



## HYBRID KNOWLEDGE MODELLING WITH AI FOR FIRE SAFETY MANAGEMENT IN CONSTRUCTION

Dilan Durmus<sup>1</sup>, Alessandro Carbonari<sup>1</sup>, Shabtai Isaac<sup>2</sup>, and Alberto Giretti<sup>1</sup>

<sup>1</sup>Università Politecnica delle Marche, Italy

<sup>2</sup>Ben-Gurion University of the Negev, Department of Civil and Environmental Engineering, Beer-Sheva, Israel

### Introduction

The construction industry faces significant challenges in fire safety management due to the complexity of decision-making processes and the dynamic nature of construction environments. Traditional decision-making tools and methods often inefficient in handling this complexity, struggling with integrating tacit knowledge and providing real-time solutions due to the impreciseness or uncertainty of information.

The introduction of knowledge-based expert systems in the 1980s marked a milestone in automating knowledge-based problem-solving. These systems utilized deep domain knowledge and heuristic reasoning to address complex, real-world problems. Their declarative nature enabled reasoning under uncertainty and provided explainable rationales for decisions (Ashlock, 2022).

The idea of expert systems in artificial intelligence (AI) was once seen as the solution to these challenges (Giarratano & Riley, 1989). However, these systems were struggled by the labor-intensive nature of knowledge acquisition, scalability limitations, and an inability to adapt creatively to evolving contexts (Ashlock, 2022). This is especially relevant in the construction industry, where information is generated at an accelerating pace and under constantly changing conditions. For this data to be transformed into actionable knowledge, it must be meaningfully interconnected. Although the logical relationships between data points are often understood by domain experts, the methods for efficiently structuring, processing, and reusing this vast and heterogeneous information are still lacking. This reinforces the urgent need for knowledge structuring methodologies that can translate raw data into consistent, usable knowledge to support effective decision-making in high risk environments like fire safety management.

To address these limitations, recent advancements in artificial intelligence (AI), particularly in Large Language Models (LLMs) such as GPT-4, present a new opportunity for enhancing knowledge engineering practices. These models are capable of processing unstructured data, identifying implicit patterns even in natural language, enabling them to support complex reasoning tasks that were once relied on human experts.

Unlike earlier rule-based systems, LLMs can dynamically adapt to new contexts, offering flexibility in environments where information changes fast and decisions must be made in real time. This research investigates how LLMs can be integrated into knowledge engineering frameworks to support fire safety decision-making in the construction industry.

### Methodology

Rather than proposing a fully automated system, the study adopts AI-in-the-loop methodology that is a hybrid human-AI approach, where LLM act as collaborator in knowledge acquisition and modeling processes, guided by domain experts (Ashkenazi et al., 2023). The study focusing on fire safety management in the context of the Rhythm Club fire incident by NFPA report (Duval, 2006) and applies the CommonKADS methodology as a structured framework to organize knowledge modeling activities into three main phases: conceptualization, operationalization, and formalization (Schreiber, 2000) (figure 1).

The conceptualization phase involves identifying and organizing critical domain knowledge from unstructured data sources, such as reports and regulatory texts. By using prompt engineering techniques, LLM extract relevant arguments and contextual details to build a coherent knowledge base. In the operationalization phase, this structured knowledge is transformed into actionable representations, such as ontologies, through iterative extraction of triples and relationships from both textual narratives and 2D layouts. The formalization phase, validated knowledge is encoded into the CLIPS (C Language Integrated Production System) environment, enabling machine-executable rules for decision support.

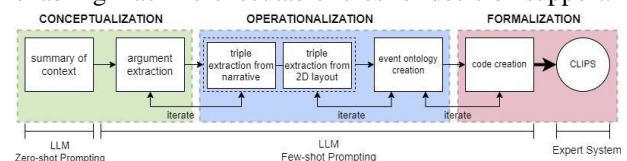


Figure 1: Methodology overview

## Results and discussion

To evaluate this approach, precision, recall, and F1-score metrics were applied to compare AI-generated outputs against a checklist by an human expert. Results indicated strong performance in conceptual data extraction but revealed limitations on structuring ontological data without expert guidance. For example, while GPT-4 achieved the F1 score of 0.97 in extracting arguments from textual data, its performance dropped to 0.55 in extracting ontological structures. However, the rules and codes generated by LLM following the formalization phase allowed a successful actionable decision within the expert system.

The results make it evident why a hybrid approach should be adopted instead of relying on the language model for full automation.

## Future Work

This research demonstrates that while LLMs alone are not yet sufficient to fully automate knowledge engineering in high-stakes domains, their integration into structured methodologies like CommonKADS holds significant promise. By combining the scalability and language-processing strengths of LLMs with the domain expertise of human professionals, it is possible to accelerate knowledge modeling and decision-support system development in fire safety management. The AI-in-the-loop approach not only reduces manual workload but also improves adaptability and responsiveness to complex, evolving situations which is an essential capability in construction environments.

Future work should explore prompt engineering techniques, compare different LLM architectures, and develop improved validation frameworks to enhance reliability. Additionally, integrating diverse digital building models and safety codes with LLM-driven reasoning could further expand the application of this hybrid methodology. This research sets the foundation for the next generation of semi-automated, knowledge-intensive decision support systems that are scalable and sustainable.

## References

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