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Ontology-Driven Project Management: A Framework for Structured Data and Automation

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Abstract

Construction project management grapples with significant complexity and knowledge integration challenges, often hindering efficient decision-making. This paper presents an ontology-oriented programming paradigm designed to model construction projects, providing a semantically rich framework for capturing domain knowledge. The methodology centers on the development of a project management ontology mirroring Work Breakdown Structure (WBS) principles. This involves hierarchically organizing core concepts like Project, Task, Resource, and Deliverable. Key relationships governing task dependencies, hierarchical structures, resource assignments, along with essential task attributes including temporal constraints and cost information, are formally defined using OWL classes and properties. This conceptual ontology was implemented using the Owlready2 Python library, facilitating structured data representation and manipulation. The paper further explores the practical application of this ontology framework through five distinct use cases: enhanced progress monitoring, data-driven informed decision-making, integrated Building Information Modeling (BIM), automated compliance checking, and synergistic Artificial Intelligence (AI) integration. A supporting workflow is also proposed. This research highlights the potential of structured ontologies, realized via tools like Owlready2, to significantly improve knowledge representation, system interoperability, and overall decision support effectiveness within the demanding construction domain.

Keywords: Ontology, Construction Project Management, Semantic Web, Knowledge Representation, Decision Support Systems, Large Language Model

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Highlights

- Ontology approach structures complex construction project knowledge.
- Developed a sample PM ontology mapping WBS concepts via Owlready2.
- Ontologies show potential to enhance decision support in construction PM.

1 Introduction

The modern built environment is increasingly shaped by complex and information-rich projects, making managing project knowledge a critical challenge(Huang, Liu, Huang, Onstein, & Merschbrock, 2023). Construction and infrastructure initiatives involve intricate planning, coordination, and decision-making, all of which demand consistent and reusable knowledge management practices(Yin, Liu, Chen, & Al-Hussein, 2019). Given the repetitive nature of many project phases, organizations must harness previous experiences to enhance future project success. However, qualitative knowledge generated throughout the project lifecycle is often stored in unstructured formats, limiting its potential for reuse and consistency(Kaltenegger, Frandsen, & Petrova, 2024). An ontology-driven approach to project management addresses this issue by using formal structures to represent shared knowledge within a specific domain(Zhong et al., 2019). Ontologies define a set of concepts and the relationships between them, creating a structured and understandable representation of project information. This structured approach improves data organization, facilitates stakeholder communication, supports better decision-making, and enhances the reuse of valuable project insights. It also promotes a shift from managing scattered information to understanding projects as interconnected systems (Patel & Jain, 2021).

This paper will delve into the theoretical underpinnings and practical applications of ontology-driven project management, with a specific focus on its potential in the construction domain. It will explore the existing academic research in this domain, elucidate the core principles of ontology-oriented programming, and examine the role of semantic web technologies such as OWL ontologies and SPARQL queries in the context of project management. Furthermore, it investigates the practical aspects of utilizing tools like Owlready2 for ontology creation and management in Python(Lamy, 2017). The study also highlights several use case applications. These include progress monitoring, where a web application built on ontologies can track planned versus actual project performance, including task updates, resource usage, and associated risks. Informed decision-making is supported by timely access to relevant information based on situational understanding. Building Information Modeling (BIM) integration is enhanced by linking structured project data, such as schedules and costs, to three-dimensional models. Ontology frameworks also aid in compliance checking by validating project data against regulations. Finally, integrating artificial intelligence, particularly large language models, offers promising possibilities. When trained on project-specific content, these models can act as intelligent assistants capable of generating project plans, risk assessments, and status reports, significantly improving the decision-making process.

2 Theoretical Foundation

2.1 Semantic Web Technologies

The Semantic Web extends the traditional World Wide Web by introducing a framework that makes internet data understandable by machines. It allows data to be shared and reused across systems and boundaries. This framework's core is the Web Ontology Language, commonly known as OWL(Allemang & Hendler, 2011). Recommended by the World Wide Web Consortium, OWL is built upon the Resource Description Framework and offers a standardized method to represent complex knowledge with formal semantics. This enables machines to store and access data and interpret and reason about the information they process. OWL provides a robust foundation for modelling project knowledge in a structured and machine-interpretable format in project management(Das, Wu, & McGuinness, 2001).

An OWL ontology consists of several key elements. Classes define the core concepts of a domain, such as tasks, resources, or projects. Properties describe the relationships and attributes of these concepts. Object properties connect individuals across classes, while data properties represent specific values such as durations or names. Individuals are specific instances of these classes, and axioms define rules and constraints, such as stating that every task must have a start date or that a subtask belongs to a more significant task(Euzenat & Shvaiko, 2007). To interact with OWL ontologies, the Semantic Web uses SPARQL, a query language designed to retrieve and manipulate data represented in RDF. SPARQL allows users to frame questions using patterns that match the structure of the ontology(McGuinness, 2019). For example, a project manager can query all tasks under a particular project, identify dependencies, or assess resource allocations. Stakeholders can access detailed and structured insights by using SPARQL to query a project management ontology. This facilitates informed decision-making, enables risk identification, supports workflow optimization, and promotes effective monitoring throughout the entire lifecycle of a project.

2.2 The Applications of Ontology in Project Management

In the Architecture, Engineering, and Construction (AEC) sector, ontologies have been successfully applied for reasoning and knowledge structuring(Saka et al., 2023). Foundational research established their utility in formalizing construction knowledge and addressing interoperability issues. Subsequent advancements include the integration of ontologies with Industry Foundation Classes (IFC) for enhanced semantic data exchange(Laakso & Kiviniemi, 2012). Ontology-based reasoning has also enabled automated compliance checking, manufacturability analysis, and validation of regulatory requirements using languages such as OWL, SWRL, and SHACL(Boje, Guerriero, Kubicki, & Rezgui, 2020; Cao, Vakaj, Soman, & Hall, 2022; Nuyts, Bonduel, & Verstraeten, 2024). These applications demonstrate how semantic technologies can automate logic-based tasks and improve design-to-production alignment. Recent developments have expanded into digital twin ecosystems, where ontologies align project plans with real-time monitoring data(J. et al., 2022; Schlenger et al., 2025). Linked data and RDF graphs facilitate dynamic reasoning, supporting decision-making and adaptive planning. In modular construction, knowledge graphs integrated with ontologies automate work packaging and task dependencies. Ontologies have also formalized industrial processes, allowing semantic querying for failure analysis and resource optimization(Kaltenegger, Frandsen, & Petrova, 2025).

Beyond reasoning, ontologies play a vital role in structured databases. Semantic web technologies and BIM support data harmonization across tools and platforms(Zhou, Bao, Shu, Li, & Li, 2023). Mid-level ontologies and platforms like PMDco and DiCon have emerged to bridge semantic gaps and standardize workflows, improving reproducibility and integration(Bayerlein et al., 2024; Zheng, Törmä, & Seppänen, 2021). Despite these advances, challenges remain. The lack of consistent linkage between evolving data models, limited scalability, and the absence of a domain-wide reference model in project management hinder broader adoption(Pauwels, Zhang, & Lee, 2017). Ontological approaches from other fields, such as healthcare, demonstrate the feasibility of robust knowledge management through clearly defined concepts and relationships—an approach that project management can emulate(Avila, Franco, Venceslau, Rolim, & Vania, 2021).

3 Methodology

This research adopts an ontology-oriented programming paradigm to model construction project management, providing a semantically rich framework for capturing domain knowledge. Ontology development begins with identifying core concepts—such as tasks, resources, timelines, and risks—and organizing them hierarchically into classes, properties, and instances that mirror real-world construction processes. This structured representation enables software systems to interpret and reason about project data contextually. Two key approaches shape ontology-oriented programming: static and dynamic. While the static approach generates code from a fixed ontology at compile-time, the dynamic approach—used in this study—supports real-time updates, runtime reasoning, and scalable integration of diverse project elements. It is particularly suited to the evolving nature of construction projects, facilitating conflict detection, compliance checking, and consistent semantic representation throughout the project lifecycle.

Central to the methodology is the integration of the Work Breakdown Structure (WBS) into the ontology. Traditionally a hierarchical breakdown of project deliverables, the WBS maps seamlessly to ontology classes and relationships. Components like phases, deliverables, and tasks become ontology classes, while dependencies and hierarchies (e.g., `dependsOn`, `hasSubTask`) are captured as object properties. Task-specific data—such as start/end dates, costs, and resources—are defined via data properties. The ontology schema models a Project as comprising a WBS, which in turn consists of interconnected Task entities. Each Task links to dimensions like timeline (`hasStartDate`), cost (`hasBudgetedCost`), resources (`requiresResource`), quality, and risk. This integrated semantic model supports interoperability, enhances stakeholder communication, and aligns with project goals. Moreover, it enables automation and intelligent analysis in areas such as risk assessment, WBS generation, and performance monitoring. Overall, this methodology advances precision, adaptability, and decision-making in construction project management.

4 Building the Ontology-Driven Project Management Framework

4.1 Implementing the Project Ontology with the Owlready2 Python Library

To implement the construction project ontology, this study employs Owlready2, a Python library that enables ontology-based programming within Python environments. Ontologies—structures representing concepts such as *Project*, *Task*, *Resource*, and *Deliverable*—are created as OWL classes. Object properties like `hasSubTask`, `dependsOn`, and `isAssignedTo` express relationships, while data properties such as `hasStartDate` or `hasDuration` capture attribute-level details. These ontologies are stored in `.owl` format and have been shared on GitHub, with links and code provided in the Supplementary Data.

Owlready2 simplifies ontology manipulation by treating OWL elements as native Python objects, streamlining tasks like creating instances, loading saved files, and dynamically updating data. Additionally, it integrates the HermiT reasoner, enabling automated inference and consistency checking. For instance, the model can infer indirect task dependencies via a transitive `dependsOn` property or detect missing tasks in a project required to have at least one.

This object-oriented ontology framework supports real-time integration with project data and tools, offering a flexible, responsive modelling environment. The approach aids intelligent project automation by facilitating semantic reasoning, rule enforcement, and enhanced visibility into dependencies and resource allocation—critical for dynamic construction project environments.

4.2 Querying and Extracting Data from the Project Ontology: SPARQL and Pythonic Approaches

After developing and serializing a project management ontology, retrieving data becomes essential for deriving insights. Two main methods support this: SPARQL queries and Pythonic access using Owlready2. SPARQL (SPARQL Protocol and RDF Query Language) enables structured querying of RDF and OWL data. It allows precise extraction of semantic information. For instance, to list tasks related to `ProjectX`, a SPARQL query might look like:

```
PREFIX ex: <http://example.com/construction_project.owl#>
SELECT ?task WHERE { ex:ProjectX ex:hasTask ?task. }
```

Such queries help uncover relationships like task dependencies or resource allocations.

In Python environments, Owlready2 supports SPARQL via the `default_world.sparql()` method, returning results as iterable tuples. This enables integration into Python workflows for further analysis or visualization. Additionally, Owlready2 offers object-oriented access. Once the ontology is loaded, users can interact with classes, instances, and properties like regular Python objects:

```
from owlready2 import *
onto = get_ontology("construction_project.owl").load()
for task in onto.Task.instances():
    print(task.name)
```

To retrieve the start date of a specific task, assuming a data property `hasStartDate` exists:

```
task_a = onto.search_one(iri="*TaskA")
if task_a and task_a.hasStartDate:
    print(task_a.hasStartDate)
```

Each approach serves distinct needs. SPARQL excels at handling complex queries involving multiple relationships, offering a concise and standard mechanism for ontology interrogation. However, familiarity with the SPARQL syntax and RDF model is required. On the other hand, Pythonic access through Owlready2 is more intuitive for those with a programming background, particularly for basic retrievals, instance creation, or updates. Together, these querying methods empower both technical and non-technical stakeholders to derive actionable insights from the ontology, enabling more intelligent, data-driven project management decisions.

5 Use Cases

5.1 Enhanced Progress Monitoring through Ontology-Based Systems

Ontology-based systems revolutionize project progress monitoring by replacing disconnected spreadsheets and static reports with a dynamic, centralized, semantically rich platform. Initial project plans, including Work Breakdown Structure (WBS), task schedules, resource allocations, and milestones, are encoded as interconnected instances within the ontology. As the project executes, this model is continuously updated with actual progress data – start/end dates, resource usage, scope changes, and identified risks – by modifying instance properties or adding new relationships. This live, integrated view enhances clarity and enables early issue detection.

As illustrated in Figure 1, stakeholders can use SPARQL queries to extract specific, real-time information, such as identifying tasks lagging behind schedule by comparing planned and actual dates or assessing resource overallocation. The system can also generate dynamic visualizations like Gantt charts directly from the ontology data, providing immediate insights into task timelines and dependencies. This approach offers a far more powerful and responsive method for tracking project status compared to traditional techniques.

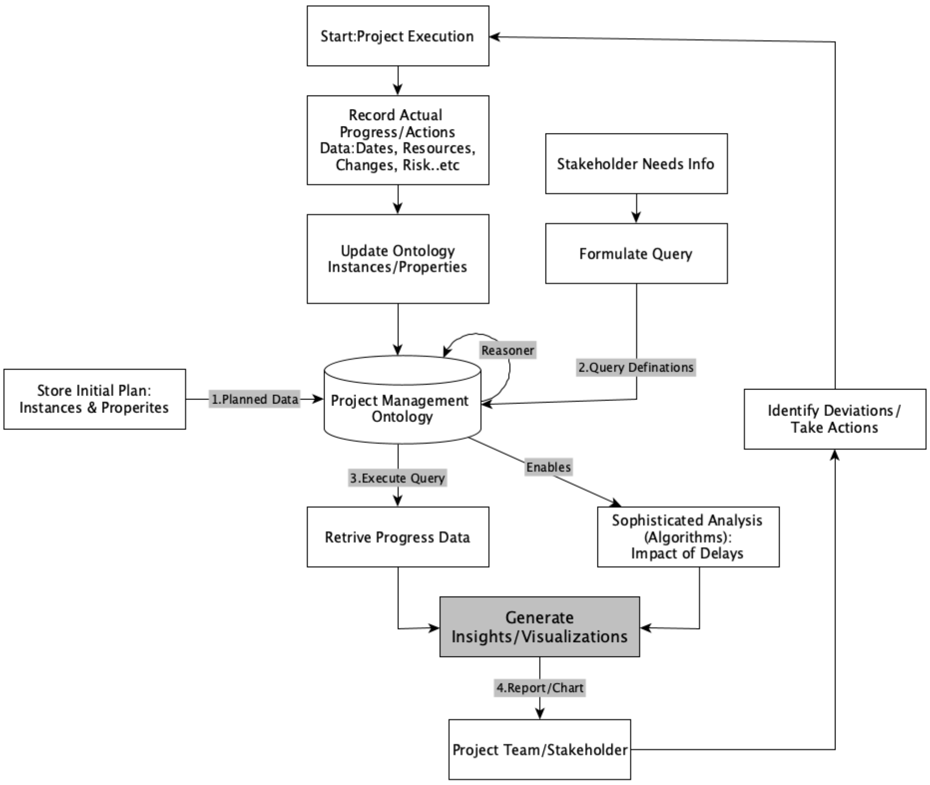

Figure 1. Workflow for Enhanced Project Progress Monitoring using an Ontology-Based System.

5.2 Ontology-Driven Informed Decision-Making in Project Management

Effective project management relies heavily on timely and informed decisions. Ontology-based systems support this by providing a structured, interconnected knowledge base that offers comprehensive visibility into the project environment, enabling data-driven decisions instead of relying on intuition or incomplete data. Consider resolving a resource conflict: the ontology holds structured data on task priorities, dependencies, resource availability, and costs. A targeted SPARQL query, as shown in the process in Figure 2, can retrieve this holistic data, allowing a manager to systematically evaluate options like rescheduling, finding alternate resources, or adjusting timelines.

Similarly, when assessing a proposed scope change, the ontology can be queried to understand its ripple effects on the schedule, budget, resource demands, and task interdependencies. By facilitating rapid, comprehensive analysis of complex scenarios through queries on interconnected data, these ontology-driven frameworks empower project managers. They can make more confident, contextually aware decisions throughout the project lifecycle, backed by a clear understanding of potential impacts derived directly from the integrated project data.

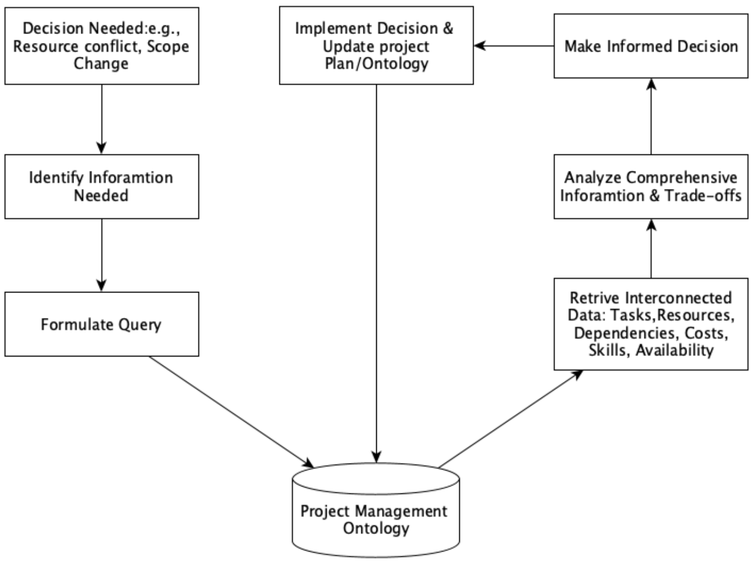

Figure 2. Workflow for Ontology-Driven Informed Decision-Making in Project Management.

5.3 Leveraging BIM Integration with Project Management Ontologies

Building Information Modeling (BIM) provides detailed 3D models, but its value is significantly amplified when integrated semantically with project management data like schedules, costs, and resources. Ontology-driven integration achieves this synergy by establishing formal semantic links between the design (BIM) and management domains. Concepts from BIM standards (e.g., Industry Foundation Classes - IFC) are mapped to corresponding elements in the project ontology. For instance, a BIM 'Wall' element can be linked to its construction 'Task' instance using a property like `isRealizedByTask`, which in turn connects to cost and resource data via other properties.

This integration, depicted in Figure 3, enables powerful cross-domain queries using SPARQL. Users can retrieve comprehensive views, such as querying for "all tasks related to constructing Wall X and their current status" or analyzing the cost and schedule impacts of a design change originating in the BIM model. This ability to seamlessly query and reason across both design and management data facilitates sophisticated insights, improves coordination (e.g., aligning material deliveries with task schedules), and helps reduce overall project risk.

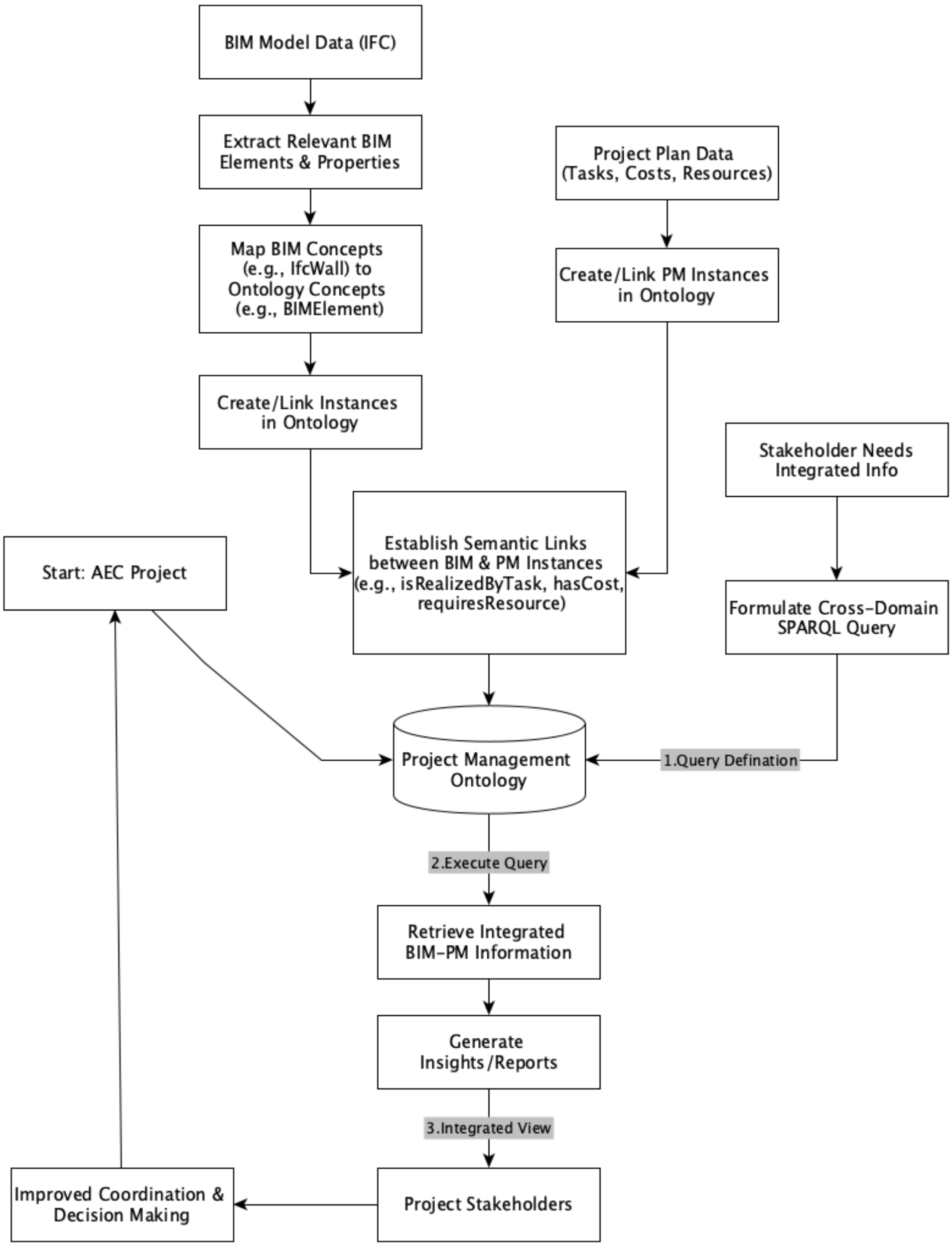

Figure 3. Workflow for Integrating BIM and Project Management Data via Ontology.

5.4 Ensuring Project Compliance through Ontology-Based Checking

Adhering to standards, regulations, and internal policies is vital for project success. Ontology-based systems offer a formal, automated approach to compliance verification. Rules and constraints derived from these requirements are embedded directly into the project management ontology as logical axioms. Reasoning tools can then systematically check if project activities and data, represented as instances in the ontology, conform to these axioms. For example, an axiom might mandate that every `HighRiskTask` must have an associated `RiskMitigationPlan`. A reasoner can automatically verify this for all relevant task instances.

The workflow, illustrated in Figure 4, involves storing project execution data (tasks, approvals, etc.) in the ontology and triggering checks. Compliance queries (SPARQL) or reasoners evaluate the data against the formalized rules. Any detected violations are automatically flagged for review and corrective action by the project team or quality assurance. This provides a scalable method for continuous compliance monitoring, reducing manual oversight, ensuring prompt responses to non-compliance, and minimizing associated risks and potential penalties.

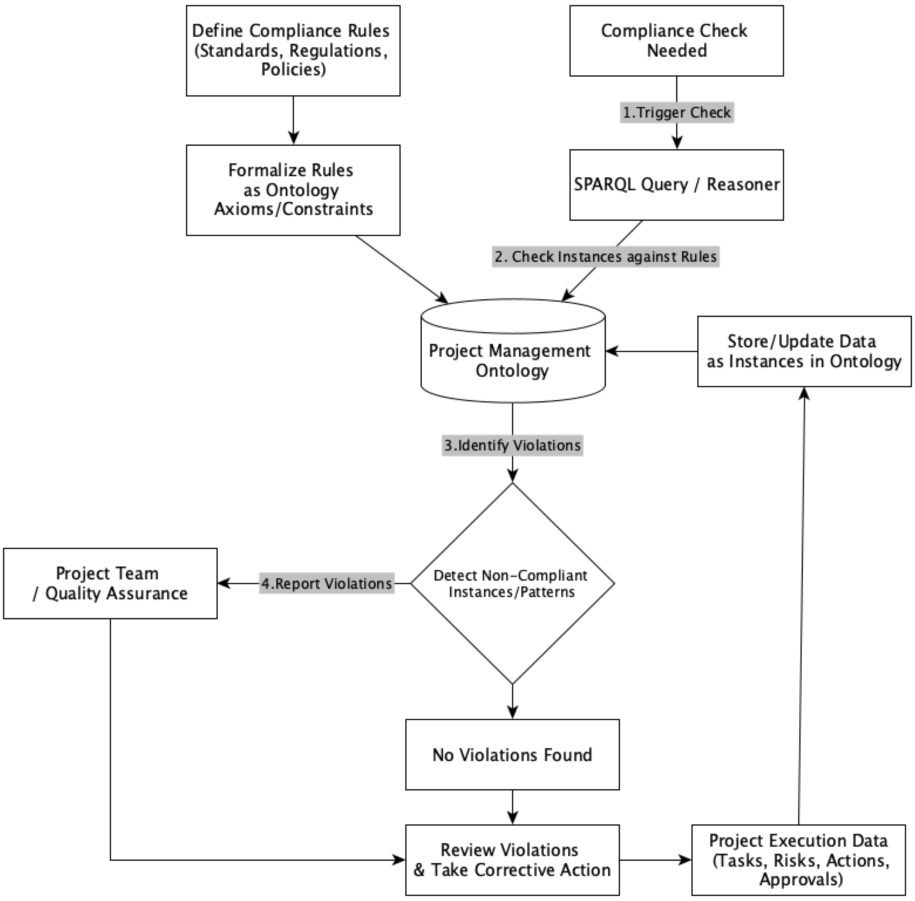

Figure 4. Workflow for Ontology-Based Project Compliance Checking.

5.5 Integrating Large Language Models with Ontology-Driven Frameworks for Advanced Project Insights

Large Language Models (LLMs) enhance ontology-driven project management by bridging unstructured text and structured semantic knowledge. Integrated LLMs act as intelligent assistants, interpreting natural language queries from stakeholders (e.g., "Which critical tasks are delayed and why?"). As shown in Figure 5, the LLM parses the query, potentially generates the corresponding SPARQL code to retrieve structured data from the project management ontology, processes the results, and summarizes the findings in a clear, human-readable response. This allows for intuitive, conversational access to complex project data.

Furthermore, LLMs can analyse unstructured documents like meeting notes or emails, extract relevant information (identifying entities, properties, relationships), and map this data onto the ontology. This semantically enriches the knowledge base, making it more complete and contextually aware. Key benefits of this integration include conversational project insights via natural language interfaces, automated generation of project documentation summaries, semantic enrichment of the ontology from text sources, and improved stakeholder communication, ultimately leading to better-supported project decisions and analysis.

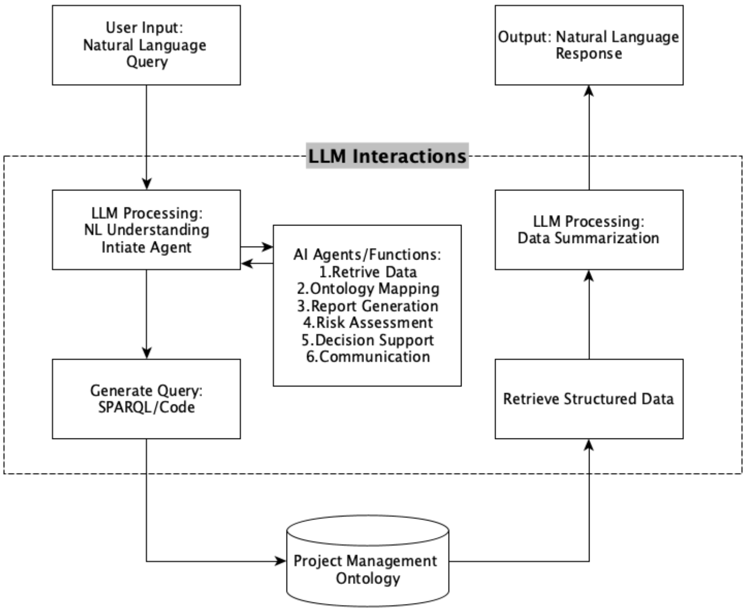

Figure 5. Workflow for Integrating LLMs with Project Management Ontology for Enhanced Insights.

The integration of LLMs with ontology-based systems unlocks advanced capabilities such as:

- Conversational project insights via natural language interfaces
- Automated generation of project documentation
- Semantic enrichment of textual data
- Enhanced stakeholder communication and decision support

Table 1. The integration of LLMs with ontology-driven frameworks offers several potential benefits

Application Area	Potential Benefits
Document Summarization	Quickly condense project reports, meeting minutes, and other textual data.
Risk Assessment	Identify potential risks and suggest mitigation strategies.
Communication	Draft clear and concise project updates, stakeholder notifications, and reports.
Decision Support	Provide context-aware answers and recommendations for project-related queries.
Report Generation	Automate the creation of project status reports, highlighting progress and risks.
Resource Allocation	Assist in optimizing resource allocation based on project needs and constraints.

6 Conclusions

This paper investigated the application of ontology-driven approaches to address persistent knowledge management and integration challenges within construction project management. A primary contribution is the development and implementation of a sample project management ontology, grounded in Work Breakdown Structure (WBS) principles and utilizing the Owlready2 library, to formally represent core project concepts and their interrelations. The practical potential of this semantic framework was further demonstrated through the conceptual exploration of five key use cases—ranging from progress monitoring and Building Information Modeling (BIM) integration to Artificial Intelligence (AI) synergy—accompanied by a proposed workflow.

The findings highlight the significant potential of ontologies to establish a structured, explicit, and shared understanding of project data. Such a framework promises enhanced data consistency, improved interoperability between diverse systems and stakeholders, and a solid foundation for advanced analytics and more informed decision-making. While this study successfully demonstrates the feasibility of the approach using readily available tools like Owlready2, it primarily presents a foundational framework and conceptual applications. The sample ontology requires further refinement and validation against the complexities of real-world projects.

Future work should focus on expanding the ontology's scope to encompass a wider range of project management knowledge areas, undertaking rigorous validation with industry data, and developing robust integrations with existing project management software and BIM platforms. Implementing and evaluating the proposed use-case applications in practical settings, potentially leveraging automated reasoning capabilities for enhanced insights and checks, will be crucial steps towards realizing the full benefits of ontology-driven construction project management.

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Data Availability Statement

The data used for this research article are openly available in GitHub
https://github.com/konevenkatesh/Ontology_PM
Which include Code, Application demonstration in video format

Conflicts of Interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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