relevance of responses based on user interaction. The CSQA approach was validated with 2 case studies that offered more contextually relevant, possibly lowering non-compliance risks, improving worker safety, and simplifying the consultation process in the construction sector. This study emphasizes its potential to transform access to crucial safety information in the construction industry.*

KEYWORDS: *Construction safety document, Large Language Models, Information extraction, Retrieval-Augmented Generation, Construction Safety Query Assistant.*

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1. INTRODUCTION

The construction industry is a significant safety risk, with workplace accidents often resulting in substantial loss of life and considerable property damage repercussions (S. V.-T. Tran et al., 2023; Tran et al., 2021). According to the Occupational Safety and Health Administration (OSHA), in 2022, the construction sector reported 1,056 of the 5,486 total occupational fatalities, marking an 11 percent increase from 2021 and representing the second-highest category of workplace deaths ("Census of Fatal Occupational Injuries Summary, 2022," 2022). In Korea, the construction industry has the highest number of fatal accidents compared to all other sectors, which amounts to over 50% ("Status of fatal accidents subject to disaster investigation in 2022," 2022). The recurrence of such incidents emphasizes the necessity for rigorous safety protocols and robust accident prevention strategies. Literature indicates that a strategic enhancement of safety measures could significantly mitigate such hazards (Bao et al., 2022; S. V. Tran et al., 2022; S. V. T. Tran et al., 2022). Therein, field compliance checking is a fundamental practice involving precise on-site evaluations to enforce safety standards. It aims to protect workers and significantly reduce accident rates (Jeong et al., 2023; Kang et al., 2023). Enhanced safety protocols and strict compliance adherence are crucial for reducing fatal accidents and adopting a safer construction environment.

Safety training is crucial in the construction industry, as it enhances workers' skills and reduces the occurrence of unsafe situations (Kou Wei-mi, 2008). It is a leading measure in driving safety performance and creating a competent workforce (N. Skeepers, 2016). The transfer of non-technical skills, such as communication and decision-making, is particularly important for migrant workers (Nielsen et al., 2022). Safety training should be tailored to the challenges faced at each level of the organization (N. Skeepers, 2016). The importance of safety education in establishing a correct safety production concept is also emphasized (Liao Guo-rong, 2013). However, finding relevant safety training information and general training materials was always challenging for construction employees (Hussain et al., 2024b). The manual review of safety information from textual documents such as codes, standards, and safety manuals present several challenges. These include the tedious and time-consuming nature of the process, the potential for ambiguities in safety objectives (Lin et al., 2015), and the difficulty in extracting relevant data for unfamiliar users (McCluskey et al., 1988). The need for better tool support for evidence management is also highlighted (Nair et al., 2014). To address these challenges, various approaches have been proposed.

Modern technologies have revolutionized the extraction of safety information, allowing for more efficient and accurate techniques to be proposed for extracting information related to accidents and injuries. For example, Feng et al. suggested a framework based on deep learning algorithms to extract event-related information such as the date, location, and type of accident from accident news reports (Feng and Chen, 2021). On the other hand, Rupasinghe et al. proposed a rule-based technique to extract hazard-related information from accident reports (Rupasinghe and Panuwatwanich, 2021). Similarly, (Baker et al., 2020) suggested using Natural Language Processing (NLP) techniques to identify injury precursors. However, there is still a lack of research focused on automatically extracting requirements from construction safety rules to ensure compliance in the field. Additionally, the automatic information extraction process needs to provide users with accurate and timely responses to their inquiries as human responses. Human-like text generation is crucial for construction safety information extraction because it significantly improves the accessibility and usability of complex safety regulations.

Large Language Models (LLMs), such as GPT and Bard, offer significant potential to support the construction industry, particularly in construction safety information extraction (Brozovsky et al., 2024). These models are adept at processing large volumes of unstructured textual data shared in construction where safety reports, incident logs, and compliance documents are prevalent (Saka et al., 2024) . LLMs can be trained to recognize descriptions of near-miss incidents and accidents from textual reports and extract relevant information such as the type of incident, involved equipment, and potential safety violations (Wang and El-Gohary, 2023). Furthermore, conversational AI, powered by LLMs, can provide real-time, context-specific responses to queries about safety protocols and regulatory compliance. For instance, each construction project is unique, with specific safety requirements, drawings, and vendor-specific rules. LLMs can be fine-tuned with project-specific datasets to evaluate these documents and deliver customized answers considering the project's unique context. This ability not only improves the accuracy of the information provided but also ensures that safety practices are tailored to the specific needs of each project. By integrating LLMs into safety management systems, construction companies can enhance compliance monitoring, proactive hazard identification, and decision-making processes, ultimately fostering a safer and more compliant construction environment (Hussain et al., 2024b; S. Tran et al., 2023).

This research proposes the Construction Safety Query Assistant (CSQA) approach. This innovative method utilizes LLM to extract and provide real-time answers to safety regulatory questions in the construction industry, thereby bridging the knowledge gap for professionals. The CSQA comprises three main components. The first, the Construction Safety Investigation module (CSI), collects comprehensive safety regulations. The second component, the Safety Condition Identification module (SCI), utilizes the database created by CSI. Here, the LLM analyzes user-generated queries, sifts through the indexed regulations, and pinpoints the most relevant information based on its extensive training in regulatory and safety contexts. The third component, the Safety Information Delivery (SID), is designed to interact directly with users. SID delivers the necessary safety information and gathers user feedback to refine and enhance the system's accuracy and performance. The paper structure provides a literature review of the current landscape of construction safety information retrieval and the application of LLMs in this field. Following this, it details the proposed CSQA method, outlining each module's role and functionality in section 4 of the paper, which is dedicated to validating the proposed approach through a series of case scenarios that demonstrate CSQA's practical application and effectiveness in real-world settings. The paper concludes by discussing the results and implications for future research and implementation in construction safety management.

2. LITERATURE REVIEW

2.1 Current state of construction safety information retrieval and extraction

Throughout its evolution, the construction industry has become synonymous with intricate projects and the inherent safety concerns they entail. Consequently, a comprehensive array of safety regulations, guidelines, and optimal methodologies has been introduced over time. Historically, the retrieval and extraction of pertinent safety data have predominantly relied on manual methodologies (Zhong et al., 2020). Professionals often encounter the arduous task of sifting through extensive physical binders or digital archives. Despite its exhaustive nature, this approach is fraught with challenges. The time-intensive process of manual searches, coupled with the potential for human error, frequently results in critical safety directives being overlooked or inadequately incorporated (Tran et al., 2024). Moreover, the dynamic nature of construction projects, with their distinct challenges and parameters, necessitates a customized understanding of safety regulations, which manual searches cannot provide efficiently (Wu et al., 2022).

Significant efforts have been made to streamline accessing safety information (Tran et al., 2021). Initially, safety information was moved to digital databases, allowing for keyword searches. While this transition did speed the retrieval process to some degree, it was not without downsides. Keyword searches often produce many results, necessitating further filtering to identify relevant information. Furthermore, the lack of contextual understanding and the static nature of these databases limited their ability to provide nuanced interpretations for specific project scenarios. To address these challenges, Feng and Chen proposed a deep learning framework for extracting event-specific information (such as date, location, and type of accident) from accident news reports for construction safety management (Feng and Chen, 2021). Similarly, Rupasinghe and Panuwatwanich suggested a rule-based technique for identifying hazards in accident reports (Rupasinghe and Panuwatwanich, 2021). Baker et al. (Baker et al., 2020) advocated for using natural language processing (NLP), which leverages a variety of textual patterns to detect precursors to injuries. These developments underscore the potential of advanced AI-driven methods for enhancing the efficiency of information retrieval and improving contextual understanding through the use of LLMs.

NLP enables computers to understand and process human language text much like a person would. Within NLP, Information Extraction (IE) is a specialized field dedicated to retrieving relevant information from text sources. Broadly speaking, there are two primary techniques for information extraction: (1) machine learning (ML) and (2) rule-based approaches. However, due to limited training data, research has predominantly focused on rule-based techniques. The emergence of LLMs has revolutionized NLP by offering a transformative solution to this challenge. LLMs like GPT, Bard, and others have made remarkable advancements in knowledge curation, demonstrating their efficacy in deciphering and organizing complex scientific information. By leveraging vast amounts of data, these models have significantly enhanced our ability to extract valuable insights from text, marking a substantial leap forward in the field of natural language processing. These models are adept at extracting critical knowledge from extensive scientific literature, excelling in protein interactions, biochemical pathways, gene regulatory networks, and identifying adverse drug events (Gu et al., 2023). (S. Tran et al., 2023) indicated that LLM can enhance safety management in the construction industry. The ability of LLMs to process and analyze large datasets with a high degree of accuracy has revolutionized the extraction information approach, making it possible to glean valuable insights at a pace and precision far exceeding traditional methods.

2.2 The need to leverage LLM for enhanced construction safety information extraction

Within the construction industry, safety is a paramount concern, and the management of extensive safety documentation and guidelines is central to ensuring the welfare of all stakeholders. LLMs are crucial in extracting relevant and actionable safety information from complex construction project documents (Saka et al., 2024).

These models exhibit exceptional proficiency in discerning the contextual nuances of inquiries, thereby empowering them to retrieve precise information about safety protocols. This capability extends to extracting specific guidelines on machinery handling procedures from an extensive repository of safety regulations. Moreover, LLMs offer the advantage of customization to project-specific datasets, thereby augmenting their efficacy in processing proprietary documents such as plans, safety regulations, and vendor-specific guidelines often archived in formats such as PDFs (S. Tran et al., 2023). Through training or fine-tuning project-specific datasets, LLMs can seamlessly integrate, and process confidential materials supplied by enterprises. This adaptability enables LLMs to furnish relevant and secure solutions while upholding the confidentiality of sensitive project-related information. The integration of LLMs into construction safety management represents a paradigm shift in conventional methodologies by automating the extraction and organization of pivotal safety data. This transformative process not only mitigates the administrative burden but also substantially enhances the precision of safety compliance measures. (Hussain et al., 2024a). LLMs excel in interpreting complex legal and technical language in diverse regulatory documents, ensuring that construction managers and safety officers are consistently well-informed without resorting to labor-intensive document reviews. Moreover, by generating customized training materials and providing insights into prevalent safety issues and trends, LLMs foster a culture of safety and continuous improvement (Bao et al., 2024; Hussain et al., 2024a; S. Tran et al., 2023). In light of the ever-changing landscape of construction sites, there's a pressing need for the development of technologies that can effectively adapt to these dynamic environments. LLMs, with their remarkable capacity to navigate the complexities of construction projects and manage diverse sets of data, emerge as invaluable assets in this pursuit. Therefore, investing in research to leverage LLMs for this purpose is not just advantageous but imperative for the advancement of construction safety.

3. MATERIALS AND METHODS

3.1 Research methodology

This study proposes a novel methodology utilizing LLMs to improve the extraction of construction safety regulations. The research framework is grounded in the design science approach articulated by Peffers et al. (Peffers et al., 2007), recognized for its efficacy in advancing technological and theoretical knowledge bases by offering innovative solutions to enhance established methodologies (vom Brocke et al.).This methodological approach unfolds through five methodical steps: (i) problem identification and motivation establishment, (ii) objectives delineation for the solution, (iii) system design and development, (iv) prototype creation, and (v) evaluation through practical application (Geerts, 2011; Kuechler and Vaishnavi, 2008; Peffers et al., 2007).

As depicted in Figure 1, the initial step involves recognizing the existing challenges in construction safety information retrieval and extraction through the lens of large language models (LLMs). The second step focuses on setting clear objectives for the solution, explicitly targeting the enhancement of construction safety information extraction using LLMs. The third step involves the architectural design of the proposed system, detailing essential modules, their interrelationships, and the selection of appropriate development platforms. A system prototype is developed in the fourth step to demonstrate its functionality. The final step entails a case study implementation to test the system's effectiveness.

3.2 Proposed approach

The primary purpose of the Construction Safety Query Assistant (CSQA) approach is to enhance the extraction and understanding of construction safety regulations using LLM, with the key features, illustrated in Figure 2, comprising three modules. The foundational element of this approach, the Construction Safety Investigation (CSI) module, focuses on the meticulous aggregation of safety regulations necessary for establishing a comprehensive information database. This module primarily processes a range of PDF documents containing safety regulations and acts as the primary repository for raw safety data. Its essential functions include text extraction, preprocessing, and global indexing. Text extraction is vital as it transforms the content of PDFs into a structured format that is more accessible for further processing. Preprocessing involves cleaning and normalizing this text, setting the stage for subsequent analytical stages. Subsequently, the Safety Condition Identification (SCI) module serves as a critical intermediary between the foundational database developed by the CSI module and the end-user interface. The principal role of the SCI module is to engage with the CSI database to extract relevant safety information in response to user queries. This module's integration of a LLM is pivotal. Leveraging its extensive training, the LLM processes and interprets user queries in real time, scrutinizing the indexed regulations within the CSI database to provide precise and contextually appropriate information. Incorporating the LLM enhances the accuracy, context sensitivity, and efficiency of the information retrieval process, ensuring swift and reliable responses to user inquiries.

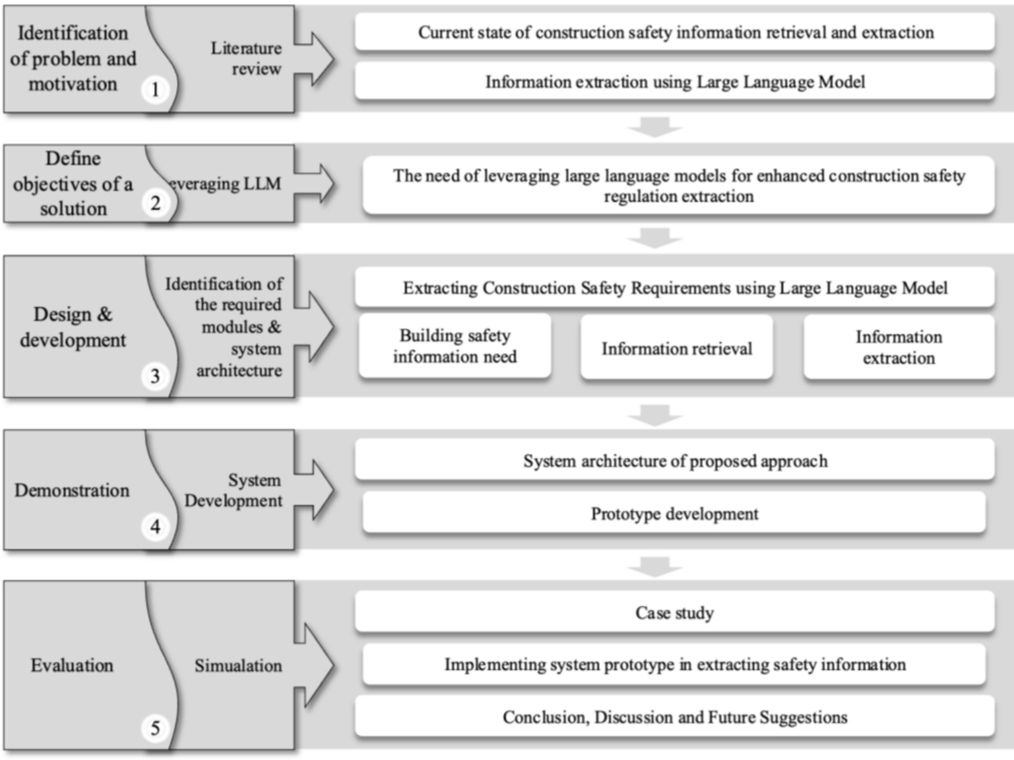

Figure 1: Research methodology.

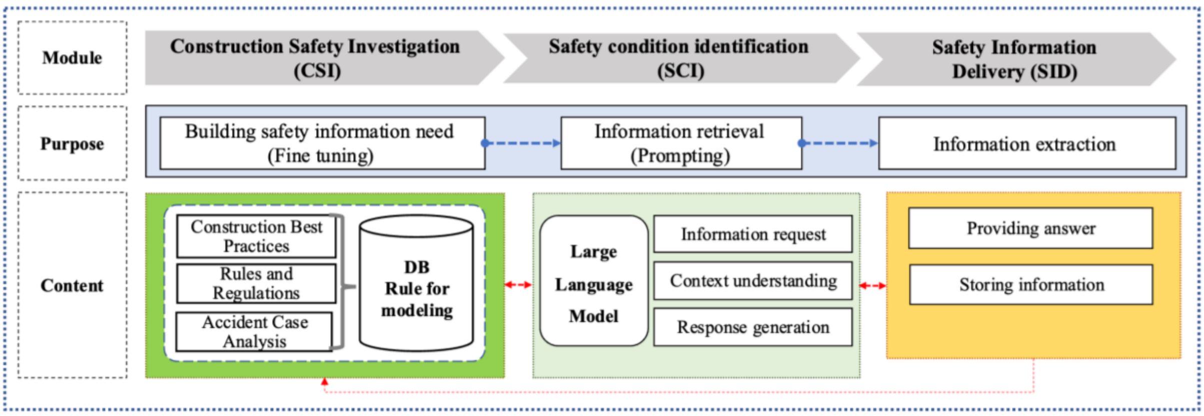

Figure 2: An approach of leveraging large language models for enhanced construction safety regulation extraction.

Furthermore, the approach includes the Safety Information Delivery (SID) module, designed to effectively present the processed safety information to end users. This module operates as the user interface, delivering clear, concise, and relevant answers to user queries. Additionally, it incorporates a feedback mechanism that allows users to assess the accuracy and relevance of the information provided. This feedback is integral to the continuous refinement of the system, enhancing its accuracy and reliability. By consistently integrating user feedback, the SID module adapts to evolving user needs and preferences, sustaining its utility and efficacy in disseminating precise construction safety information.

3.3 Prototype development

Figure 3 depicts the prototype development process and tool used for the proposed approach. This prototype builds the RAG (Retrieval-Augmented Generation) pipeline using Langchain as the selected library and Chroma as the vector storage solution. The RAG pipeline is an essential component of Large Language Models (LLMs) and is crucial for applications that require context-aware question-answering (Chen et al., 2024). The process flow starts with unstructured information in the form of PDFs given by the users, as illustrated in Figure 4. The Chroma generates a vector database (VD) of high dimensional vectors of the unstructured information provided. Next, a query asks for information, the query is converted to vector form, and a similarity is checked between VD vectors, resulting in the chunk of vectors related to the query. The following step takes the chunks and queries, decodes them into hard text, inserts them in the LLM prompt, which is processed by LLM, and outputs a generated formatted text required by the query asked.

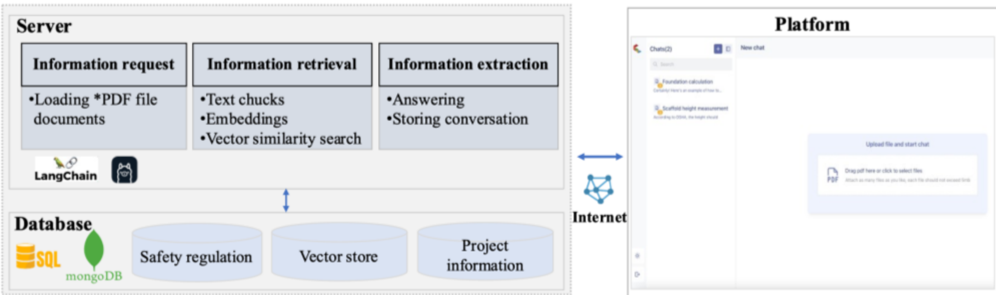

Figure 3: System architecture.

To begin with, the authors carefully evaluated the available libraries in the LLM domain and identified Langchain and LlamaIndex as the two leading options. After considering various factors, such as familiarity and integration capabilities, we decided to proceed with Langchain for this project. One of the critical components of the RAG framework is vector storage, which enables efficient retrieval of relevant contexts based on user queries. We extensively researched different vector storage solutions and found that Chroma offers excellent integration capabilities with Langchain. Therefore, Chroma was chosen as the vector storage solution for this project. Implementing the ' ingest ' method is the first step in building the RAG pipeline. This method is responsible for loading a document into vector storage. To accommodate the token limit of the LLM, we employ a two-step process. Firstly, the document is split into smaller chunks using the RecursiveCharacterSplitter provided by Langchain. This ensures that each chunk falls within the acceptable token limit. Next, these chunks are vectorized using Qdrant FastEmbeddings, a lightweight embedding model. The vectorized chunks are then stored in Chroma, allowing efficient retrieval during the question-answering process.

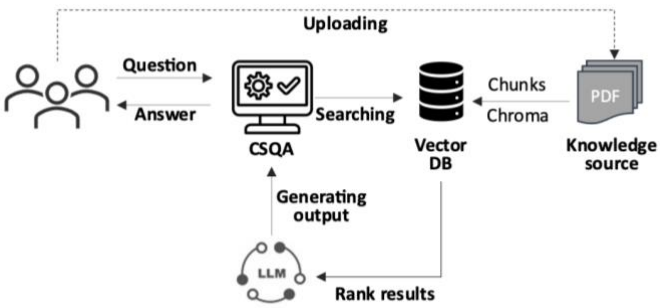

Figure 4: The workflow of CSQA.

The second method in the RAG pipeline is the `ask` method, which handles user queries. When a user poses a question, the RetrievalQAChain is employed to retrieve relevant contexts (document chunks) using vector similarity search techniques. These contexts and the user's question are used to compose a prompt. The prompt is sourced from the Langchain hub, specifically the Langchain RAG Prompt for Mistral, which has been extensively tested and proven reliable for LLM prompting techniques. The composed prompt is then used to request a prediction from the LLM server, which utilizes the "Mistral 7B" LLM model (Jiang et al., 2023). While implementing the `ingest` method, we utilize PyPDFLoader to load PDF files the user uploads.

Additionally, we employ the `filter_complex_metadata` function from Langchain to filter out complex metadata that ChromaDB does not support. This ensures that only relevant and compatible information is stored in Chroma for efficient retrieval. Chroma is used in conjunction with Qdrant FastEmbeddings for vector storage as the embedding model. Quadrant FastEmbeddings is a lightweight model transformed into a retriever with a score threshold of 0.5 and k=3. This means the retriever returns the top three chunks with the highest scores above 0.5, ensuring high-quality and relevant context retrieval. Furthermore, we construct a simple conversation chain using the Langchain Expression Language (LECL), which facilitates seamless communication between the various components of the RAG pipeline. The `ask` method passes the user's question into the predefined conversation chain and returns the result, providing the user with the relevant answer or information they seek.

4. CASE STUDY

The effectiveness of the proposed CSQA system is validated through rigorous evaluation in two meticulously designed case studies. These studies were purposefully crafted to address the disparate needs of safety managers and construction students. Figure 5 outlines the parameters of each case study, including the target audience, a scenario exemplifying a real-world situation, and the type of safety documentation employed. In the first case study, safety management professionals are presented with the CSQA system as a tool to bolster existing safety protocols specifically regarding ladder use. The seamless interface of the CSQA system facilitates expedient access to critical safety regulations and guidelines, empowering safety managers to make informed decisions and implement proactive risk mitigation strategies. The second case study is designed to underscore the pedagogical potential of the CSQA system. Construction students leverage the system's functionalities as an learning environment to comprehensively explore scaffold safety regulations and best practices. Engaging in interactive dialogue facilitated by the CSQA platform, students not only cultivate a nuanced understanding of scaffold safety principles but also refine their analytical acumen and critical thinking skills . This dual approach, catering to both safety managers and construction students, underscores the versatility and adaptability of the CSQA system in meeting the diverse educational and operational needs within the construction industry.

Case Study	1	2
Example Scenario	Use of Ladder	Use of Scaffold
Proposed User	Safety Managers	Construction Students
Document/Pdf	Stairways and Ladders A Guide to OSHA Rule (1)	A Guide to Scaffold Use in the Construction Industry (2)

Figure 5: The case study design.

4.1 Case-I: Use of Ladder

This case study was designed to investigate the efficacy of the CSQA system in promoting safety in ladder usage, with a focus on safety professionals within the construction sector during hazards identifcation and mitigation process.The proper utilization of ladders is critical in construction environments to mitigate the risk of accidents and injuries. To assess the system's effectiveness, safety professionals are provided with the document “Stairways and Ladders: A Guide to OSHA Rules” (OSHA, 2003), which delineates essential safety regulations and guidelines concerning ladder usage in construction settings. This document serves as the foundation for inquiries within the CSQA prototype system, enabling safety professionals to extract pertinent safety information according to their specific needs and concerns.

Through the extraction and comprehension of each safety instructions stipulated by OSHA regulations, safety professionals can reinforce safety protocols and implement proactive measures to safeguard worker well-being. The CSQA system facilitates seamless access to critical safety information, empowering safety professionals to make informed decisions and devise comprehensive safety strategies tailored to the unique requirements of construction projects. Engaging with the CSQA platform, safety professionals can explore various safety scenarios and seek information regarding ladder inspection procedures, appropriate ladder placement, weight capacity considerations, and suitable ladder selection based on task requirements and environmental conditions. For instance, safety professionals may inquire about: The frequency and procedures for ladder inspection as outlined by OSHA regulations, Guidelines for selecting the appropriate ladder type based on task requirements, Safety measures to prevent ladder-related accidents in high-risk work environments. By addressing these crucial safety aspects, safety professionals can effectively mitigate the risk of ladder-related incidents, including falls and injuries, thereby fostering a culture of safety within the construction industry.

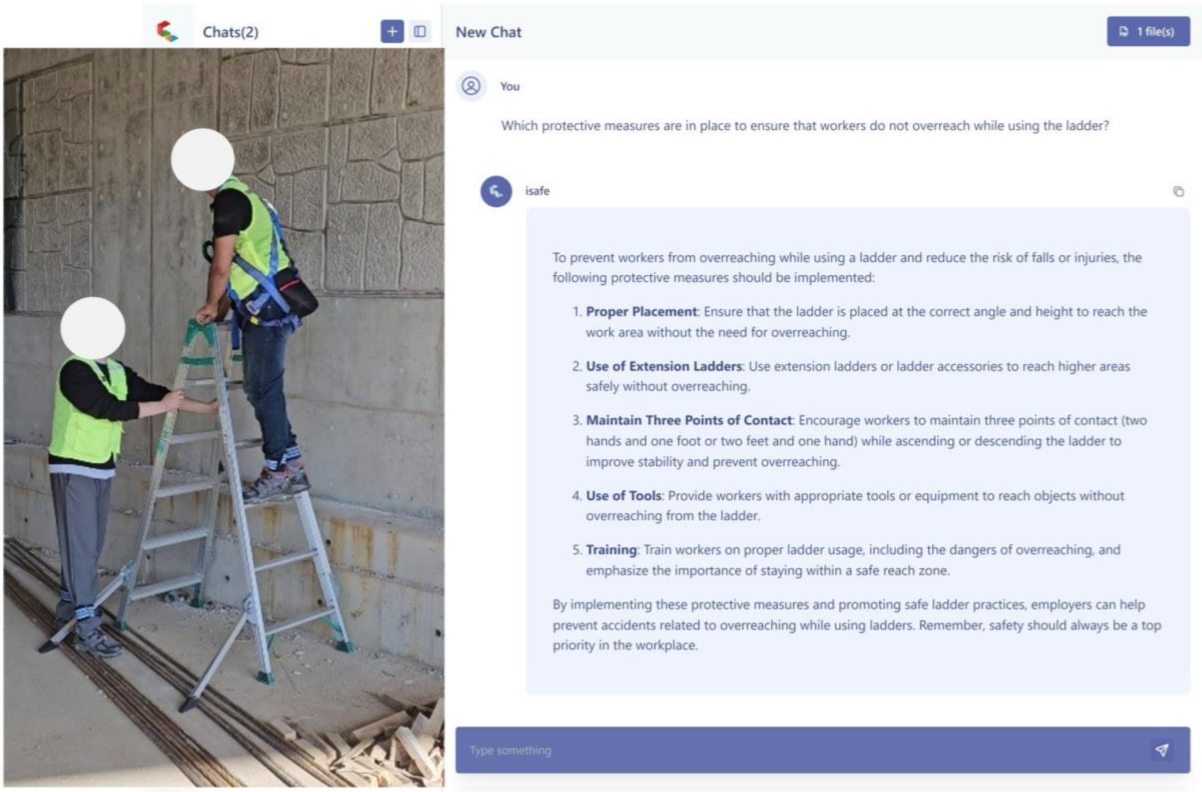

Figure 6: Case Scenario for Ladder and CSQA Sample interface.

In this case, an A-type ladder with two workers working together was presented as a construction scenario (as illustrated in Figure 6). To prepare for the safety inspection process, the safety manager considers some potential hazard situations that may occur during the use of the ladder. The results of the prompting process were illustrated in Figure 6. In the scenario, a user inquires about protective measures to prevent workers from overreaching while using a ladder. The system, referred to as 'isafe,' provides a detailed response, outlining five key measures: (1) ensuring proper placement of the ladder at the correct angle and height to eliminate the need for overreaching, (2) using extension ladders or ladder accessories to reach higher areas safely, (3) maintaining three points of contact to improve stability and prevent overreaching, (4) providing appropriate tools or equipment to reach objects without overreaching, and (5) training workers on proper ladder usage, emphasizing the dangers of overreaching and the importance of staying within a safe reach zone.

4.2 Case-II: Use of Scaffold

In the second case study, the authors evaluated the pedagogical efficacy of the CSQA approach by focusing on extracting safety information about scaffolding, which is critical for students studying construction safety regulations, particularly OSHA 1926 Subpart L. This regulation is essential for ensuring safety in construction settings where scaffolding is prevalent. For this study, a document titled "A Guide to Scaffold Use in the Construction Industry" (OSHA, 2002) was provided as a PDF and uploaded to the CSQA prototype system. Students then interacted with the system, querying it according to their specific informational needs. For example, one student inquired about the requirements for dismantling scaffolding by asking, "What are the OSHA regulations regarding scaffold dismantling procedures?" Through this interaction, students could deeply engage with and understand the safety provisions mandated by OSHA, which is crucial for preventing scaffold-related accidents such as falls, structural collapses, and falling objects.

This learning process underscores the importance of comprehensive safety regulation knowledge in fostering a safety culture within the construction industry, emphasizing the prioritization of worker well-being to ensure successful and safe construction projects. The case study also included scenarios involving fixed and mobile scaffolding at the construction site, as detailed in Figure 7. To facilitate the learning process about potential hazards, students also queried the system about specific safety scenarios, such as the maximum number of workers allowed on the scaffolding at one time. As shown in Figure 5, the responses illustrated the extracted information relevant to these safety queries. The CSQA responds with a detailed explanation that the maximum number of workers depends on several factors, such as the scaffold's load capacity, platform dimensions, and type. It emphasizes the importance of ensuring that scaffolds are not overloaded and that OSHA guidelines are followed, including the use of guardrails and fall protection. The response further notes that different types of scaffolds may have varying capacity limits and that worker training, supervision, and engineering evaluations may be necessary to determine safe load and worker limits.

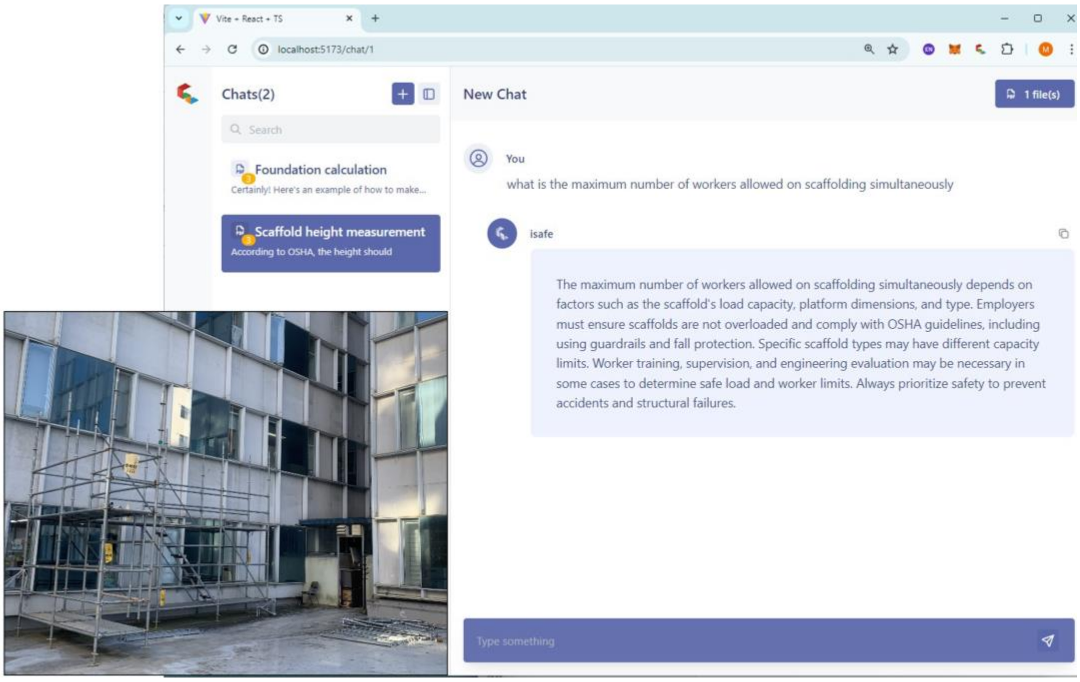

Figure 7: Case Scenario for Scaffold and CSQA Sample interface.

4.3 System evaluation and results

To comprehensively evaluate the effectiveness of the CSQA system, a subjective assessment was conducted using a structured questionnaire. The questionnaire targeted four key criteria: learnability, interaction, communication and relevancy, as listed in Table 1. These criteria were chosen to ensure a thorough examination of the system's performance in extracting rules and understanding level of users. The questionnaire was distributed to a group of 26 participants, including 10 undergraduate students, 7 graduate students (Master's and PhD courses), and 9 industry professionals, selected through purposive sampling to ensure varied perspectives and expertise in the field. The evaluation utilized a Likert scale with possible scores ranging from 1 to 5, where 1 indicated strong disagreement and 5 indicated strong agreement.

Table 1: Mean score of evaluation criteria.

Evaluation Criteria	Purpose	Min	Max	Mean Score
Learnability	Measure the system's effectiveness in facilitating comprehension and learning of construction safety rules compared to conventional methods. Example Question: Did using the construction safety rules extraction system enhance your understanding of safety regulations and protocols?	3	5	3.8
Interaction	Assess the ease and intuitiveness of user interaction with the system for navigating and accessing construction safety information. Example Question: How easy was it to navigate through the system and access information on construction safety rules?	4	5	4.5
Communication	Evaluate the clarity and effectiveness of communication between users and the system in providing explanations and guidance on construction safety regulations. Example Question: Were the explanations and guidance provided by the system clear and helpful in understanding construction safety regulations?	3	5	4.1
Relevancy	Determine the system's capability to deliver accurate and pertinent answers to users' inquiries regarding construction safety protocols and regulations. Example Question: Did the system provide relevant and accurate answers to your queries about construction safety protocols?	4	5	4.4

5. DISCUSSIONS

In this study, the authors introduced the CSQA approach to enhance information retrieval from regulatory documents. The CSQA system leverages LLMs to provide accurate, context-specific responses to safety-related queries. A proof-of-concept prototype was developed and implemented, as outlined in section 3.2. Evaluation results from a case study with safety managers and construction students ascertained that the CQSA could effectively support project participants in retrieving accurate information pertinent to their inquiries regarding construction safety protocols and regulations. Additionally, user feedback confirmed that the proposed approach was convenient to use, and would empower safety professionals in making decisions and implement risk mitigation strategies. Analysis of participants' responses revealed positive feedback across various evaluation criteria, with mean scores ranging from 3.8 to 4.5 on a scale of 1 to 5. Interaction received the highest mean score of 4.5, indicating that users found the system intuitive and easy to use. Communication and relevancy also scored well, with mean scores of 4.4 and 4.3, respectively, highlighting the system's effectiveness in providing clear and relevant responses. Learnability received a slightly lower mean score of 3.8, suggesting that while the system aided understanding, there may be areas for improvement in facilitating learning. Standard deviation values ranged from 0.6 to 1.0, indicating moderate to high variability in participant responses across different aspects of the system's performance.

Construction professionals, such as designers, may utilize our system to extract rules or information from documents during the design phase. Similarly, safety managers may rely on the CSQA system during the hazard mitigation process, while construction students may use it for educational purposes or to deepen their understanding of safety regulations. Similarly, site supervisors may also benefit from the system's capabilities, particularly during routine safety inspections or when encountering unexpected safety concerns on the job site. Moreover, contractors and subcontractors may find value in utilizing the CSQA system to ensure compliance with safety regulations and standards throughout the construction process.

However, while the CQSA shows promise in addressing the shortcomings of current methods for searching for safety information, several considerations and limitations warrant further attention. Firstly, the study primarily focuses on the optimization of a database containing safety requirement information, without expounding on the architecture of the algorithm employed and its precision in information retrieval. It would be worthwhile for future works to delve further into this in order to provide insights into the scalability and overall efficiency of the proposed methodology. Additionally, investigating the precision of the algorithm in information retrieval is essential for evaluating its accuracy and reliability in extracting safety requirement information. Hence, this step would contribute to the validation of the proposed approach. Secondly, the case study focused solely on the extraction of scaffolding-related information. It would be necessary to examine the approach for retrieval of information in a broader range of tasks and settings, to shed light on the the versatility and applicability of the proposed approach across various safety-critical domains within the construction industry. Thirdly, the evaluation did not address the risk of hallucinations or misunderstandings by the CSQA approach. These hallucinations can lead to the provision of incorrect or irrelevant information. Hence, there is a need to incorporate continuous feedback loops to mitigate this risk, allowing users to report inaccuracies. This feedback is used to refine the model and improve the accuracy of responses over time. Future studies can also explore how this retrieval approach can be integrated into practice to enrich other safety management processes, such as Job Hazard Analysis (JHA) and safety training.

6. CONCLUSION

The present study proposed the Construction Safety Query Assistant (CSQA), a novel system leveraging Large Language Models (LLMs) to enhance the extraction and comprehension of construction safety regulations. This approach seeks to mitigate the complexities inherent in retrieving and understanding detailed safety requirements from voluminous and intricate regulatory documents. Comprising three core modules—Construction Safety Investigation (CSI), Safety Condition Identification (SCI), and Safety Information Delivery (SID)—the CSQA system presents a structured and efficient methodology for processing, querying, and delivering safety information tailored to specific user needs. The demonstration through two case studies highlights the potential of CSQA to significantly improve safety management and training within the construction industry, enabling precise and rapid access to critical safety information.

The study's findings underscore the transformative potential of integrating LLMs into construction safety management, offering a robust solution to longstanding challenges in safety regulation compliance and education. By providing clear, context-specific responses, the CSQA system can enhance the efficiency and effectiveness of safety management practices. The broader implications of this study suggest that such technology can be instrumental in creating safer construction environments and fostering a culture of compliance and continuous improvement.

Future research will aim to expand the scope of the CSQA system to encompass a broader range of safety regulations and practical applications, providing a comprehensive tool for safety management across the construction industry. Implementing continuous feedback loops and enhancing the training data can help address this issue, thereby improving the system's robustness and trustworthiness in practical applications. This effort will ensure a safer working environment for all stakeholders and foster the adoption of intelligent systems in safety management practices.

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