A Shared Construction Resource Ontology for Semantically Aligning Cost and Time Domains in Construction Projects

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Abstract
In the construction industry, project scheduling and cost estimation are strongly interconnected by their nature. However, this interconnection is primarily neglected in their virtual representations in building models and the accompanying data schemes for cost data and schedules. In current projects, there is usually only a relation defined between the building model and the cost on the one hand and the building model and the schedule on the other hand. This results in a duplication of resource definitions: once by costing, which allocates resources to labour, equipment and similar entities, and again by scheduling, which assigns resources to the same elements. These resources usually contradict each other because different people with different viewpoints and interpretations of the project define them. Thus, a plausibility check is inevitable. Therefore, the cost and time domains are mapped into the realm of linked data, where they are represented as ontologies. For the time domain, the Digital Twin Construction (DTC) ontology is used to describe tasks. In the cost domain, we build on the authors' previous work by encoding a cost ontology in OWL. Next, both ontologies are aligned with a shared concept of modeling the resource domain as an ontology itself. Already established ontology patterns will be reused. In our work, all three ontologies are eventually aligned with each other and are demonstrated in a use case that will show the advantages of sharing resource entities following the same conceptual design for the time and cost domains.

Keywords
Construction Management, Cost Calculation, Resource Planning, Construction Scheduling, Ontology Engineering

1. Introduction

Semantic Web Technologies (SWT) and ontologies play a transformative role in the Architecture, Engineering, and Construction (AEC) sector by addressing interoperability challenges and enhancing data integration [1, 2]. These technologies provide a logic-based framework for unifying diverse information domains, such as architectural and structural building data heating, ventilation, air conditioning systems, and energy distribution systems, while also enabling cross-disciplinary applications [3]. Building on this potential, recent research has explored the use of ontologies to support various aspects of construction project management with Building Information Modeling (BIM), including scheduling, cost estimation, and resource planning (as outlined in Section 2). One of the key motivations for this research is that project scheduling and cost estimation, although inherently related, are still not consistently integrated within BIM workflows and data environments [4, 5, 6]. Although several software solutions are available to support cost and schedule integration [7], in real-world applications, cost and schedule data are often still independently linked to the building model, resulting in duplicate or conflicting resource definitions, fragmented workflows, and the need for manual reconciliation between planning domains [5, 6]. This fragmentation stems not only from technical limitations, such as insufficient interoperability, heterogeneous data formats, and lack of standardization [7] but also from organizational divides among project

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stakeholders, who operate with distinct breakdown structures (e.g., Work Breakdown Structure (WBS) vs. Cost Breakdown Structure (CBS)) and differing objectives [4].

The inconsistencies and conflicts in resource allocation that result from maintaining separate time and cost data are particularly evident in practice when labor, equipment, and material resources are not aligned across domains [8]. For example, required labor resources may differ between scheduling and costing due to different calculation methods or underlying assumptions. Similarly, material quantities required at a given time may not match those defined in the cost model, complicating site logistics. Another common problem is the duplicate representation of the same equipment or labor with inconsistent usage rates or durations across domains. In many cases, resources are not explicitly modeled but are implicitly embedded in task definitions or cost items, making alignment even more difficult. In addition, scheduling and costing are often performed by different stakeholders who do not share a common resource pool, further increasing the risk of inconsistencies [9]. These discrepancies require additional plausibility checks and coordination efforts, adding complexity and inefficiency to the planning process.

Beyond organizational and technical fragmentation, aligning model-based planning with traditional cost estimation practices presents a structural challenge [10]. Classification systems for CBS vary worldwide in how they break down construction projects - from object-based systems such as Uniclass (UK), Omniclass (US) or CoClass (Sweden) to process-based systems [10]. In Germany, cost estimation follows DIN 276 [11], while in Italy, in public tenders, it is essential to follow regional price lists, catalogs of standard cost items. Each cost item is characterized by a clear and transparent price analysis that allows to understand which and how many resources (materials, equipment, and labor) have to be used to obtain the unit cost value per each cost item. Then, to this value, overheads and profits must be added [12]. A major advantage of the model-based approach is the automatic quantity take-off (QTO), which should be better integrated with the mandatory CBS. Recent research highlights the need for standardized measurement rules and a transition from process- to object-based classification systems to fully leverage BIM [10]. An ontology-based approach supports both aspects by providing a semantically consistent representation across domains. Since resources are central to both scheduling and costing, the resource-oriented perspective promotes a unified view and helps avoid inconsistencies.

To address the stated challenges, this paper introduces a shared resource concept leveraging SWT and ontology-based integration. Separate ontologies for cost, time, resources, and geometrical products from Industry Foundation Classes (IFC) are implemented or reused and systematically aligned within a Linked Data framework. This alignment is facilitated by modeling the resource domain as a centralized ontology in an ontology network for construction project management, utilizing established ontology patterns. The proposed approach is demonstrated through a use case, showcasing the benefits of semantically aligned resource entities in achieving a cohesive and efficient integration of cost and time data in construction projects. The investigation revealed that there is no existing ontology that adequately supports scheduling and cost-calculation tasks while encompassing all necessary information for both domains. As a result, the development of a tailored solution is necessary. The paper relies on the previous work of the authors on ontologically modeling tasks [3] and cost items [13] related to IFC models.

2. Related Works

To ensure efficiency and interoperability, it is crucial to analyze existing ontologies before developing new ones or extending them. Reusing and building on established ontologies promotes standardization, reduces redundancy, and allows better integration with existing systems and data sets [2]. In addition, leveraging previous work saves time and resources while fostering collaboration within the research community [2]. Pauwels and Terkaj [14] explore the integration of SWT with the IFC standard by transforming the IFC schema into a Web Ontology Language (OWL) format. As an ontology representation of IFC [15], ifcOWL enables the continued use of the well-established IFC standard while leveraging semantic web capabilities such as data distribution, extensibility, querying, and reasoning.

Several ontologies relevant to construction project management have also already been developed, each addressing specific aspects of the domain. Some ontologies focus on the representation of processes, particularly in the context of construction scheduling [16, 17], while others are dedicated to modeling costs [18, 19, 20, 21]. Furthermore, some ontologies aim to integrate multiple domains into a unified conceptual framework [22, 23, 24]. Since resources are central to both cost and scheduling, ontologies that consider resources to optimize their management and relationships between domains are explored.

2.1. Cost and schedule ontologies

Ontologies dedicated to cost-related challenges address various aspects of cost modeling, ranging from the representation of cost-driving features in building product models to the automation of cost estimation through semantic reasoning and BIM integration [19, 18, 20, 21]. These ontologies primarily aim to improve cost estimation accuracy [21], extract quantities from BIM models [20], or associate cost items with geometric objects [19]. Despite their efforts, significant gaps remain, particularly in structuring and standardizing cost item data. Much of the cost data is still represented as simple natural language descriptions, which lack the necessary structure for machine interpretation and analysis. Resources are not explicitly taken into account in all cost-related ontologies.

Furthermore, challenges persist in integrating cost models with BIM, especially when linking cost data to BIM models. The lack of structured cost data hinders the connection between BIM's geometric data and corresponding cost items, limiting automation potential. Achieving alignment requires standardized and structured cost data to enhance accuracy, validation, and interoperability. To address these gaps and challenges, Cassandro et al. [12] proposed the development of a new ontology in an earlier paper, focusing on the standardization of cost items and establishing a structured procedure for verifying and validating their relationships with model objects.

There are also a number of ontologies that have been developed for the field of construction scheduling [5, 17, 22, 23, 25, 26]. Schlenger et al. [17] conducted a thorough analysis of existing ontologies, identifying significant gaps, particularly in process dependencies and hierarchical structures for automated interpretation. To address the identified gaps in data representation the authors [17] introduced a new ontology tailored to construction scheduling. The Construction Scheduling Ontology emphasizes the explicit representation of process decomposition criteria, with a view to better capturing hierarchical structures and dependencies in construction processes.

A significant limitation of numerous ontologies, a common issue in the AEC sector, is their narrow focus on specific purposes, such as cost estimation or scheduling [23]. Some ontologies lack a published definition [17, 18, 19], further hindering their reusability and adoption. As pointed out in [2], reusability is one of the most critical principles to consider during ontology development, ensuring that ontologies can serve multiple purposes and adapt to various contexts. Equally important is the integration of new ontologies with existing ones, which is essential for fully leveraging the potential of the Semantic Web [2]. By linking ontologies, cross-domain frameworks can be created, enabling richer semantic insights and more comprehensive decision-making capabilities across interrelated project domains.

2.2. Resource-related ontologies

One of the first attempts to develop a domain-wide ontology for infrastructure and construction and to integrate different concepts into a single framework was proposed in [22]. IC-PRO-Onto supports knowledge-based process management and coordination between actors, disciplines, and projects. It models key concepts such as actors, resources, actions, products, projects, mechanisms, and constraints. Although it effectively conceptualizes activity-related constraints and interrelationships, IC-PRO-Onto lacks detail on how processes depend on constructed products and specific entity information. Zheng et al. developed DiCon [23], a set of interrelated ontologies designed to formalize and integrate construction workflow information. DiCon has prioritized the reuse and integration of existing ontologies to enrich construction workflow data content without redundant modeling, providing a comprehensive framework for managing and executing construction workflows. In the DiCon ontology, activities are associated with resources ("flows"), including agents, materials, equipment, locations and information. Resources are defined as static entities ("continuants") linked to activities through properties and constraints.

A comprehensive process-centered ontology to represent key concepts essential for digital twins of construction sites has been developed as part of the EU Horizon 2020 project BIM2TWIN [24]. The Digital Twin Construction Ontology (DTC) enables the representation of both project intent – such as schedules and 3D designs – and project status, reflecting observed on-site conditions. The ontology defines resources, working zones, preconditions, and resulting building elements, while using the Building Topology Ontology (BOT) to describe spatial structures. The LinkOnt ontology, developed by Soman et al. [25], leverages SWT to model and validate complex scheduling constraints, supporting predictive planning. This ontology extends ifcOWL by introducing additional classes necessary for dynamic constraint-checking. The proposed approach employs the Shapes Constraint Language (SHACL) for modeling and validation, integrating process information through RDF and ifcOWL. Farghaly et al. [26] focus on integrating scheduling and resource data for enhanced construction production control. The proposed cSite ontology unifies data from planning schedules, resource deliveries, and other domains, addressing challenges in fragmented systems and enabling seamless integration. The ontology uses SPARQL to link heterogeneous data, providing real-time insights into scheduling and resource allocation.

2.3. Research gap

Previous work on ontologies has been investigated, and it has shown that applicable ontologies are scarce, particularly at the intersection of cost and resource domains, while schedules are predominantly interconnected with resources [22, 23, 24, 25, 26]. While ifcOWL is capable of representing the interconnection between costs and geometry as well as tasks and geometry, the `IfcCostItem` and the `IfcTask` are not covering all the relevant information from cost estimation and scheduling, nor should the IFC schema be overloaded with these details. This leads to the decision for this research to utilize an existing ontology for representing time information from schedules, implement a new minimal ontology for resources that can easily be aligned with existing ontologies, develop a new cost ontology based on the experience from preliminary work, and eventually integrate the interconnections between all domains. An ontology that provides a comprehensive vocabulary for construction scheduling is the DTC ontology [24]. This publicly available ontology serves as a robust and future-proof foundation for this work and can be further refined and extended based on insights gained from related research [17]. Consequently, it has been adopted for semantic integration in this study.

3. Methodology

This paper employs the Linked Open Terms (LOT) methodology by Poveda-Villalón et al. [27] for ontology engineering, which is a structured approach for documenting ontology-related artifacts, such as terms, vocabularies, and ontologies, in a standardized and semantic way. It aims to improve reusability, interoperability, and findability in Linked Data and Semantic Web applications according to the FAIR principles [28]. By leveraging established metadata standards and encouraging interlinking with existing vocabularies, LOT ensures that ontological components are both machine-readable and accessible to a broader audience. This approach not only aligns with Linked Data principles but also supports the sustainable maintenance and evolution of semantic artifacts, making it a critical tool for fostering interoperability in ontology-driven domains. The LOT methodology closely ties to Competency Questions (CQs) as a fundamental requirements engineering part of the ontology development and documentation process [29, 30]. Competency questions are natural language queries that define the scope, requirements, and intended use cases of an ontology [29]. They help ensure the ontology meets its design objectives and remains practically applicable [30].

Lastly, we foster ontology reuse in this paper as a cornerstone of efficient and interoperable knowledge representation in linked data ecosystems [28]. Promoting reuse not only reduces redundancy but also fosters a collaborative environment for evolving semantic resources, underscoring the sustainability of ontology-driven solutions. Ontology reuse in this research is facilitated by the Onto4Reuse framework [31]. According to Farghaly et al. [2], ontologies can be integrated using two methodologies, semantically bridging or ontology mapping, of which both methodologies are applied in this research. Ontology mapping is used for integrating existing ontologies, while we use the semantically bridging approach for newly developed ontologies that can directly be connected from the conceptualization stage. For the visualization of ontologies, the Ontology Design Template of Donkers [32] is used.

4. A shared resource concept for integrating cost and time domains

For realizing a shared resource concept with a centralized ontology representing resources and the interconnections to the scheduling domain and the cost domain, the requirements are established as CQs in the first step. Afterwards, it is conceptualized how the scheduling domain can be represented by ontologies reused and how cost items can be represented in an ontological schema. Furthermore, the centralized resource ontology, as well as the interconnections between the domains, are conceptualized, and a recurring pattern for these assignments is provided. The ontology requirements are first elicited based on the Italian cost estimation system, while the concept is later extended to accommodate German cost estimation practices. It is considered how national and international classification systems can be incorporated, e.g., for the cost items. Lastly, a multilingual vocabulary is defined to be reused across all domain ontologies. After the conceptualization, the ontologies are implemented and evaluated based on the CQs defined in the requirements. Further evaluation of the developed resource-centric ontology network in a project management case study is provided by Cassandro et al. [8] by introducing advanced project management consistency checks.

4.1. Requirements

The requirements are elicited as a result of previous work [3, 8] as CQs for each domain (cost, time, resource) as presented in Table 1. The CQs C1–C4 guide the development and evaluation of the cost domain ontology for cost calculation. Similarly, T1–T3 support the definition and evaluation of the ontology for the time domain for scheduling, while CQs R1–R4 focus on the resource domain, addressing resource utilization for both cost and time domains. These requirements focus on the interrelations between the domains, including also the relation to the IFC model referred to as the geometry domain.

Table 1
Ontology Requirements grouped by domains

Cost	Time	Resource
C1: How is a cost item defined?	T1: How is a task defined?	R1: How is resource defined?
C2: Which types of cost components constitute a cost item?	T2: How is a task connected to a cost item?	R2: Which type of resources exist?
C3: How is the cost item connected to the building product in the IFC model?	T3: How is the task connected to the building product in the IFC model?	R3: How is a resource connected to a cost item?
C4: How is the quantity of the building product used for the cost estimation?		R4: How is a resource with a specific utilization rate connected to a task?

Each of the domain ontologies is first constituted by a central Class Expression (CE) that can be retrieved through the CQs C1 for the cost item, T1 for the task, and R1 for the resources. For the cost domain, it is further defined in the requirements in C2 that a cost item is aggregated. It is further defined as CQ C3 how the cost item is related to a building product from the IFC model. Eventually, for the cost domain ontology, the quantity of the building product plays a crucial role and has to be derived from the IFC model, which is the main requirement in C4 for the interconnection of the cost item to the building product.

Since the review of ontologies in Section 2 has shown already a sufficient amount of ontologies for describing construction tasks, the main emphasis is on connecting these tasks to the other domains. Therefore, in T2, it is asked how to connect a task to a cost item, while in T3 the interconnection to the building product in the IFC model is required. For the resource domain, it is asked in R2 which types of resources exist and can be modeled with the ontology aiming for a sub-typing pattern. Afterwards, the the interrelations between the resource and the cost domain are required by R3. For the interconnection between the resource and the task, additional information apply here to define the utilization rate of a resource (R4). These requirements are used for conceptualizing and evaluating the ontology.

4.2. Conceptualization and Implementation

This section outlines the core components of the conceptual framework developed for the project, detailing the reuse and extension of existing ontologies, the development of new domain-specific ontologies, and their integration into a cohesive system. First, it explains how the existing process-centered ontology (DTC [24]) is leveraged as a foundational framework, highlighting adaptations or extensions needed to align with project-specific requirements. In the second step, the conceptual design of an ontology for the cost domain is introduced, focusing on its structure and role in modeling cost-related data for construction project management. The third part elaborates on the development of a resource ontology with an emphasis on modeling resources such as labor, equipment, and materials. It also discusses the assignment patterns between different domains, demonstrating how resources are allocated and interlinked across the construction process.

After designing the core ontologies, it is focused on integrating standardized classification systems, with particular emphasis on the German DIN 276 for the classification of cost groups. Eventually, this section addresses the integration of multi-lingual domain-specific terminology, ensuring consistent semantic representation across the ontologies. By systematically addressing these components, the conceptualization phase establishes a robust foundation for the project's ontology-driven approach to construction process management. The used ontologies and namespaces in this research are defined in Table 2. The newly developed ontologies and instance data for the evaluation can be found in the online repository[1].

Table 2
Ontologies and namespaces used in research

Prefix	URI	Description
rdf:	<http://www.w3.org/1999/02/22-rdf-syntax-ns#>	Resource Description Framework (RDF)
rdfs:	<http://www.w3.org/2000/01/rdf-schema#>	RDF Schema (RDFS)
owl:	<http://www.w3.org/2002/07/owl#>	Web Ontology Language (OWL)
ci:	<http://w3id.org/ci#>	Cost Item (CI) Ontology
cr:	<http://w3id.org/cr#>	Construction Resources (CR) Ontology
cterm:	<http://w3id.org/cterm#>	Construction Terminology (CTERM)
din-276:	<https://www.dinmedia.de/en/standard/din-276#>	DIN 276 Building Costs - Cost Group Classification [11]
unit:	<http://qudt.org/2.1/vocab/unit#>	QUDT Units Version 2.1.46 [33]
dtc:	<https://dtc-ontology.cms.ed.tum.de/ontology#>	Digital Twin Construction Ontology [24]
ifc:	<http://ifcowl.openbimstandards.org/IFC4_ADD2#>	ifcOWL Version IFC4 ADD2

4.2.1. Reuse of an ontology for construction schedules

For the representation of construction schedules, the detailed requirements were retrieved from construction schedules of professional engineers provided in Microsoft Project and exported as Microsoft Project XML files. For semantic integration, these XML files can be converted into the respective ontologies. The core concept from the DTC ontology [24] utilized in this approach is depicted in Figure 1 focusing on the `dtc:Task` class. While this class is the backbone of the research, other classes from the ontology can be used as needed.

A relevant pattern is the precondition of a task, represented by instances of the class `dtc:Precondition`. Preconditions can be subtyped into external factor preconditions, informa-

[1]https://cpm-ont-network.github.io/, last accessed: 07.04.2025

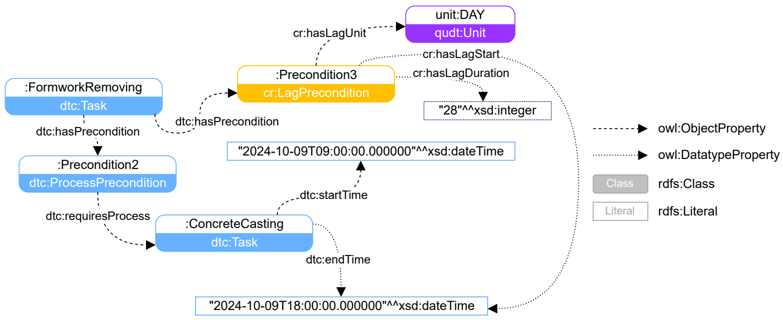

Figure 1: Used core entities from the DTC ontology [24] and extension of the `cr:LagPrecondition`

tion preconditions, process preconditions (as shown in Figure 1), resource assignments, and zone preconditions. Based on construction scheduling in Mircosoft Project, the predominantly existing conditions are the process precondition and a predefined lag for representing waiting time between two tasks. However, the latter one is not yet considered in the DTC ontology and is extended for the purpose of this research, for instance, to represent waiting times, (as depicted in Figure 1 the yellow entity with the type `cr:LagPrecondition`). The lag precondition unifies a lag duration datatype property, a corresponding lag unit typed as a `qudt:Unit`, and a reference to the lag start to calculate the precondition, which is, for example, set to the end of the concreting task.

4.2.2. Cost Item (CI) Ontology

The cost domain ontology, developed as the Cost Item (CI) ontology, builds on the work of Cassandro et al. [13] and aligns with the`IfcCostItem` definition in `IFC4X3_ADD2`[2]. Its core pattern is shown in Figure 2. The figure shows the aggregation pattern of the `ci:CostItem` entity via the `ci:hasPart` object property to `ci:CostComponent` entities. Cost components can be instantiated from three subclasses: can be instantiated from three subclasses: one that represents costs directly associated with construction products (e.g., material usage), another that captures costs associated with construction processes (e.g., labor), and a third for temporary costs arising during construction but not directly attributable to specific components (e.g., rental of temporary supports or formwork elements).

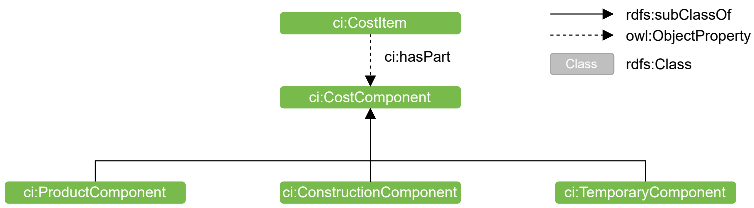

Figure 2: Core pattern of the CI ontology

In Figure 3, the detailed interconnection between classes in the domain is shown, and shared data properties are introduced. This detailed concept enables the representation of cost items and cost components with descriptions, classification codes, and units, as well as a reference quantity in the unit of measure retrieved from the Quantities, Units, Dimensions, and Types (QUDT) ontologies [33].

It further introduces a class `ci:Work` that represents the specific work items, e.g., as usually found in the bill of quantities. Work items can be specialized for construction, product, or temporary components and are related to a respective unit and a reference quantity in the unit of measure. Moreover, the CI ontology integrates activities that are closely connected to the activities from the DTC ontology. All classes in CI ontology can be detailed with terminology on categories, functions, usages, aspects, objects, types, parameters, and families based on the multi-lingual terminology proposed in Section 4.2.4.

[2]https://ifc43-docs.standards.buildingsmart.org/IFC/RELEASE/IFC4x3/HTML/lexical/IfcCostItem.htm, last accessed: 13.01.2025

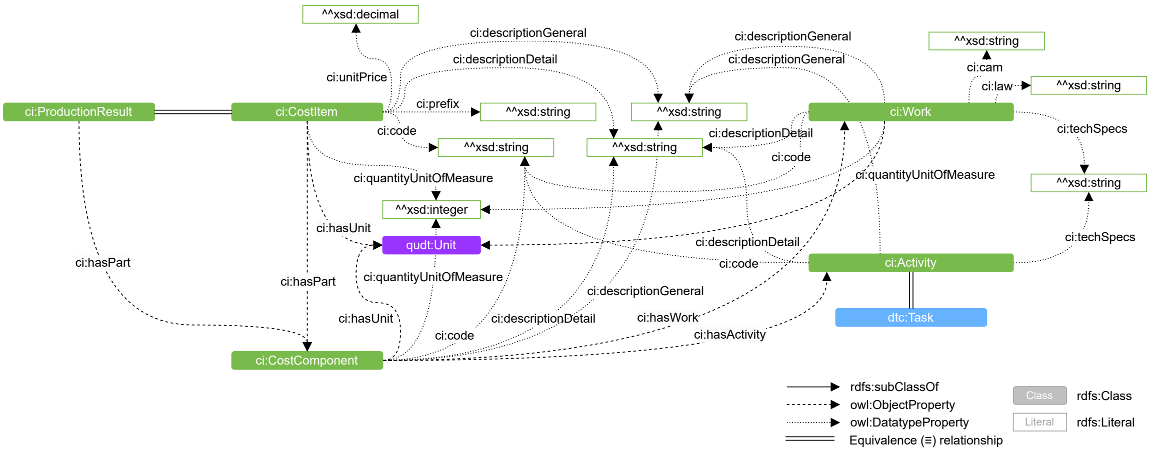

Figure 3: Extended patterns and properties of the CI ontology

4.2.3. Construction Resource (CR) Ontology and Assignments between domains

The Construction Resource (CR) Ontology defines resources that can be utilized by the cost and the time domain. The resources are defined as `cr:Resource` with subclasses `cr:EquipmentResource`, `cr:LabourResource`, and `cr:MaterialResource` based on the requirements from the cost domain [13] and preliminary definition from the time domain in the DTC ontology [24] as depicted in Figure 4. These three subclasses are aligned with the respective definitions provided in the DTC ontology for `dtc:AsPlannedEquipment`, `dtc:AsPlannedMaterial`, `dtc:AsPlannedWorker` through class equivalency.

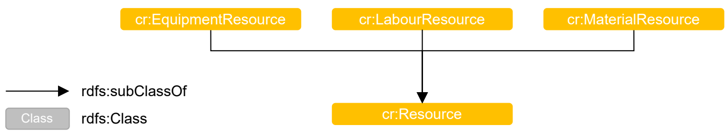

Figure 4: Core classes of the Construction Resource (CR) Ontology

The CR ontology provides information on the consumption of resources with the class `cr:Consumption` and the object property `cr:hasConsumption` that is restricted to equipment and material resources. Furthermore, resources can be aggregated using the transitive object property `cr:hasSubResource`. Further data properties such as the qualification level of laborers, the technical specifications, or rental information of equipment can be specified.

Another core component of the CR ontology is the management of assignments of resources, as shown in Figure 5. The assignments follow a specific pattern where an `cr:AssignmentSet` hosts multiple occurrences of 1-to-1 `cr:Assignment` between entities of different domains. For the assignment of entities, the object property `cr:ref` is incorporated as a generic referencing super property. For each type of referenced entity, a subproperty is introduced, e.g., `cr:refCostItem`, `cr:refTask`, `cr:refGeometry`, or `cr:refResource`. Based on these properties, specific types of assignments can be introduced as subclasses of `cr:Assignment`. These subclasses are depicted in Figure 5, e.g., `cr:CostItemToGeometryAssignment`, and represent a specific 1-to-1 assignment between two domains, where the referenced elements are restricted through the respective properties. Full documentation of the assignments can be found under https://w3id.org/cr#.

From the definition of the CR ontology, the range of the `cr:refGeometry` is the `ifc:IfcProduct` class, of the `cr:refCostItem` is the `ci:CostItem` class, of the `cr:refTask` is the `dtc:Task` class, and of the `cr:refResource` is the `cr:Resource` class. Additionally, the subclasses of `cr:Assignment` can implement certain parameters that characterize the assignment. Therefore, the superproperty `cr:refParameter` is introduced as a datatype property.

At this stage of the research, four parameters are defined for the displayed assignments, as

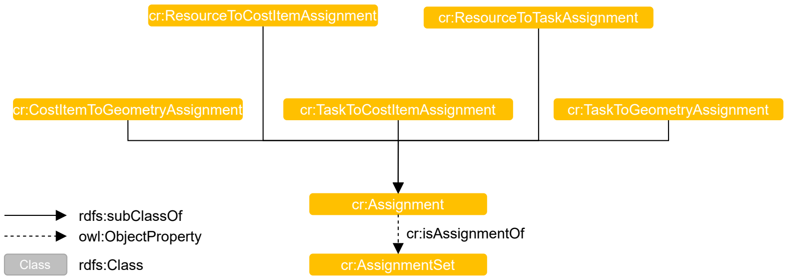

Figure 5: Assignment pattern

Table 3
Assignments and additional defining properties

Assignment	Properties
`cr:Assignment`	`cr:refParameter`
`cr:ResourceToTaskAssignment`	`cr:refParamUtilizationRate`
`cr:ResourceToCostItemAssignment`	`cr:refParamUtilizationFactor`
`cr:CostItemToGeometryAssignment`	`cr:refParamQuantity`, `cr:refParamFormula`

shown in Table 3. The parameter `cr:refParamUtilizationRate` is defined as a subproperty of `cr:refParameter` for the `cr:ResourceToTaskAssignment` to indicate how much of a resource is utilized during the task. For the `cr:ResourceToCostItemAssignment`, the parameter `cr:refParamUtilizationFactor` is integrated into the ontology as a correspondence to the `cr:refParamUtilizationRate`. Eventually, for the class `cr:CostItemToGeometryAssignment`, the parameters `cr:refParamQuantity` and `cr:refParamFormula` are provided in order to show how the quantity of an IFC element is used in cost calculations. The `cr:refParamFormula` defines a mathematical formula to derive a specific quantity from the original IFC quantities referenced by the `cr:refParamQuantity` property. These presented patterns can be utilized and extended also to implement further specific assignments. An example of the data modeled in the presented ontologies is provided in Figure 6.

In Figure 6, a concrete foundation slab is displayed with its construction process and resulting costs. The task `:ConcreteCasting` is connected to the resource `:ConcretePump` which utilizes 100 % of the assigned resource as defined by the utilization rate property. At the same time, the cost item

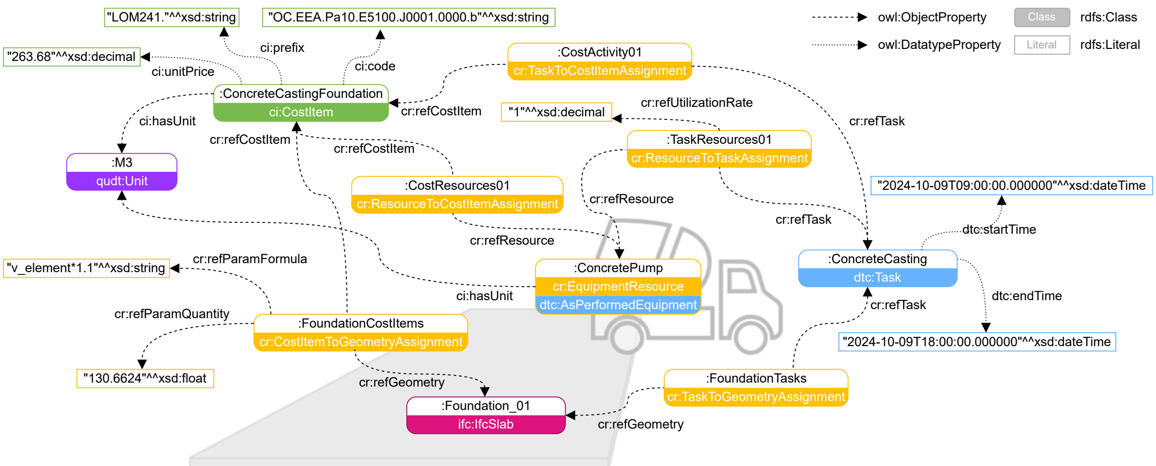

Figure 6: Example entities of the cost, resource, time, and building product domain using the developed and aligned ontologies for the creation of a concrete foundation

:ConcreteCastingFoundation is assigned to the concrete pump and to the IFC Slab as well. The assignment with the concrete pump ensures that both the scheduling and cost estimation use the same resources for the calculatios. Moreover, from the assignment between the slab and the cost item, the volume for the bill of quantities can be retrieved with the provided formula with the property cr:refParamFormula. This is because sometimes the quantities of IFC geometric elements do not correspond exactly to the quantities used for the cost calculation. It is therefore necessary to moderate the quantities according to specific formulas. Based on this calculation, the final price of the element can be calculated with the given unit price from the cost item.

4.2.4. Supplementing terminology and classification systems

It is important to provide a dataset of terminology that can be utilized to define these entities with construction-specific vocabulary for the specification of work items and cost components and the semantic annotation of tasks. A proposed structure for this Construction Terminology (CTERM) Ontology can be found in Figure 7.

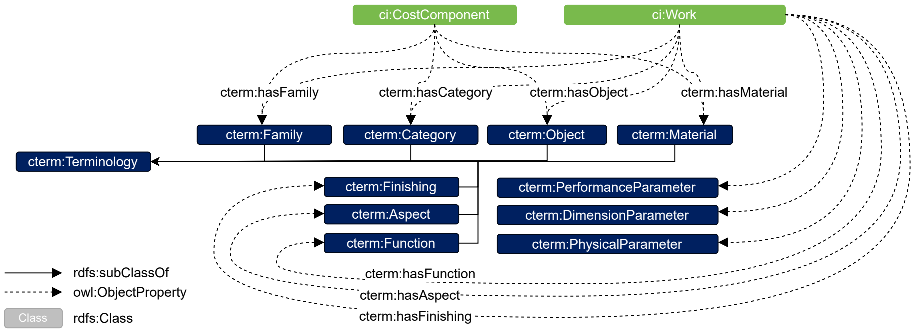

Figure 7: Applying terminology to the CI entities

The ontology contains vocabulary as instances of the classes cterm:Family, cterm:Category, cterm:Object cterm:Material, cterm:Function, cterm:Aspect, cterm:Finishing. These instances can be utilized, e.g., by the CI ontology, as depicted in Figure 7. An example of this is the cterm:Reinforcement that, for instance, is an individual of type cterm:Function when applied to a work item or cterm:Use when applied to a material. It has labels in English "Reinforcement"@en, German "Bewehrung"@de, and Italian "Armatura"@it, enabling the semantic term to be utilized in three languages. The CTERM ontology will also be made available as SKOS vocabulary in future work.

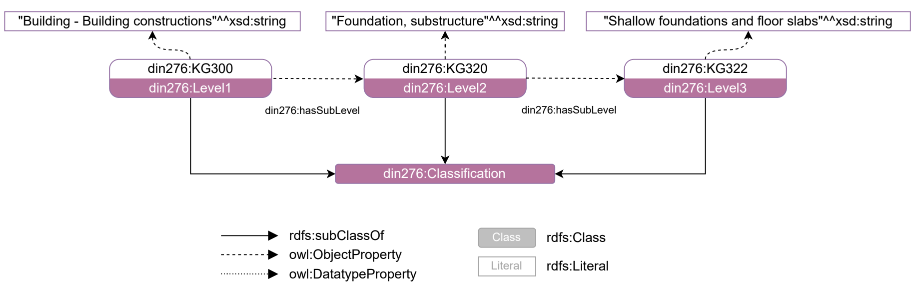

Figure 8: Example of the German DIN 276 classification system

Moreover, the CTERM ontology provides mechanisms to define parameters as cterm:Parameter or one of its subclasses for dimension, performance, or physical parameters. Each parameter specifies a type such as cterm:CompressionStrength, two symbols and two values as well as a unit that constitute a parameter that can be added, e.g., to a cost item. Standardized classification systems are relevant for systematizing the cost estimation procedure or classifying the work breakdown structure for scheduling. Therefore, the `cterm:Classification` class is implemented. A classification comprises an identifying code and a corresponding `cterm:ClassificationSystem`. In the CTERM Ontology, there are already six classification systems referenced: the German `cterm:DIN276` and `cterm:StLB`, the Italian `cterm:UNI8290` as well as `cterm:Omniclass`, `cterm:Uniclass`, `cterm:Uniformat`. Figure 8 shows an example of the German DIN 276 classification system defining cost groups in three detail levels that can be utilized for automatically mapping geometry elements to cost items.

4.3. Evaluation

The evaluation of the conceptualized and implemented resource-centric ontology network for construction project management is based on a sample dataset that can be retrieved via Appendix A. The assessment uses the CQs defined in Table 1. First, a query is defined for evaluating CQs C1–C4 as can be found in Listing 1. The query retrieves all cost items, their components, and related geometry, as well as formulas and calculated quantities. The results are limited to one for brevity in this paper and can be found in Table 4. The query results show that the requirements defined at the beginning of this chapter are met for the cost domain.

```
PREFIX cr: <https://w3id.org/cr#>
PREFIX ci: <https://w3id.org/ci#>
PREFIX dtc: <https://dtc-ontology.cms.ed.tum.de/ontology#>
SELECT ?item ?component ?type ?product ?qty ?formula
WHERE {
    ?item a ci:CostItem .
    ?item ci:hasPart ?component .
    ?component a ?type .
    ?assignment cr:refCostItem ?item .
    ?assignment cr:refGeometry ?product .
    ?assignment cr:refParamQuantity ?qty .
    ?assignment cr:refParamFormula ?formula .
} LIMIT 1
```

Listing 1: SPARQL Code for CQs C1–C4

Table 4
Results of the query for CQs C1–C4

item	component	type	product	qty	formula
:Foundation_LOM241. OC.EEA.Pa10.E5100. J0001.0000.b	:ConstructionComponent_OC.EEA. Pa10.E5100. J0001.0000.b	ci:ConstructionComponent	geometry:IfcSlab_910	130.6624	Volume*1.1

In the second step, the time domain, as represented by the DTC ontology, is evaluated based on the CQs T1–T3. The corresponding SPARQL query can be found in Listing 2. It retrieves the tasks as `dtc:Task` entities assigned to a cost item and geometry, as seen in Table 5. For the sake of brevity, the number of results is again limited to one. It can be seen that the task *"lean concrete casting"* is connected to the cost item for sub-foundations and to the `geometry:IfcSlab_2649` entity from the IFC model, and thus, the requirements for the time domain are fulfilled.

```
SELECT ?task ?ci ?product
WHERE {
 ?task a dtc:Task.
 ?assignment1 cr:refTask ?task.
 ?assignment1 cr:refCostItem ?ci.
 ?assignment2 cr:refTask ?task.
 ?assignment2 cr:refGeometry ?product.
 } LIMIT 1
```

Listing 2: SPARQL Code for CQs T1–T3

```
SELECT ?res ?type ?ci ?task
WHERE {
 ?res a ?type .
 { ?assignment1 cr:refResource ?res.
   ?assignment1 cr:refCostItem ?ci. }
UNION
 { ?assignment2 cr:refResource ?res.
   ?assignment2 cr:refTask ?task. }
 }
```

Listing 3: SPARQL Code for CQs R1–R4

Table 5
Results of the query for CQs T1–T3

task	ci	product
scheduling:Task_LEANCONCRETECASTING_4152F6CF-A19D-EF11-A011-A059508B7099	:CI-Foundation_LOM241.OC.EEA.Pa10.A6415.J0001.0025.-	geometry:IfcSlab_2649

Eventually, also the CQs R1–R4 are evaluated by querying the sample dataset with the query defined in Listing 3. The query contains the resource and its type and a union of two assignments of the resource to a cost item `?ci` and a task `?task`. The query results are provided in Table 6 and show two labor resources, one defined in the cost estimation process and one specified in the scheduling process. Although these entities represent the same real-world resource, they are specified differently due to the input of two people using Microsoft Project and the cost database. Such inconsistencies - where the same entity is described in different ways - can lead to project delays or cost overruns. This issue is further explored in a detailed project management case study by Cassandro et al. [8], which uses the developed ontology network to introduce advanced consistency checks and explore entity mapping approaches to minimize such inconsistencies.

Table 6
Results of the query for CQs R1–R4

res	type	ci	task
:LabourResource_RU.00.00.00.0005.-	cr:LabourResource	:ReinfocmentBar_LOM241.OC.EEA.Pa02.E9700.Sb017.0255.-	
scheduling:Resource_WORKER1_6A52F6CF-A19D-EF11-A011-A059508B7099	cr:LabourResource		scheduling:Task_REBARS_4952F6CF-A19D-EF11-A011-A059508B7099

5. Conclusion

This paper presents a shared construction resource ontology designed to semantically align the cost and time domains in construction projects. It addresses key challenges such as the inconsistent integration of resources in scheduling and cost estimation data and the lack of generalized, object-oriented cost classification systems compatible with model-based planning. The approach integrates geometric, cost, and time data using SWT, reusing established ontology patterns. By linking directly to IFC-based geometry, the ontology enables consistent use of geometric properties and model-based QTOs as the basis for resource utilization. This link allows changes in geometry to be reflected in cost and schedule data, improving responsiveness, traceability and verification across domains. Integration into a single knowledge graph provides a unified view of resource usage across BIM-based scheduling and cost estimation, thereby enabling plausibility checks and improving overall data consistency. By querying the resulting integrated project management knowledge graph, construction professionals can identify cross-domain inconsistencies and coordination issues. However, this assumes that equivalent resources are represented consistently in both domains. If the resources are modeled differently, manual validation is still required. This is a challenge that will be addressed in future research.

The general structure of the ontology is designed to support adaptation to different national and regional cost classification systems, but this generalizability remains to be validated in cross-context applications. In addition, future work should investigate whether the ontology sufficiently covers all concepts relevant to practical cost estimation and scheduling tasks.

While the ontological framework has been evaluated for the defined requirements, an in-depth analysis using real construction project data remains the subject of future work. Possible scenarios include tracking project costs up to a specific date, comparing the work to be performed by labor resources defined in the two domains, or analyzing weekly resource requirements. Further research could also explore the automated mapping of unlinked resources, and the generation of construction schedules based on semantic representations of cost items, construction resources and reusable templates for construction schedules.

Declaration on Generative AI

During the preparation of this work, the authors used chat GPT/Grammarly in order to grammar and spelling check, paraphrase and reword. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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A. Online Resources

The sources and documentation of the ontologies are available via https://cpm-ont-network.github.io/.