



SEMANTIC INTEGRATION OF COST, TIME AND GEOMETRY FOR A RESOURCE-CENTRED PERSPECTIVE OF MANAGING CONSTRUCTION PROJECTS

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Abstract

Cost and time must be continuously balanced for construction project success based on resource utilization. However, resources are usually planned implicitly and not aligned between scheduling and cost estimation, leading to inconsistencies in project management processes. To address this issue, this paper proposes a resource-centric approach that integrates building geometry with schedule and cost data using ontologies as the semantic foundation. A web prototype converts and links the original data into an RDF graph, enabling advanced SPARQL queries for cross-domain consistency checks, particularly on resource usage. These checks validate the alignment of interconnected project domains, providing insights unattainable with traditional methods.

Introduction

Costing calculation and scheduling are critical, interrelated processes in construction project management. Nevertheless, they are frequently carried out independently by different project stakeholders, leading to fragmented workflows and inefficiencies that hinder effective coordination and resource allocation (Liu et al., 2015; Boje et al., 2020). The lack of an integrated framework for aligning construction schedules and cost estimates is a significant cause of this fragmentation. Existing tools typically focus on one domain, addressing scheduling or costing at the product element level rather than the construction operation level (Liu et al., 2015).

Building Information Modeling (BIM) provides a strong foundation for unifying scheduling (also known as 4D BIM) and costing (often referred to as 5D BIM) into a unified framework. These model-based approaches enable detailed and reliable calculations early in a project, aiding financial planning and execution (Sacks et al., 2018). However, fragmented practices and inconsistent application of 4D and 5D BIM limit their potential, leading to data loss across project stages and missed opportunities for integration (Wahab and Wang, 2022; Boje et al., 2020).

Resources, a critical factor in scheduling and costing, are often not explicitly planned or managed separately within each domain. While time control is typically based on the Work Breakdown Structure (WBS), budget management uses the Cost Breakdown Structure (CBS), which may fol-

low different structuring principles and cost calculation methods (Cerezo-Narváez et al., 2020). This lack of integration often leads to inconsistencies in practice, such as different labor durations based on separate calculation methods or misaligned material requirements that complicate procurement and logistics. In addition, the separation of planning and costing hinders consistent cost monitoring, prevents real-time tracking across domains, and makes it difficult to determine the causes of cost overruns or delays when they occur (Cho et al., 2010). Seamless integration of resources, costs, and construction processes information within the BIM workflow is critical to the efficient design and execution of construction projects.

Semantic Web Technologies (SWT) and Linked Data (LD) provide solutions to the challenges posed by data heterogeneity by enabling the semantic integration of data (Pauwels et al., 2017). Recent research has introduced several ontologies that address costs, resources, and processes (Farghaly et al., 2020; Hagedorn et al., 2025). Once integrated with the Resource Description Framework (RDF), SPARQL – a query language tailored for RDF graphs – enables complex queries, such as retrieving spatial, scheduling, or cost-related information, thereby supporting decision-making with deeper insights. The conversion of original data into RDF offers advantages as discussed in Boje et al. (2020) and, in this paper, conversion is performed only for specific analyses and reasoning, while the original data remains in their formats.

The alignment of cost and time domains into a resource-centric semantic concept is explored in a previous article by Hagedorn et al. (2025). Building on this foundation, this research integrates these ontologies into RDF graphs and demonstrates the potential of semantic analysis by developing complex SPARQL queries. After a brief review of the background and related work, the methodology is presented in three phases: integration of the original data from the planning, estimation, and IFC model into a web platform, transformation into ontologies for semantic analysis, and development of advanced SPARQL queries. These queries enable advanced analysis and integration of geometry, cost, time, and resource data, providing comprehensive insight into project budgets, economic control, resource allocation, and scheduling by exploiting semantic relationships within interrelated project domains. Future

work aims to extend the scope and applicability of these validations.

Background

BIM adoption is widely recognized in the literature as a transformative approach to project management, offering benefits across all project stakeholders (Sacks et al., 2018). By enhancing accuracy, efficiency, and collaboration throughout the project lifecycle, BIM significantly improves planning and execution processes. Central to these advantages are 3D BIM models, which serve as rich repositories of geometric and alphanumeric data. These models support critical downstream activities such as scheduling and cost estimation. In particular, automated quantity take-offs (QTOs) enabled by BIM provide faster, more detailed, and precise cost estimates compared to traditional 2D methods (Sacks et al., 2018). BIM further improves cost estimation by reducing human errors (Yang et al., 2022; Kim et al., 2019) and allowing seamless data integration, ensuring consistency in cost management (Fazeli et al., 2021). Furthermore, BIM-based scheduling facilitates real-time updates, visual planning, and improved coordination, minimizing delays and optimizing project timelines.

However, despite these advantages, challenges persist. The adoption of 4D and 5D BIM methodologies faces hurdles due to fragmented information flows (Wahab and Wang, 2022; Moses et al., 2020). Model-based scheduling and cost estimation remain critical but underutilized in everyday practice (Borrmann et al., 2018). Traditional reliance on fragmented WBS for scheduling and CBS for budgeting further highlights the lack of integration, leaving advanced project control techniques, such as earned value management, underexplored (Boje et al., 2020; Cerezo-Narváez et al., 2020).

An additional layer of complexity arises from the inherent diversity of the tools, documents, and human resources involved in construction projects. Each stakeholder often employs distinct software platforms, documentation standards, and workflows, leading to a lack of uniformity in data representation and exchange (Liu et al., 2015). Furthermore, the practitioners, composed of professionals with different expertise and responsibilities, contribute to inconsistencies in data creation and validation (Ibrahim et al., 2024). These disparities make it exceedingly challenging to manage and integrate data across domains, verify its accuracy, and ensure that information remains consistent and reliable throughout the project lifecycle. The inability to effectively coordinate these diverse elements exacerbates issues such as data redundancy, miscommunication, and delays, undermining the potential efficiencies promised by BIM (Boje et al., 2020).

OpenBIM standards, particularly the Industry Foundation Classes (IFC), offer promising solutions by enabling greater interoperability and seamless data exchange across stakeholders and software (Fürstenberg et al., 2021). IFC provides a standardized, object-oriented schema for both

geometric and semantic data, including entities for costs (*IfcCostSchedule*, *IfcCostItem*, *IfcCostValue*), processes (*IfcTask*, *IfcProcess*), and resources (*IfcResource*) (Cassandro et al., 2024). However, these capabilities are rarely exploited and used in practice; therefore, the lack of use of standardized formats for non-geometric information exchange remains a significant gap in holistic interoperability.

Given the complexity and diversity of data in construction, ontologies play a crucial role in representing and integrating knowledge (Farghaly et al., 2022). Several ontologies developed to address specific areas can be found in the literature, such as construction planning (Getuli, 2020; Koo et al., 2007; Liu et al., 2015; Bonduel, 2021; Schlenger and Borrmann, 2024) and cost modelling (Staub-French et al., 2003; Lee et al., 2014; Liu et al., 2016; Abanda et al., 2017). Other studies aim to unify multiple domains, improving the interoperability between programming, cost estimation, and related processes (El-Gohary and El-Diraby, 2010; Zheng et al., 2021; Schlenger et al., 2022).

These interoperability gaps, fragmented data structures, and lack of standardized integration methods underline the urgent need for a structured and standardized approach that not only exploits the potential of BIM to harmonize schedules, costs, and resources in an integrated framework but also addresses the diversity of tools, documents, and human resources. The definition of standardized processes for data validation and the seamless integration of heterogeneous information systems are essential steps to overcome the current fragmentation of information. In this way, the construction industry can move closer to achieving a truly collaborative and efficient project management paradigm.

Previous Work

This research builds upon previous work utilized for an in-depth analysis of construction management. Therefore, this section describes the existing work on the ontological data schema and the integration framework.

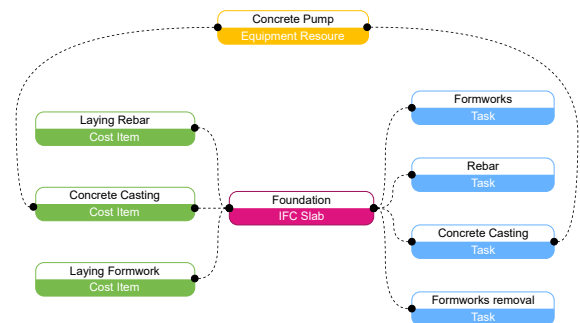


Figure 1: Conceptual overview of the network composed of ontologies for cost, tasks, resources, and products

Resource-centric ontology network

For the formal semantic representation of costs, tasks, resources, and the interconnections between these domains into a construction management data schema, the authors utilized existing ontologies and aligned them with newly developed ontologies in previous work (Hagedorn et al., 2025). In Figure 1, an overview is given for an example of concrete casting for a slab foundation, displaying the interconnections of domains.

The figure shows on a conceptual level the slab as an instance of the ifcOWL representation of an IFC model, green instances from the Cost Item (CI) ontology constituting the price for the constructed slab, blue instances from the Digital Twin Construction (DTC) ontology providing the necessary task information, and finally the yellow instance from the Construction Resources (CR) ontology for the concrete pump utilized both for calculating the price and for determining the task time. The DTC ontology is reused from the work of Schlenger et al. (2022), while the other ontologies, specifically, the CR ontology with the interrelations between domains, are newly developed and aligned in Hagedorn et al. (2025). The ontologies used in this research are defined in Table 1 with their respective namespaces and prefixes that will be used throughout this paper.

Table 1: Ontologies and namespaces used in this research

Prefix	URI	Description
ci:	<http://w3id.org/ci#>	Cost Item (CI)
cr:	<http://w3id.org/cr#>	Construction Resources (CR)
dtc:	<https://dtc-ontology.cms.ed.tum.de/ontology#>	Digital Twin Construction (DTC)
ifc:	<http://ifcowl.openbimstandards.org/IFC4_ADD2#>	ifcOWL IFC4 ADD2

Integration Framework

Schedule-integrated and cost-integrated IFC models can be maintained within a unified context using information containers. The Information Container for Linked Document Delivery (ICDD) standardized in ISO 21597-1 (2020) facilitates the creation of these containers and the semantic linking of documents and their entities through Semantic Web technologies. This standardized method offers a robust framework for managing linked domain models and encourages cross-domain data exchange. Previous research has demonstrated the application of ICDD containers for schedule-integrated models, as evidenced in Hagedorn et al. (2023b,c), where an IFC model and an XML schedule were stored with links defined in an RDF linkset. Additionally, these containers have been utilized for cost-integrated models to combine IFC models and Bills of Quantities (BoQ) (Sigalov et al., 2021).

For this research, the ICDD web application developed by Hagedorn et al. (2023a) has been extended to allow the creation of RDF data according to the ontology network from schedules and to import and read data from the other

domains presented in the previous section. Furthermore, the web application has implemented a function for creating assignments between domains. Existing functions of the platform are utilized, such as merging domain RDF graphs and querying merged graphs.

Methodology

The methodology adopted in this study is structured into three phases, each designed to enhance project management practices within the building sector by organizing project data and applying advanced analytical tools for improved decision-making (see Figure 2).

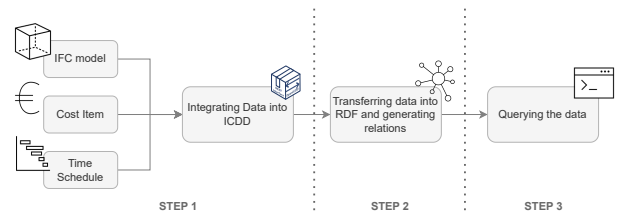


Figure 2: Three steps of the proposed methodology

The first phase focuses on integrating project data into the ICDD platform. This platform serves as a unified container capable of importing and visualizing a variety of data formats, such as XML, IFC, and RDF/Turtle. Combining diverse data types ensures that the relationships between geometric elements, scheduling information, and cost data are appropriately defined. This foundational integration lays the groundwork for comprehensive data analysis and management in the consistency checks performed in this research.

In the second phase, the imported data is transformed into RDF graphs according to ontologies presented in the previous work section, further enhancing the ability to perform semantic analysis. The ontologies capture the intricate relationships between various project documents by converting the project data into a structured and standardized format. This step facilitates the extraction of meaningful insights and ensures that the data can be interpreted consistently across different systems and stakeholders.

The final phase of the methodology involves developing advanced SPARQL queries for the cross-domain consistency check. These queries extract detailed information from the integrated data, supporting project management processes and decision-making. Unlike traditional approaches, which rely on isolated and fragmented datasets, this phase leverages the data's interconnected nature to conduct more complex analyses. By utilizing the full potential of the data integrated into the ICDD platform, the methodology offers a more robust approach to project management, allowing for more informed and accurate decisions throughout the project lifecycle.

The described procedure is conducted in a case study on a real-world construction project of a three-story office building in the Lombardy region, Italy (see Figure 3). The case study building is provided as an IFC 4 structural de-

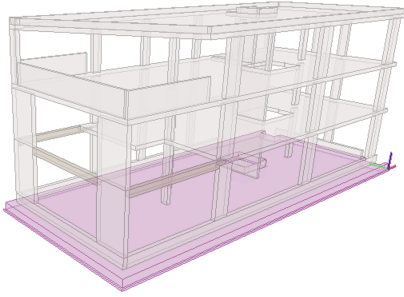


Figure 3: Case study building

sign model. At the same time, the cost data for the contained elements, including cost calculations for labor and equipment resources, is retrieved from the official price list of Regione Lombardia converted into RDF. A Microsoft Project Schedule is provided as an XML file, including resource planning for the construction site. These three documents serve as input data for the case study (see Figure 2, Step 1).

Cross-domain consistency checking

Specific SPARQL queries were executed on the office building dataset to demonstrate the feasibility of the proposed approach. Using the developed ontologies, the original data was transformed into an aggregated RDF graph to perform consistency checks. The resulting structure, stored in an ICDD container, is shown in Figure 4 (left panel). The analysis was carried out in two phases. The first phase involved a general examination of the project, using SPARQL queries (Q1 and Q2), which could also be performed with traditional tools, as they referenced data within a single document. The second phase focused on detailed analysis, involving previously infeasible checks without interconnected data, made possible by the proposed approach (Q3 and Q4). Due to the scope of this paper, these latter queries were applied to specific objects, namely the subfoundation and the foundation. The following sections provide a detailed explanation of these queries, with Figure 4 serving as an illustrative example.

Q1 – Total Cost of the Project

Query Q1 calculates the total cost of a project by integrating cost and geometry data (see Listing 1). This enables an assessment of the budget required to complete the project, ensuring accuracy and transparency by associating geometric elements with their respective costs. Specifically, the query examines each cost assignment (*?subject*) associated with a set of assignments (*?set*). For each element, the specific quantity (*?quantity*) and corresponding unit price (*?unitPrice*) are determined. The total cost of each element is calculated by multiplying these two parameters. Then a cumulative sum is performed to obtain the total cost of the project, rounded to two decimal places for reasonable precision. The output of the query is the total project cost (*?totalPrice*), representing the aggregated value of all resources and activities planned.

```

1 PREFIX ci: <https://w3id.org/ci#>
2 PREFIX cr: <https://w3id.org/cr#>
3 SELECT ((ROUND(SUM(?uPrice * ?qty) * 100) / 100.0) AS
         ?totalPrice)
4 WHERE {
5   ?set cr:hasAssignment ?subject.
6   ?subject a cr:CostItemToGeometryAssignment.
7   ?subject cr:refParamQuantity ?qty.
8   ?subject cr:refCostItem ?costItem.
9   ?costItem ci:unitPrice ?uPrice.
10 }

```

Listing 1: SPARQL Code for Q1

Q2 – Cost Based on Element

Query Q2 provides a detailed analysis of the costs associated with each geometric element of the IFC model by integrating geometric and financial data (see Listing 2). The query calculates the total cost of each element based on specific quantities (*?quantity*) and the associated unit price (*?unitPrice*), returning aggregated results that directly link costs to the elements in the model. This integration supports the economic control of construction projects by providing accurate cost breakdowns for individual components.

Specifically, each element is uniquely identified through its name (*?label*) and its IFC GlobalId (*?ifcguid*), ensuring clear traceability between financial data and the physical objects represented in the model. The query uses standard IFC properties to extract this information, adopting a structure that ensures compatibility with the IFC4 format. By aggregating the data (*SUM(?quantity)*), it calculates the total quantity of each element. Subsequently, it computes the total cost, rounded to two digits, by multiplying quantity and unit price. The output of the query includes the element's name (*?label*), its unique IFC identifier (*?ifcguid*), the total quantity (*?totalQuantity*), and the rounded total cost (*?totalPrice*). The query results are demonstrated in Figure 4.

```

1 PREFIX ci: <https://w3id.org/ci#>
2 PREFIX cr: <https://w3id.org/cr#>
3 PREFIX ifc2x3: <https://standards.buildingsmart.org/IFC/DEV/IFC2X3/FINAL/OM#>
4 PREFIX ifc42: <https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2/OM#>
5 PREFIX exp: <https://w3id.org/express#>
6 SELECT ?label (SUM(?quantity) AS ?totalQuantity)
         ((ROUND(SUM(?uPrice * ?qty) * 100) / 100.0) AS
         ?totalPrice) ?ifcguid
7 WHERE {
8   ?subject a cr:CostItemToGeometryAssignment.
9   ?subject cr:refParamQuantity ?qty.
10  ?subject cr:refCostItem ?costItem.
11  ?subject cr:refGeometry ?e.
12  ?costItem ci:unitPrice ?uPrice.
13  {
14    ?e ifc42:name_IfcRoot/exp:hasString ?label.
15    ?e ifc42:globalId_IfcRoot/exp:hasString ?ifcguid.
16  }
17  UNION
18  {
19    ?e ifc2x3:name_IfcRoot/exp:hasString ?label.
20    ?e ifc2x3:globalId_IfcRoot/exp:hasString ?ifcguid.
21  }
22 } GROUP BY ?label ?ifcguid

```

Listing 2: SPARQL Code for Q2

This query is essential for directly and transparently linking financial data to IFC objects. It allows for cost tracking of model elements, facilitating budget control, and enhancing economic forecasting capabilities. Furthermore, standard IFC properties ensure interoperability, making the query applicable in openBIM scenarios. Therefore, Q2 represents a crucial step towards more integrated, data-driven cost management in the construction industry.

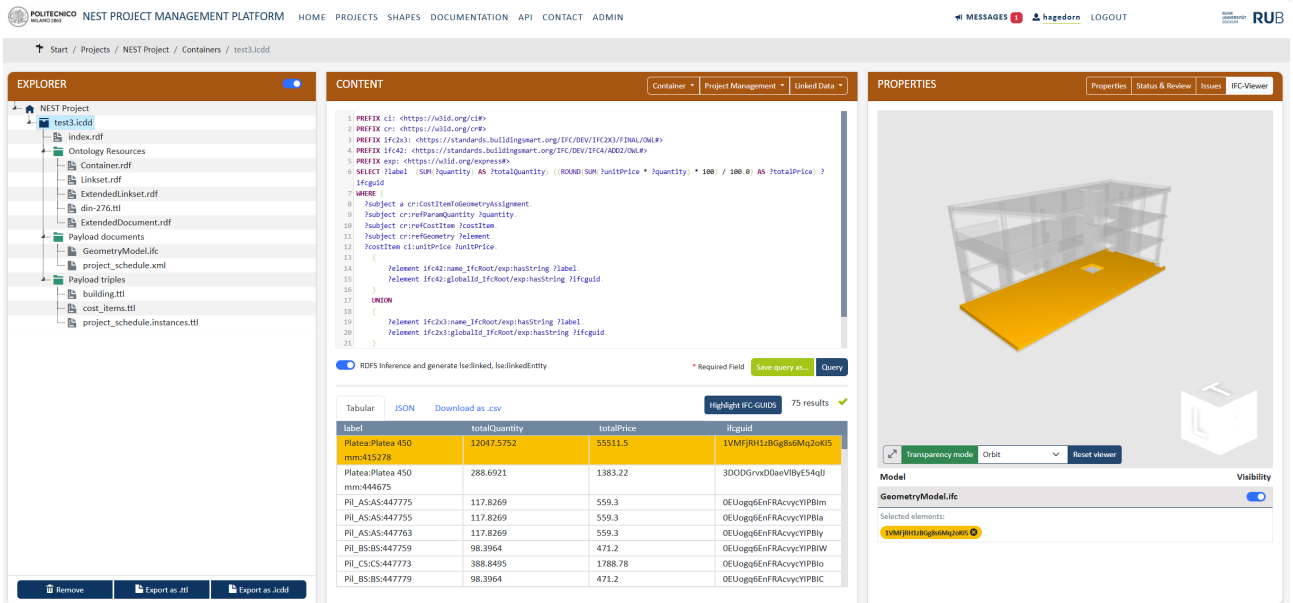


Figure 4: Screenshot of the ICDD platform showing the structure of the generated ICDD container (left panel), the IFC model in the 3D viewer (right panel), and the SPARQL query (Q2) in the center panel.

Q3 - Labor Time Comparison Across Cost and Schedule Analyses

Query Q3 calculates and compares the total time required for human resources based on two complementary perspectives: cost analysis and scheduling analysis. Resource utilization time is derived from cost parameters in cost analysis, while in scheduling analysis, time is determined directly from planned activities. By integrating semantic relationships between tasks, costs, geometries, and labor resources, the query facilitates the comparison of these calculations and produces two key indicators:

- *?costResourceTime*: the total time calculated for each labor resource, based on the quantity required for a geometric element (*?quantity*) and the utilization factor for the resource in price analysis to determine the unit price (*?utilizationFactor*).
- *?taskResourceTime*: the time required for human resources, derived directly from the activity duration (*msproj:duration*) and the associated utilization rate (*?rate*).

The code of the query Q3 is provided as an external appendix¹. It uses advanced logic to interpret the duration of activities, handling complex time formats expressed in days, hours, minutes, and seconds. By using binding functions (*BIND*), the temporal values are normalized and converted into a unified format (hours), which is then multiplied by the utilization rate to calculate the total resource time.

The aggregation function (*MAX*) ensures that the maximum time required for a human resource is considered

¹https://cpm-ont-network.github.io/case-studies/queries/q3_labor-time.rq, SPARQL Code for Q3, last accessed: 28.01.2025

within the cost analysis for each task. The comparison between *?costResourceTime* and *?taskResourceTime* helps to highlight discrepancies between the two approaches, supporting the identification of inconsistencies in scheduling and cost estimation. This analysis, otherwise complex and manual, is automated through the query, providing an objective basis to optimize the allocation of human resources and improve consistency between costs and times in construction projects.

In Figure 5, the relationships between the entities involved in the query are depicted. This visualization shows how integrating different domains (tasks, costs, geometries, and resources) enables cross-referenced querying and data evaluation. The figure illustrates how this integration enhances decision-making in construction project management by linking various domains. In addition, overcoming the challenges of information fragmentation allows for seamless assessment of discrepancies.

Q4 – Amount of Resources Needed Next Week

Query Q4 determines the total material resources required to complete the planned activities within a specific time frame. The code of the query Q4 is provided as an external appendix². The SPARQL query analyzes the semantic relationships between tasks, costs, geometries, and resources to provide a detailed overview of the material demands. Specifically, the query examines the relationships between tasks and costs (*cr:refTask* and *cr:refCostItem*), tasks and geometries (*cr:refTask* and *cr:refGeometry*), costs and geometries (*cr:refCostItem* and *cr:refGeometry*), and costs and resources (*cr:refCostItem* and *cr:refResource*). This allows for the identification of the necessary resources

²https://cpm-ont-network.github.io/case-studies/queries/q4_resources-needed.rq, SPARQL Code for Q4, last accessed: 28.01.2025

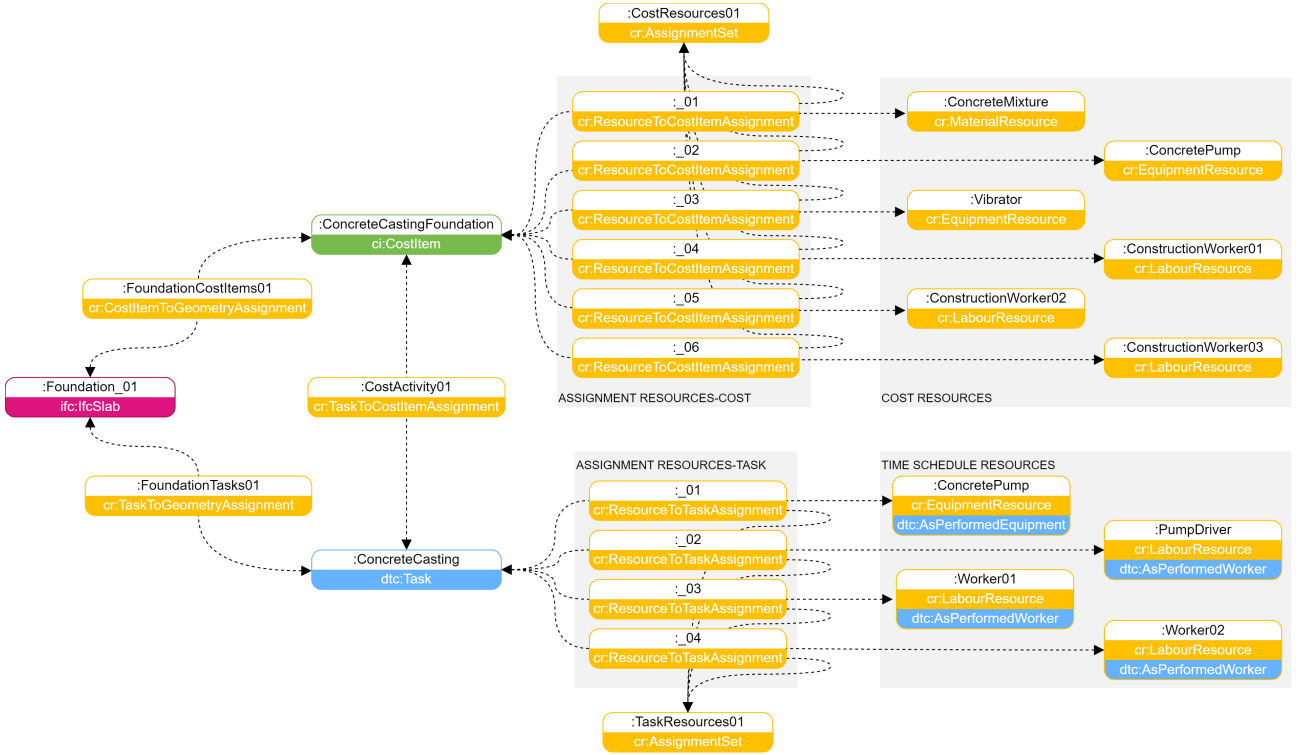


Figure 5: Ontology-based structure illustrating the relationships between task domain, cost, resources, and geometry

(*cr:MaterialResource*), including attributes such as the class (*cterm:hasObject*), material (*cterm:hasMaterial*), unit of measure (*cr:hasUnit*), and other relevant data.

In the query, the utilization factor (*cr:refParamUtilizationFactor*) is multiplied by the physical quantity of the geometric object (*cr:refParamQuantity*) and the unit of measure for the material (*cr:quantityUnitOfMeasure*) to calculate the specific amount of resource needed for each activity. This calculation is performed through the *BIND* operation, defining the variable *?materialQuantity*. The *SUM* aggregation function is then applied to obtain the total resources required, grouped by material type and material object and ordered by key attributes such as *?materialType* and *?materialObject*. The temporal filter (*FILTER*) ensures that only activities with start dates between *October 1st and 15th, 2024* are considered.

The query's output provides a detailed view of the total quantities of materials needed for each type of material and unit of measure, ordered chronologically by the start date of the activities (*ORDER BY ?start*). This approach supports accurate construction site logistics planning, ensuring that the required material resources are available in quantity and at the right time to meet the project's progress requirements.

Discussion and Conclusion

Consistent planning and utilization of resources in terms of time and cost are critical factors for the success of construction projects. Achieving this consistency requires consolidating data from multiple sources to enable cross-domain analysis. SWT offer a promising solution by pro-

viding a logic-based framework for aligning geometric, cost, and time domains. This framework allows for the semantic representation of shared resources, including labor, equipment, and materials.

This study builds on an ontology network developed in previous work (Hagedorn et al., 2025) and explores the potential of structured semantic linking of cross-domain data through a resource-centric approach. By integrating ontologies for geometry, construction tasks, cost items, and resources into a prototype web platform, the methodology consolidates original project data into an aggregated RDF graph. This structured format captures complex relationships between schedules, bills of quantities, and the IFC model, providing new opportunities for advanced consistency checking. Although current ontologies offer a robust framework, they certainly have the potential for further extension to structure additional information and support more advanced analyses.

The explicit modeling of resources and the development of advanced SPARQL queries demonstrate the benefits of this approach. These queries provide an objective basis for optimizing the allocation of human resources and improving the alignment of costs and schedules in construction projects. In addition, they enable the precise planning of material logistics, ensuring that resources are available in the correct quantity and at the right time to meet project progress requirements.

Although this study does not propose a single framework for fully coordinated BIM-based planning of construction processes and costs, it provides a valuable tool for consistency checks. It highlights the opportunities that can

arise from a shared, structured, semantic data environment. These checks help identify deficiencies in fragmented design processes at an early stage, enabling more reliable and streamlined project management. In contrast to traditional methods based on isolated data sets, this method uses interlinked data to carry out more comprehensive analyses. Integrating project data into the ICDD platform allows query results to be visualized directly on the IFC model, providing an intuitive view of the relationships and elements involved. This visual feedback lets stakeholders understand the link between financial data, scheduling, and geometric elements.

Ensuring consistent data interpretation between systems and stakeholders promotes cross-discipline collaboration within the AEC industry while supporting robust project management and informed decision-making. Automatically integrating data into a semantic framework cannot uncover all inconsistencies, as those embedded in the original data will persist. Future research can address this limitation by further integrating and developing AI-based methods. An AI module is planned to verify semantic consistency between the time and cost domains, using Natural Language Processing models to identify and compare semantic information. For example, it could detect nuanced inconsistencies, such as mismatches between general and specialized labor categories or inconsistencies in equipment usage.

To enhance this capability, adopting Large Language Models is proposed, tailored to evaluate the alignment of semantic information between the task and cost domains (as shown in Hölting et al. (2025)). This approach would allow the identification of subtle relationships and inconsistencies, thereby improving the alignment of specifications and schedules. By integrating such AI tools into the software development pipeline in an agentic mode, context-specific tasks could be addressed directly and efficiently, streamlining the detection of inconsistencies and improving overall project management.

Online Resources

The sources and documentation of the ontologies and the utilized case study data with queries are available via <https://cpm-ont-network.github.io/>.

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