

A shared resource concept 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 domains, such as architectural and structural building data with Building Information Modeling (BIM), heating, ventilation, and air conditioning systems, and energy distribution systems, while also enabling cross-disciplinary applications [3].

Yet, their potential for aligning cost and time domains in construction project management remains largely underexplored [4, 5]. In construction, project scheduling and cost estimation are inherently interconnected; however, their virtual representations in building models and data schemes often fail to reflect this interdependence. Typically, cost data and schedules are associated with the building model independently, resulting in duplicate and conflicting definitions of resources (labor, equipment, materials). This divergence arises from different perspectives and interpretations, necessitating resource plausibility checks that add complexity and inefficiency.

To overcome these 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

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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, 6] and cost items [7, 8] related to IFC models. It is structured into Section 2 for displaying related works, into Section 3 for introducing the methodological approach, into Section 4 for the requirements, conceptualization, implementation, and evaluation of the ontology, and eventually into the Section Section 5 for conclusions and outlook.

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 [9] explore the integration of SWT with the IFC standard by transforming the IFC schema into a Web Ontology Language (OWL) format. IfcOWL, as an ontology representation of IFC [10], 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 [4, 11, 12, 13, 14], while others are dedicated to modeling costs [15, 16, 17, 18]. Furthermore, some ontologies aim to integrate multiple domains into a unified conceptual framework [19, 20, 21]. Since resources are central to both cost and scheduling, ontologies that consider resources to optimize their management and relationships between domains are explored in more detail.

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 [15, 16, 17, 18]. These ontologies primarily aim to improve cost estimation accuracy [18], extract quantities from BIM models [17], or associate cost items with geometric objects [16]. 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. [22] 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 [4, 5, 11, 14, 19, 20, 23, 24]. Schlenger et al. [14] 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 [14] 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 [20]. Some ontologies lack a published definition [11, 12, 14, 15, 16], 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 [19]. 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 [20], 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, called "flows", which include agents, materials, equipment, locations and information. Resources are defined as static entities ("continuants") and are 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 [21]. 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. [23], 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. [24] 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 queries 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 [19, 20, 21, 23, 24]. 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 [21]. 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 [14]. 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. [25] 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 [26]. 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 [27, 28]. Competency questions are natural language queries that define the scope, requirements, and intended use cases of an ontology [27]. They help ensure the ontology meets its design objectives and remains practically applicable [28].

Lastly, we foster ontology reuse in this paper as a cornerstone of efficient and interoperable knowledge representation in linked data ecosystems [26, 29]. 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 [30]. According to Farghaly et al. [2], ontologies can be integrated into 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.

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. 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. [31] by introducing advanced project management consistency checks.

4.1. Requirements

The requirements are elicited as a result of previous work [6, 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 interrelation to the IFC model which is 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 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 both the conceptualization and evaluation of 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 [21]) 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 repository¹.

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
unit:	<http://qudt.org/2.1/vocab/unit#>	QUDT Units Version 2.1.46 [32]
dtc:	<https://dtc-ontology.cms.ed.tum.de/ontology#>	Digital Twin Construction Ontology [21]
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 [21] 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.

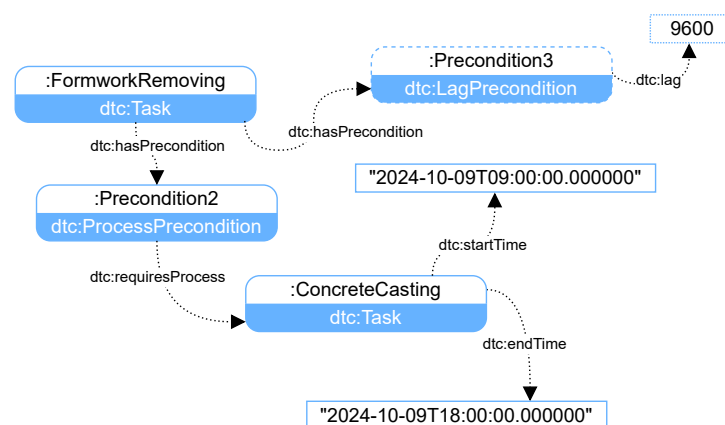


Figure 1: Used core entities from the DTC ontology [21] and extension of the lag precondition

The most relevant pattern is the precondition of a task, represented by instances of the class `dtc:Precondition`. Preconditions can be subtyped into external factor preconditions, information preconditions, process preconditions (as shown in Figure 1), resource assignments, and zone preconditions. Based on state-of-the-art construction scheduling in Microsoft Project, the predominantly existing conditions are the process precondition and a predefined lag for representing waiting time between two

¹<https://cpm-ont-network.github.io/>, last accessed: 13.01.2025

tasks. However, the latter one is not yet considered in the DTC ontology and is extended for the purpose of this research (as depicted in Figure 1 the dotted entity with the type `dtc:LagPrecondition`).

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. [7] and aligns with the `IfcCostItem` definition in IFC4X3_ADD2². 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: 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).

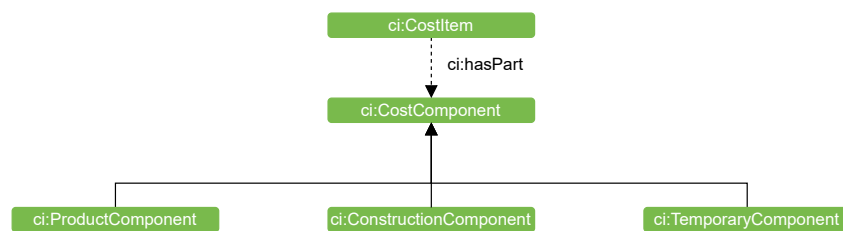


Figure 2: Core pattern of the CI ontology

In Figure 3, the detailed interconnection between classes in the domain is shown, and shared data properties are introduced. This detailed concept provides the required structures to represent cost items and cost components with descriptions, classification codes, and units as well as a reference quantity in the unit of measure that are retrieved from the Quantities, Units, Dimensions, and Types (QUDT) ontologies [32].

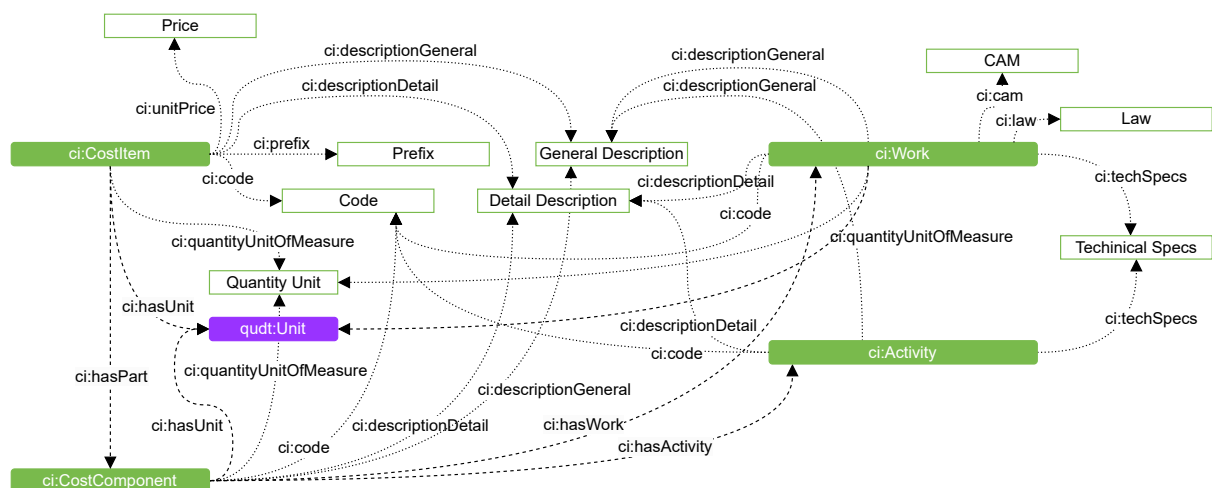


Figure 3: Extended patterns and properties of the CI ontology

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

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

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.

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 [7] and preliminary definition from the time domain in the DTC ontology [21] 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.

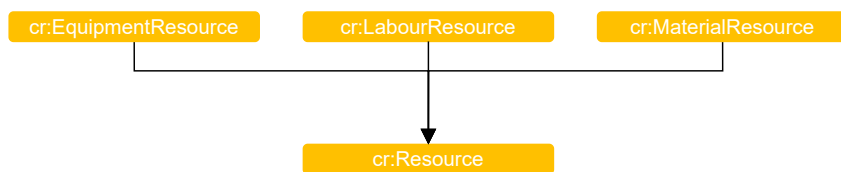


Figure 4: Core classes of the Construction Resource (CR) Ontology

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#>.

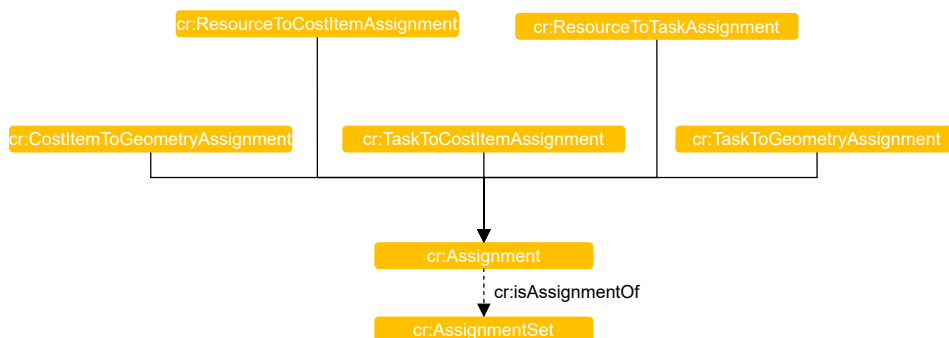


Figure 5: Assignment pattern

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.

Table 3
Assignments and additional defining properties

Assignment	Properties
<code>cr:Assignment</code>	<code>cr:refParameter</code>
<code>cr:ResourceToTaskAssignment</code>	<code>cr:refParamUtilizationRate</code>
<code>cr:ResourceToCostItemAssignment</code>	<code>cr:refParamUtilizationFactor</code>
<code>cr:CostItemToGeometryAssignment</code>	<code>cr:refParamQuantity</code> , <code>cr:refParamFormula</code>

At this stage of the research, four parameters are defined for the displayed assignments, as 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 `: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 calculations. 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`. Based on this calculation, the final price of the element can be calculated with the given unit price from the cost item.

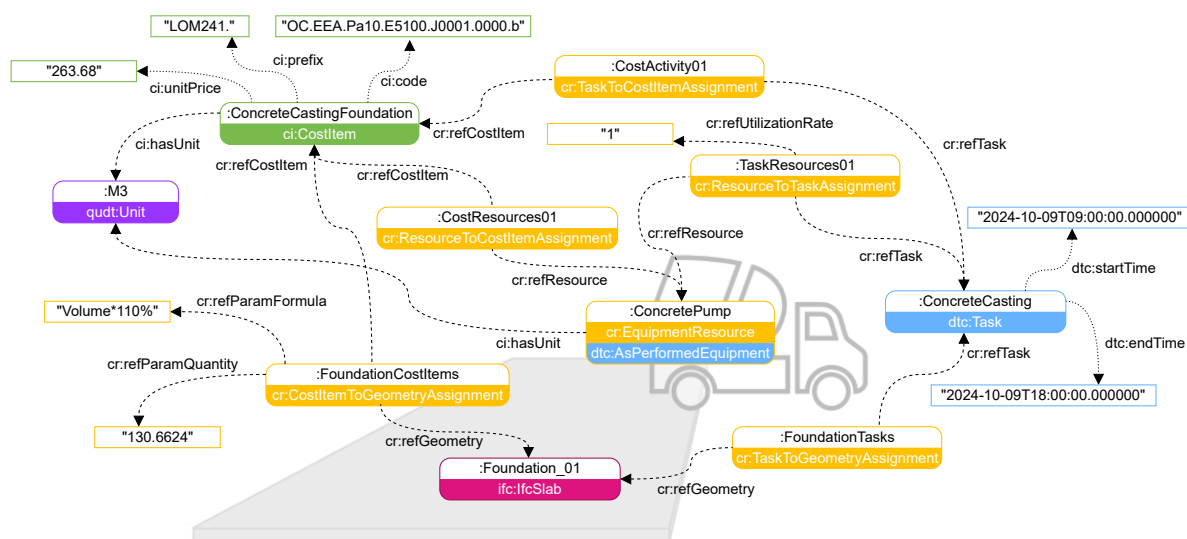


Figure 6: Example entities of the cost, resource, time, and building product domain using the developed and aligned ontologies for the creation of a concrete foundation

4.2.4. Supplementing terminology and classification systems

It is vital 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.

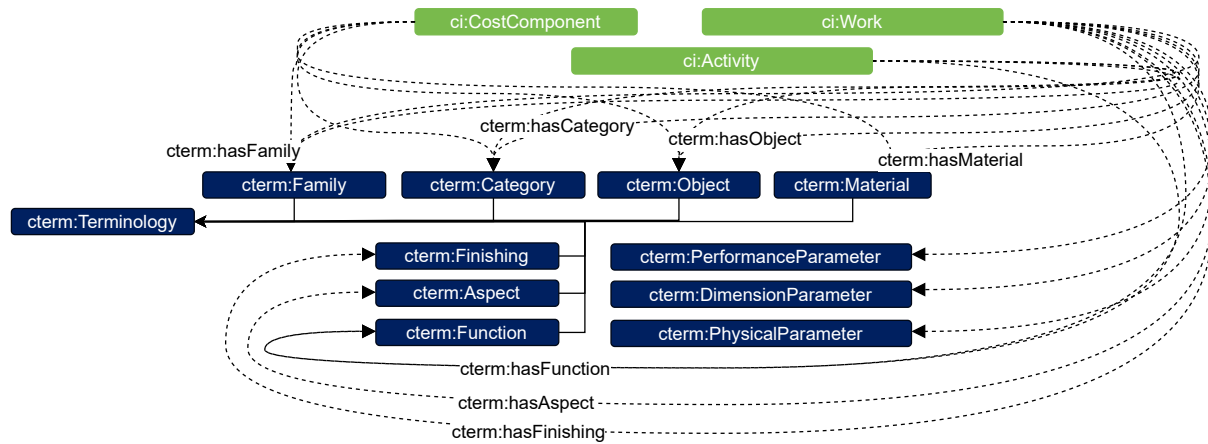


Figure 7: Applying terminology to the CI entities

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 would be the `cterm:Reinforcement` that, for instance, is a named 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 that enables the same semantic term to be utilized already in three languages.

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 `cter: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.

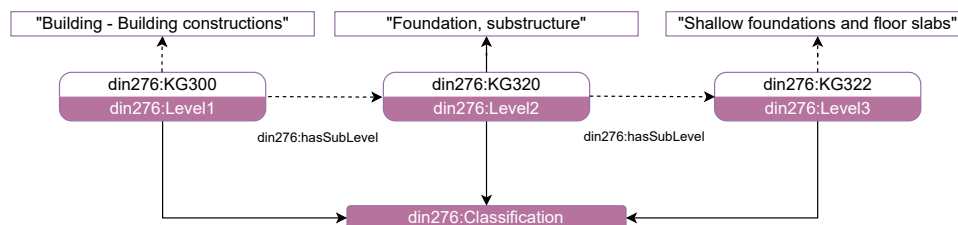


Figure 8: Example of the German DIN 276 classification system

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.

```

1 PREFIX cr: <https://w3id.org/cr#>
2 PREFIX ci: <https://w3id.org/ci#>
3 PREFIX dtc: <https://dtc-ontology.cms.ed.tum.de/ontology#>
4 SELECT ?item ?component ?type ?product ?qty ?formula
5 WHERE {
6   ?item a ci:CostItem .
7   ?item ci:hasPart ?component .
8   ?component a ?type .
9   ?assignment cr:refCostItem ?item .
10  ?assignment cr:refGeometry ?product .
11  ?assignment cr:refParamQuantity ?qty .
12  ?assignment cr:refParamFormula ?formula .
13 } 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:lfc-Slab_905	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:lfcSlab_2649` entity from the IFC model, and thus, the requirements for the time domain are fulfilled.

```

1 SELECT ?task ?ci ?product
2 WHERE {
3   ?task a dtc:Task.
4   ?assignment1 cr:refTask ?task.
5   ?assignment1 cr:refCostItem ?ci.
6   ?assignment2 cr:refTask ?task.
7   ?assignment2 cr:refGeometry ?product.
8 } LIMIT 1

```

Listing 2: SPARQL Code for CQs T1–T3

```

1 SELECT ?res ?type ?ci ?task
2 WHERE {
3   ?res a ?type .
4   { ?assignment1 cr:refResource ?res .
5     ?assignment1 cr:refCostItem ?ci . }
6   UNION
7   { ?assignment2 cr:refResource ?res .
8     ?assignment2 cr:refTask ?task . }
9 }

```

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	:SubFoundation_LOM241.OC.EEA.Pa10.A6415.J0001.0025.-	geometry:lfcSlab_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. [31], 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	:Reinforcement- Bar_LOM241.OC.EEA. Pa02.E9700.Sb017.0255.-	
scheduling:Resource_WORKER1_6A52F6CF-A19D-EF11-A011-A059508B7099	cr:LabourResource		scheduling:Task_RE- BARS_4952F6CF-A19D-EF11- A011-A059508B7099

5. Conclusion

This paper addresses the disconnection between cost calculation and construction scheduling by defining a shared resource concept for semantically aligning these two domains in an ontological framework. Specifically, our approach successfully integrated the cost and time domains by using SWT, by reusing established ontology patterns, and by introducing a shared resource ontology. The integration of multiple domains enables a unified representation of the usage of resources for scheduling and cost estimation, ensuring consistency across the provided data, which is not given the way project management is executed without this integration. This allows construction managers to discover irregularities in either domain by querying the resulting integrated project management knowledge graph.

The results of this study have significant implications for the construction industry. By bridging the gap between cost estimation and project scheduling, the proposed framework facilitates better collaboration among stakeholders, reduces the risk of conflicting resource definitions, and supports automated plausibility checks. Furthermore, this approach lays the foundation for more advanced digital twin applications, paving the way for more integrated and dynamic project management processes.

While the ontological framework has been evaluated for the defined requirements, the in-depth evaluation with a real-world construction management knowledge graph still needs to be done in future work. Criteria that can be analyzed in detail are the costs of a project up to a certain date, the comparison of work to be done by labor resources defined in the two domains, or the amount of resources needed in a specific week. Future work could also include an analysis of methods for computing the automated mapping of unconnected resources or how to refine schedules or costs computationally based on insights from the knowledge graph.

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A. Online Resources

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