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Ontology-Based Framework for Construction Cost Management Using BIM for Small-Scale Public Infrastructure Projects

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Ontology-Based Framework for Construction Cost Management Using BIM for Small-Scale Public Infrastructure Projects

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Abstract

Effective cost management in the Architecture, Engineering, and Construction (AEC) sector faces persistent challenges due to fragmented data environments, inconsistent information structures, and limited semantic interoperability among stakeholders. Although Building Information Modelling (BIM) is widely applied for cost estimation (5D BIM), its integration into comprehensive cost management remains constrained by data discontinuities and limited reuse of structured knowledge.

This study proposes an ontology-based framework for managing cost-related information in small-scale public infrastructure projects, focusing on standardized railway stations. The research methodology combines an empirical analysis of current 5D BIM practices in Germany, a narrative literature review of ontology-based approaches for construction cost estimation, and a case study of a representative railway station project. Established ontology engineering methods were adapted to define classes, properties, and taxonomies integrating product- and process-oriented perspectives.

The results indicate that cost development can be structured into four phases aligned with the Level of Development (LOD) concept: Level of Geometry (LoG), Level of Information Need (LoIN), Level of Cost Item (LoCI), and Level of Work Item (LoWI). The proposed framework enables a granular allocation of costs to building components and construction works, supports structured comparisons of tendered, budgeted, and executed costs, and promotes the systematic reuse of cost-related information. To assess its practical applicability, the proposed model for cost-information and knowledge structuring was implemented for the definitive cost estimate (LOD 3).

The novelty of this research lies in extending and adapting established AEC ontologies to the largely unexplored domain of small-scale railway stations. By bridging component- and activity-based cost perspectives, the research contributes to semantically enriched, interoperable cost management in public infrastructure delivery.

Keywords: cost management; ontology-based framework; infrastructure projects; railway stations.

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Introduction

The AEC industry is inherently complex and multidisciplinary. Effective cost management is essential for the successful delivery of building and infrastructure projects. While BIM aims to enhance cost planning, estimation, and control, its integration into cost management remains inconsistent. Various workflows were developed to enable smoother BIM implementation in cost management processes (Baldrich Aragó et al., 2021; Moses et al., 2020; Pishdad & Onungwa, 2023). These efforts have addressed the problem of information utilization for cost planning and analysis but have not resolved issues related to unstructured data and data interoperability. Furthermore, such studies tend to replicate traditional processes within new digital environments like BIM.

Two main research approaches can be identified in the application of BIM environments for construction cost management: (1) extracting all relevant information directly from BIM models and linking it to external cost databases, or (2) enriching BIM with additional semantic information for direct estimation (Wang & Guo, 2020). The first method often results in model rework by other stakeholders who do not use the same external database, limiting the potential of BIM. The second method can be advantageous; however, the information available within the BIM environment alone is insufficient for comprehensive cost management. This necessitates the integration of additional information sources, but data heterogeneity and semantic gaps remain major challenges.

To overcome these challenges and enhance cost efficiency across project phases, several studies have focused on ontology-based methods. Ontologies formalize cost-related knowledge, fostering a shared understanding and improved integration among project stakeholders (Signorini et al., 2025). Ma et al. (2013) developed an algorithm for semi-automatic classification of construction products into cost items, while Lee et al. (2014) presented a prototype system linking BIM data to cost items based on work condition and work item ontologies. The automation of construction cost estimation for tendering has been addressed in several studies (Liu & Ma, 2015; Abanda et al., 2017; Cassandro et al., 2023). Various ontology types – such as concept model, work item, construction condition, cost, and measurement ontologies – have been developed to make the cost estimation process more efficient and less error-prone (Liu et al., 2016; Abanda et al., 2017; Im et al., 2021; Signorini et al., 2025).

However, a systematic literature analysis by Farghaly et al. (2023) highlights that existing solutions remain overly generic and are not tailored to specific domains or project types. Reinforced concrete structures appear to be the most extensively tested use case for ontology-based cost estimation (Ma et al., 2013; Liu & Ma, 2015; Niknam & Karshenas, 2015; Im et al., 2021; Yun, 2021). The application of national specifications and standards further constrains the transferability of such approaches (Liu & Ma, 2015; Liu et al., 2016; Abanda et al., 2017). Moreover, broad implementation and evaluation of these ontology-based methods under different conditions remain largely unexplored.

Against this background, the present research focuses on a specific category of infrastructure projects – small-scale railway stations – and adopts a holistic perspective on cost management, ranging from the cost framework to the analysis of cost data for future projects. This study examines the entire project type to better understand relationships between various cost line items and aims to establish a structured cost data model that enables granular yet continuous cost updates.

Background

A. Cost management and BIM application

Cost management activities – such as cost estimating, monitoring, and control – are core tasks in any AEC project. Despite their importance, traditional cost estimation practices face persistent challenges (e.g., limited information sharing and weak collaboration between design and construction teams) that affect total project cost (Moses et al., 2020). The total expenditure of a project is often unknown until after the conceptual design phase and, in some cases, even after construction has been completed. As a result, cost overruns remain a pervasive problem across projects and countries.

To address this issue, BIM should be embedded in costing processes as a key component of the sector's digital transformation. 5D BIM encompasses "a cost-dependent view of a BIM model in which budget line items are associated with specific measurable features of model objects," enabling both the prediction of future project costs and the control of actual costs (Eastman et al., 2011). Numerous studies have shown that 5D BIM improves communication through cost visualization, reduces errors via automated quantity take-off, saves time due to faster quantity determination, as well as supports informed decision-making (Eastman et al., 2011; Monteiro & Martins, 2013; Abanda et al., 2017). Nevertheless, limitations in model data quality, software compatibility, interoperability, and process integration persist (Bender & Stoy, 2021; Signorini et al., 2025).

Although 5D BIM has delivered measurable benefits in specific estimation workflows, the identified challenges have not been addressed comprehensively. Several studies proposed 5D BIM workflows that largely preserve traditional cost-management practices rather than transforming them (Abanda et al., 2017; Baldrich Aragó et al., 2021; Pishdad & Onungwa, 2023). For example, billing, tendering, and cost tracking are frequently executed using conventional documentation rather than being driven directly by BIM models. Information discontinuities and the lack of data reuse in cost management therefore persist throughout the project life cycle, mirroring conventional practice.

The reason for these disconnects in the information system of cost management is the lack of semantic interoperability. Cost data are fragmented, inconsistent, and often context dependent, which makes their integration across different phases of the project life cycle particularly challenging (Signorini et al., 2025). Existing BIM standards such as IFC (Industry Foundation Classes), IDM (Information Delivery Manual), MVD (Model View Definition), and BCF (BIM Collaboration Format) provide technical frameworks for information exchange; however, they do not sufficiently address the semantic structuring of cost-related information (Di Martino et al., 2020).

On one hand, information granularity fluctuates across project phases: too little detail is available during early planning, whereas excessive detail appears in later stages, complicating meaningful cost analysis. BIM model data, on the other hand, are suitable for cost calculation only at specific levels of detail (Monteiro & Martins, 2013). Moreover, the building-element-based perspective used for cost estimation in the early project stages shifts toward a process-based perspective in the tendering and construction phases (Fürstenberg et al., 2023). Due to these limitations, the problem of information discontinuities in cost management cannot be resolved solely through 5D BIM workflows.

B. Ontological approach in cost management

To address semantic interoperability in the AEC sector, researchers have increasingly turned to ontologies and knowledge-based systems. Ontologies, in particular, provide a shared conceptual model for structuring cost data across systems and project phases (Anumba et al., 2008). This enables consistent cost information management, supports interoperability, and fosters a shared understanding among diverse stakeholders (Anumba et al., 2008). Ontologies can also align with existing standards such as ISO 12006, Uniclass (NBS, 2025), MasterFormat (CSI, 2025), Construction Classification International (CCI) based on the ISO/IEC 81346, and the ISO 19650 series, which emphasize structured information organization (Di Martino et al., 2020).

A growing body of research has explored ontology-driven frameworks for cost estimation and management (e.g., Lee et al., 2014; Im et al., 2021; Cassandro et al., 2023). These studies have developed either building-component-based (Ma et al., 2013; Abanda et al., 2017) or resource-based ontologies (Lee et al., 2014; Liu et al., 2016), often focusing on elemental costing (Abanda et al., 2017; Cassandro et al., 2023) or specific use cases (Liu & Ma, 2015; Yun, 2021). While such ontologies demonstrate potential for automated reasoning, enhance data integration, and improve cost estimation accuracy, they also reveal limitations. Many approaches either overlook process-oriented aspects of cost management or fail to bridge the gap between building-component-based and activity-based cost perspectives. As Staub-French et al. (2003) and subsequent studies highlight, a comprehensive ontology must integrate both perspectives to support the full range of cost management tasks.

Despite significant progress, no unified, industry-wide ontology for cost management has been established in the AEC sector. First, existing efforts remain fragmented across domains and often lack broad applicability (e.g., Liu et al., 2016; Hagedorn et al., 2025) or scalability (e.g., Lee et al., 2014; Liu & Ma, 2015; Yun, 2021). Second, the standardization of cost-related information remains a significant obstacle to national implementation (Cassandro et al., 2023). Third, as Akinyemi et al. (2018) note, different ontologies embody different conceptualizations of the domain, complicating integration and reuse. Moreover, most studies focus on the cost estimation of structural works, with limited attention to other project types or construction works (e.g., Niknam & Karshenas, 2015; Cassandro et al., 2023). There is therefore a continued need for ontology-based research and development that can provide semantic interoperability among stakeholders, support both object- and process-oriented perspectives, and ensure consistent, comparable, and reusable cost information.

Materials and Methods

A. Methodological approach

The methodology combines empirical, conceptual, and case study methods. An iterative research process was applied throughout the study to refine and improve the results. The outcome of this work is a conceptual framework that has been partially implemented and subjected to application-oriented validation, while full-scale implementation remain the subject of ongoing research.

Step 1: Analysis of the current situation in the AEC industry. An empirical study was conducted to assess the implementation status of the BIM methodology in cost planning, cost estimation, and cost management among selected stakeholders in the German AEC industry, including clients, designers, and contractors. This qualitative, exploratory study is currently under review.

Step 2: Literature review on ontological approaches in cost management. A comprehensive review was performed to identify existing solutions for achieving semantic interoperability.

Step 3: Definition of the case study approach. This step included: (a) assessing the degree of project standardization; (b) selecting the project type; and (c) developing a reference project.

Step 4: Ontology development strategy. The framework development was guided by the principles of Ontology Development 101 (Noy & McGuinness, 2001), adapted for small-scale public projects.

Step 5: Implementation and application. The proposed model for cost-information and knowledge structuring was implemented for the definitive cost estimate and applied to a focused subset of Bill of Quantities (BoQ) items from a reference project in order to assess its practical applicability. The selected cost-item descriptions were semantically analysed and structured, and cost and geometric data were integrated through the reuse of existing ontologies.

This study is grounded in two key assertions. First, component-based tendering, contracting, billing, and cost control are prerequisites for the comprehensive BIM application in cost management. Such process orientation is essential to establish consistent links between project delivery and model-based information structures, thereby enabling structured information reuse in future projects. Second, direct allocation of both estimated and actual costs to BIM model components is necessary to achieve structured, component-oriented cost analysis and continuous cost tracking.

B. Ontology development strategy

To develop an ontology-based framework for cost management, we adapted iterative methodological steps commonly used in prior work (e.g., Noy & McGuinness, 2001; Park & Shin, 2023):

1. Determine the domain, scope and purpose of the ontology (ontology requirements specification).
2. Survey & assess existing ontologies for potential reuse, with emphasis on those in the AEC domain.
3. Acquire domain knowledge by enumerating key terms and relationships among them.
4. Represent knowledge formally by specifying classes, class hierarchies and defining class properties.
5. Create instances to verify adequacy for static information storage.

C. Ontology requirements specification

The aim of the ontology-based framework is to enable better and more transparent cost management for small-scale public infrastructure projects using BIM, while representing cost-related information. The intended user groups are clients, planners, and contractors. Envisioned applications include: (a) cost planning; (b) cost tracking by building component, asset, and station type; (c) comparison of tender, contract, and executed costs; (d) generation of cost benchmarks for follow-up projects.

Following Seiß et al. (2025), the requirements are divided into non-functional (coverage and completeness, consistency, usability, extensibility and reusability, clarity and conciseness) and functional requirements, expressed via competency questions derived from the target applications, e.g.: (1) How much does a building component cost during the development, planning, and construction phases? (2) What are the cost parameters or cost items for a building component, considering its characteristics and project requirements (scope of works and work conditions)?

D. Available existing ontologies

Ontologies comprise terms, taxonomies, hierarchies, and relationships, as well as articulate the linkage between information and knowledge for a specific task and domain (Park & Shin, 2023). Farghaly et al. (2023) highlighted the proliferation of ontologies and the challenges associated with maintaining and updating them; consequently, they emphasized the need to assess the reuse potential of existing ontologies before developing new ones. Furthermore, ontology mapping is required to achieve information interoperability, enabling two or more information sources to exchange and reuse data.

To enable granular analysis of costs by building component or asset, the ontologies considered must cover building design and construction, cost estimation, cost items, work items, elementary resources, cost data structures, and cost management processes among different project stakeholders. The following ontologies were examined with respect to reuse potential: Digital Construction Ontologies (DiCon), Building Product Ontology (BPO), IFC Ontology (ifcOWL), Quantity (QUDT), Construction Resources (CR) Ontology, Cost Item (CI) Ontology.

Case Study

A. Description of the reference project

A typical railway station project is used as a case study to address semantic interoperability and to develop domain-specific solutions for AEC projects. The railway station domain was selected because: (a) it exhibits a high degree of standardization; (b) such project types are rarely considered in the research literature; and (c) these projects encompass both building and infrastructure construction.

Standardization is widely recognized as a prerequisite for BIM implementation (Moses et al., 2020), for the effective use of 5D BIM (Nast et al., 2023), and for the development of domain-specific ontologies (Signorini et al., 2025). In this context, standardization provides the basis for semantic interoperability, and BIM aligns closely with the integration of standardized building components.

The German railway company DB InfraGO AG has established construction standards for all major facilities within the railway station domain (DB InfraGO AG [a], 2025). These standards apply to planning, engineering, and construction activities at passenger stations and comprise standard drawings and details, sample service specifications (BoQ), structural design calculations, technical specifications, and approved building components. Additionally, a BIM component library provides a digital foundation for project information content (DB InfraGO AG [b], 2025).

Transport stations constitute a specific category of building projects within the infrastructure sector and are of considerable relevance to public construction. A typical railway station project, however, does not correspond to large central hubs such as Berlin, London, or Paris. In Germany, approximately 80–90% of railway stations are small-scale facilities with side platforms (around 9,300 stations) (DB InfraGO AG [c], 2023) (see **Fig. 1**). Adopting a holistic perspective on small-scale projects enables findings to be scaled or transferred to other public infrastructure facilities – such as bus stops, rest areas, or petrol stations – while accounting for contextual differences.

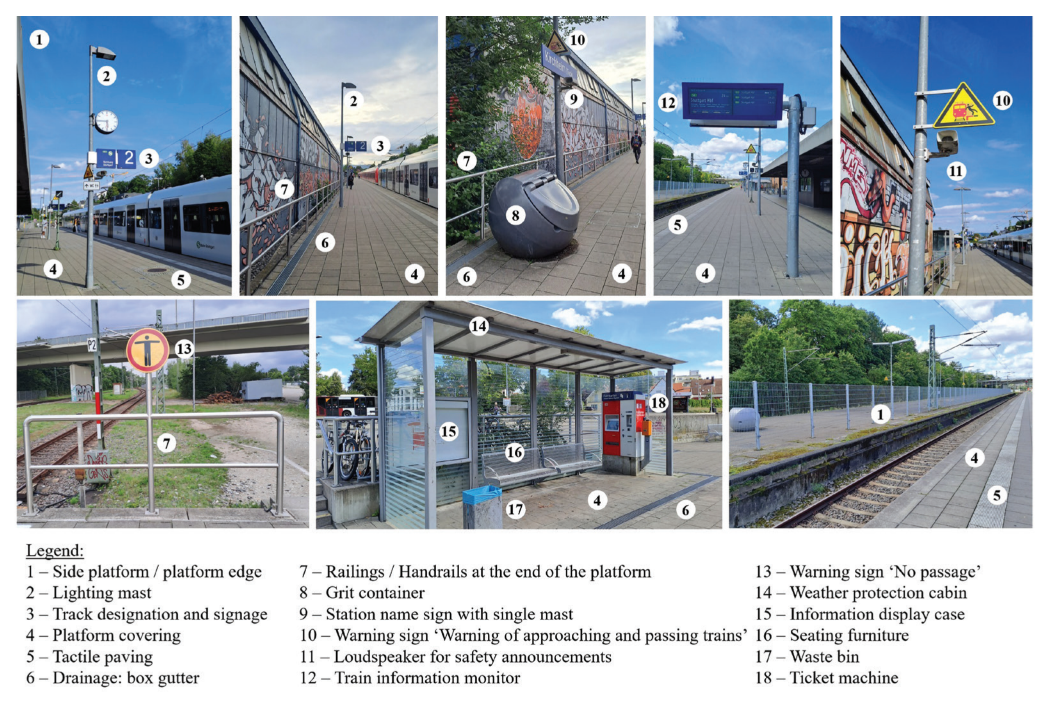


Fig. 1

Typical railway station project and examples of construction standards.

A reference project was developed as a case study, reflecting the typical characteristics of small-scale railway stations. The project involves the renovation of a passenger station, including access routes and lighting, as well as the modernization of platform equipment. The core scope is the construction of a new side platform – elevated and extended to ensure accessibility and improve infrastructure. The new construction closes the service gap between locations A–B and is designed in a contemporary style, with a length of 140 m, an average width of 2.50 m, and a height of 76 cm.

In Germany, stations are rarely built on greenfield sites; instead, projects typically entail the comprehensive reconstruction and renovation of existing facilities. In the reference project, the existing platform will be fully deconstructed and replaced at the same location. All structural elements – including platform edges, foundations, surface covering, and underground cabling – will be dismantled and substituted with new facilities.

The construction process is divided into three phases:

- **Phase 1** (*subject to track closures*): Site clearance and establishment of construction facilities; deconstruction of the existing platform, foundations, and lighting; installation of the ballast bed.
- **Phase 2** (*subject to track closures*): Demolition of platform edge foundations; construction of the new Platform 1, including foundation works for the weather protection cabin; relocation of signaling equipment; installation of underground cabling and drainage pipes; construction of new drainage channels; installation of new lighting and equipment.
- **Phase 3:** Construction of platform access routes and bicycle racks; installation of new handrails; dismantling of construction-site facilities; restoration of surrounding areas.

B. Cost management process

Project management in railway station projects encompasses processes for cost estimation, cost management, and cost control. The public client is responsible for commissioning, reviewing, and managing all technical cost calculations and financing activities. All cost-relevant information is stored within the client's information system. Planners and contractors obtain this information from the client, process it within their internal workflows, and reuse it for project deliverables such as cost estimates, quotations, invoices, and cost-control documentation. Fig. 2 provides an overview of the principal phases of cost management from the public client's perspective. Cost-related processes are mapped to the key project roles while the corresponding documents and data formats are illustrated as examples.

1. **Cost framework** or **rough estimate** derives from requirements planning and comprises initial calculations of planning and construction costs based on the project objectives: *Total project value = Rough cost estimate (planning + construction costs) + risk surcharge.* This "first number" forms the basis for the project order, the procurement of design services, and project financing. The aim is to capture all costs for the project execution, using empirical data and key performance figures.

   For the reference project, construction costs can be allocated to: *building structures* (side platform, access route, weather protection cabin), *technical installations* (lighting system – lighting masts), *customer information* (wayfinding, information, and warning signage; tactile guidance system for visually impaired users; dynamic display boards), *travel essentials* (ticket machine), *cleanliness* (waste bins, grit containers), *additional costs* (e.g., site preparation or ancillary building costs), and *risk allowances on construction costs* (e.g., limited design maturity).

2. **Preliminary estimate** is a rough calculation based on preliminary planning. Planning costs are divided into project management, planning, and construction supervision. Construction costs are organized into cost groups to provide a detailed and transparent overview. The resulting breakdown supports project decision-making, with the aim of identifying the most economical solution.

   For the reference project, construction costs allocated to building structures are subdivided into *platform body* and *platform covering*. Cost items mapped from the cost framework are represented across the following areas: demolition, new construction, additional construction, related measures, construction-site setup, safety measures, and other measures.

3. **Budget estimate** is based on design planning. The resulting, more granular breakdown of construction costs, forms part of technical planning and project management. The aim is to set target values (the budget) for the forthcoming contracts.

   In the reference project, cost items are broken down in greater detail. For example, new platform body costs are subdivided into: *platform-edge construction, earthworks, excavation* *enclosure, cable duct, installation of new empty conduits,* and *protection of existing cables*. The new platform covering includes a new *cable-duct cover, concrete boards, railings*, and other associated items.

4. **Tendering and awarding of contracts** or **definitive estimate** require the preparation of a BoQ – the service specification – which bidders complete with unit rates. The service specification should cover all construction works required for the project. Planners prepare the BoQ on behalf of the client, and contractors price their bids. Prior to contract award, negotiations are conducted and bids may be adjusted. The aim is to procure the required construction works and determine construction costs as accurately as possible. The outcome is a definitive cost estimate aligned with the awarded services.

   For the reference project, the BoQ can be structured into the following chapters: *general infrastructure services* (e.g., technical processing, construction-site setup and clearing, traffic management), *platform body* (e.g., earthworks, drainage works, concrete works, underground cable works, demolition), *platform covering* (e.g., drainage works, underground cable works), *cables and wires, lighting system, installation works, electrical engineering auxiliary services, platform equipment.*

5. **Construction cost control** is derived from approved construction invoices and is carried out successively for completed works. Services that deviate from the contract – or quantity increases exceeding 10% – must be recorded as a supplementary item and are processed through the standard invoicing procedure. Cost control is complete once all final invoices have been submitted and all construction works have been executed. The aim is to capture the actual costs.

   In the reference project, service specification items (BoQ items) constitute the billing positions. The contractor's invoices are based on these items, and any deviations must be substantiated accordingly.

6. **Cost monitoring** encompasses cash flow planning and controlling the use of financing. The aim is to oversee incurred costs and implement corrective actions when deviations arise.

   In the reference project, cost monitoring activities are aligned with the project stage.

7. **Analysis of cost data** should be conducted no later than the end of the project, ideally as part of a lessons learned process. Actual costs incurred per BoQ item must be determined, forming the basis for deriving cost elements. The aim is to develop reliable parameters for future projects, including reference values for all cost development stages.

In the reference project, cost parameters and items are defined for each project phase. Numerous information sources – such as project descriptions, transport requirements, design and tendering documents – are essential for effective cost management. Project-related data may exist in various forms: documents, data schemas, or BIM models. Throughout the project life cycle, cost information and BIM objects are consolidated within, or linked across, multiple data structures.

The following data structures are typically required: project plan, financing, BIM model, cost parameter, cost item (element), contracting unit, BoQ, facility unit structures. For accurate cost determination, product properties, quantities, measurement units and rules are crucial – both for individual building components and for the overall construction. Document analysis revealed that identical information was often created repeatedly by different stakeholders but was seldom reused. This occurred because similar content was expressed differently across software applications and information systems, preventing alignment of corresponding data structures.

C. Cost information based on BIM

Data and information derived from BIM models are intended to support the cost management

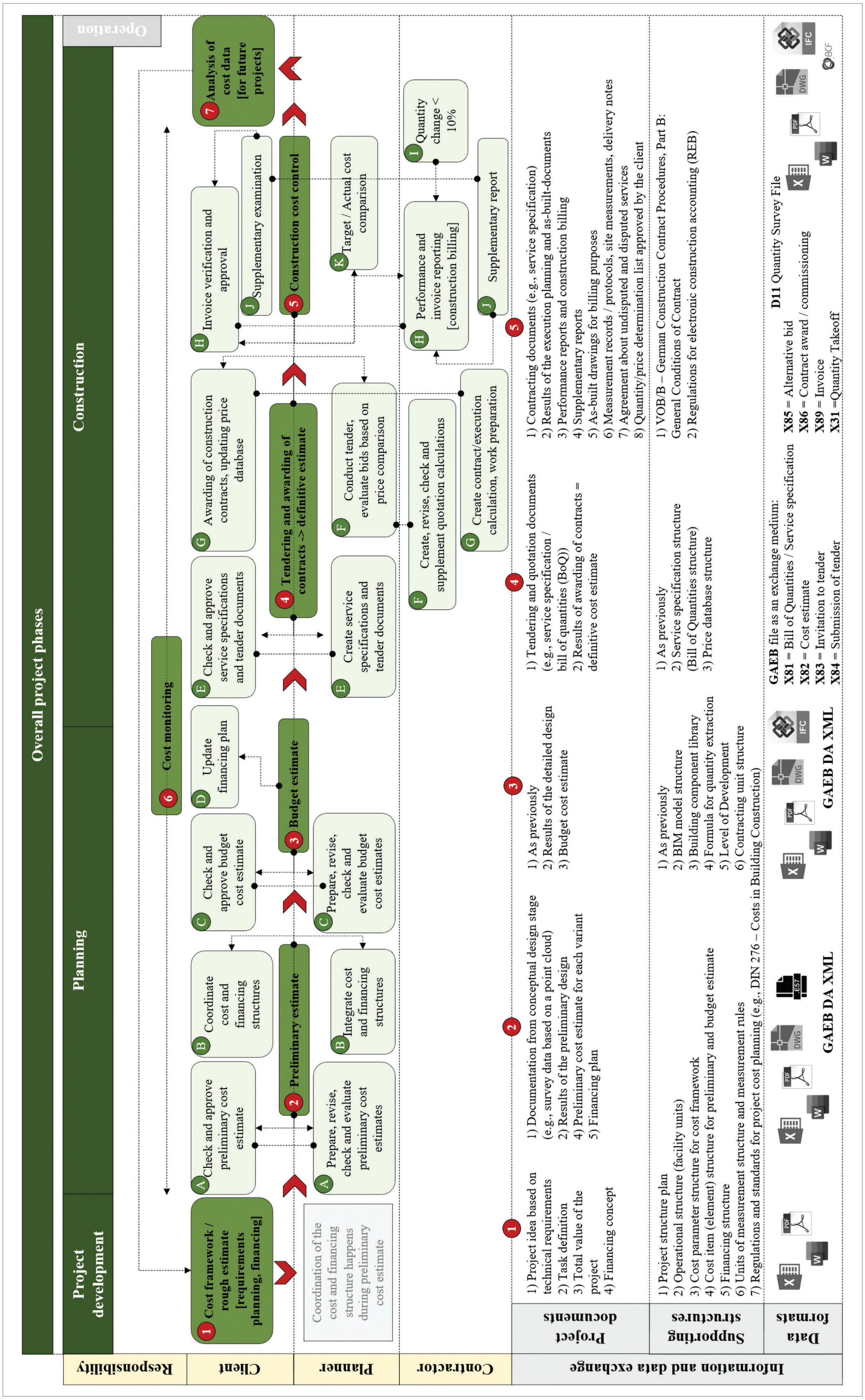
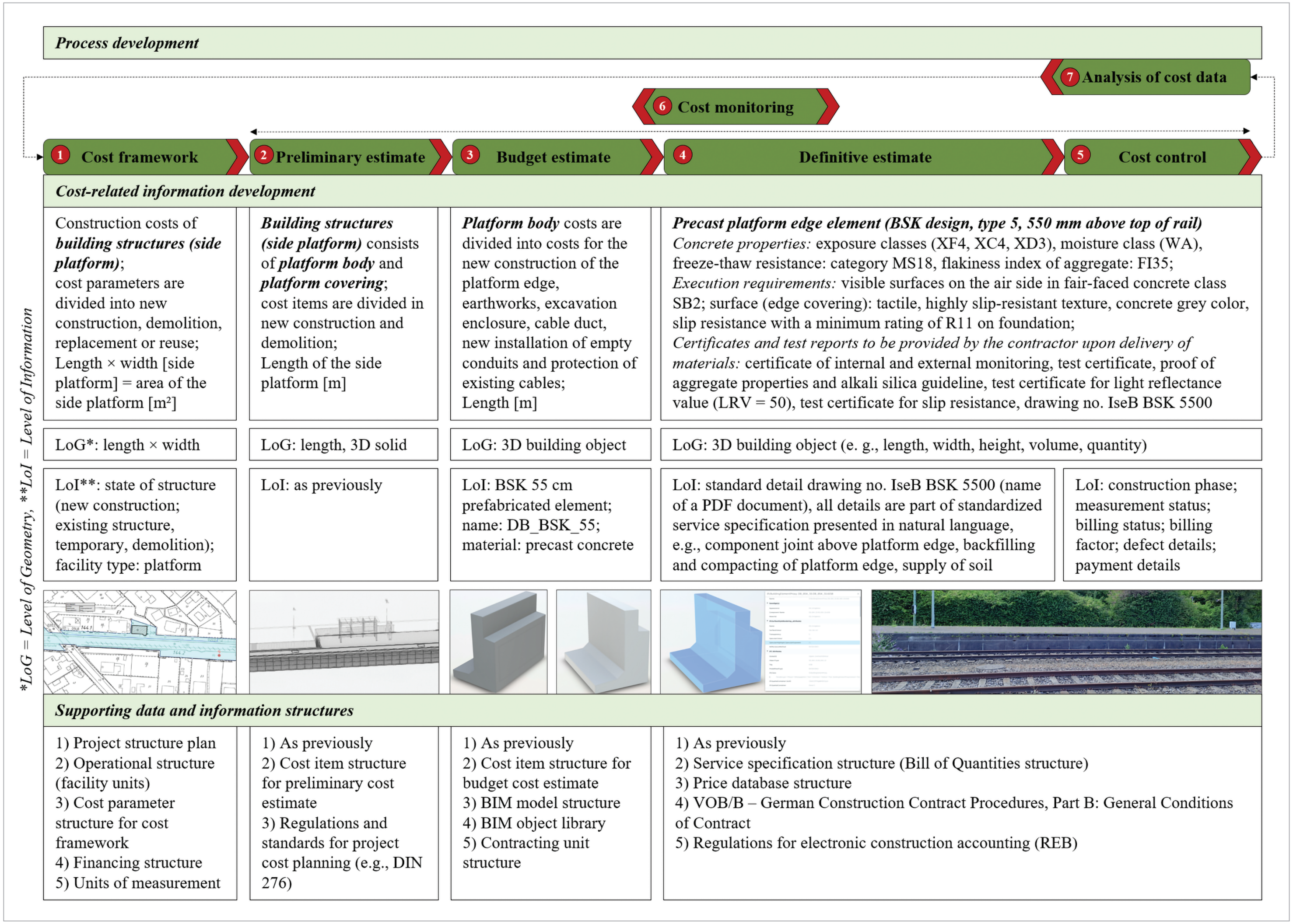


Fig. 2

Process map for cost estimation, cost management, and cost control.

process of the reference project. To achieve this, two fundamental questions must be addressed: (1) What information is required during each phase of the cost management process? and (2) How do building components evolve throughout these phases?



	① Cost framework	② Preliminary estimate	③ Budget estimate	④ Definitive estimate	⑤ Cost control
Cost-related information development	Construction costs of ***building structures (side platform)***; cost parameters are divided into new construction, demolition, replacement or reuse; Length × width [side platform] = area of the side platform [m²]	***Building structures (side platform)*** consists of ***platform body*** and ***platform covering***; cost items are divided in new construction and demolition; Length of the side platform [m]	***Platform body*** costs are divided into costs for the new construction of the platform edge, earthworks, excavation enclosure, cable duct, new installation of empty conduits and protection of existing cables; Length [m]	***Precast platform edge element (BSK design, type 5, 550 mm above top of rail)*** *Concrete properties:* exposure classes (XF4, XC4, XD3), moisture class (WA), freeze-thaw resistance: category MS18, flakiness index of aggregate: FI35; *Execution requirements:* visible surfaces on the air side in fair-faced concrete class SB2; surface (edge covering): tactile, highly slip-resistant texture, concrete grey color, slip resistance with a minimum rating of R11 on foundation; *Certificates and test reports to be provided by the contractor upon delivery of materials:* certificate of internal and external monitoring, test certificate, proof of aggregate properties and alkali silica guideline, test certificate for light reflectance value (LRV = 50), test certificate for slip resistance, drawing no. IseB BSK 5500	
	LoG*: length × width	LoG: length, 3D solid	LoG: 3D building object	LoG: 3D building object (e. g., length, width, height, volume, quantity)	
	LoI**: state of structure (new construction; existing structure, temporary, demolition); facility type: platform	LoI: as previously	LoI: BSK 55 cm prefabricated element; name: DB_BSK_55; material: precast concrete	LoI: standard detail drawing no. IseB BSK 5500 (name of a PDF document), all details are part of standardized service specification presented in natural language, e.g., component joint above platform edge, backfilling and compacting of platform edge, supply of soil	LoI: construction phase; measurement status; billing status; billing factor; defect details; payment details
Supporting data and information structures	1) Project structure plan 2) Operational structure (facility units) 3) Cost parameter structure for cost framework 4) Financing structure 5) Units of measurement	1) As previously 2) Cost item structure for preliminary cost estimate 3) Regulations and standards for project cost planning (e.g., DIN 276)	1) As previously 2) Cost item structure for budget cost estimate 3) BIM model structure 4) BIM object library 5) Contracting unit structure	1) As previously 2) Service specification structure (Bill of Quantities structure) 3) Price database structure 4) VOB/B – German Construction Contract Procedures, Part B: General Conditions of Contract 5) Regulations for electronic construction accounting (REB)	

*LoG = *Level of Geometry*, **LoI = *Level of Information*

Fig. 3

Process and cost-related information development based on the platform edge component.

Fig. 3 demonstrates that BIM objects play only a limited role. Cost-relevant information resides primarily in the service specification. From the BIM model, only the length can be extracted during

Phase 3 *Budget estimate* and the number of platform edges during Phase 4 *Definitive estimate.* Earlier phases of cost estimation do not substantially benefit from the 3D representation, as many inputs required for modelling are not yet available. A significant proportion of cost-related information is expressed in natural language and is therefore not machine-readable. Following construction, costs are typically analyzed only at a highly aggregated level for use in subsequent projects.

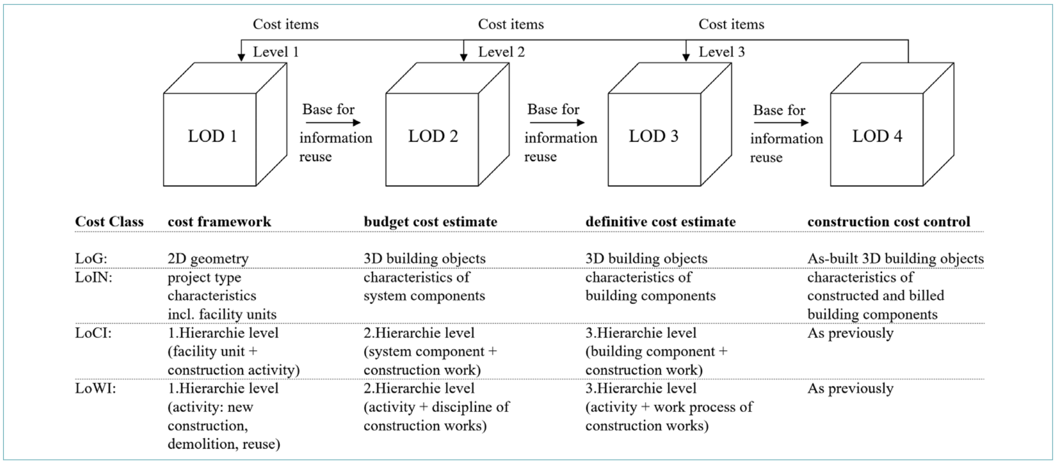
Another important characteristic of cost estimation is the transition from component-based to process-based costing. Initially, costs are calculated and assigned per component. Subsequently, attention shifts to the construction services required to produce these components. Cerezo-Narváez et al. (2020) describe that as a sequence: **cost** *(cost of performing)* → **activity** *(work to be performed)* → **product.** This sequence presents significant challenges for integrating the BIM and cost management domains.

Results

A. *Proposed model for knowledge structure*

Analysis of cost estimate data from the reference project revealed that there is often no significant difference between preliminary and budgeted cost estimates. Building on the single-phase planning method (Frankenstein et al., 2024), which has already been implemented in practice, cost development can generally be structured into four phases. These phases represent the main cost classes, mapped to the LOD concept, that is further characterized by four dimensions: Level of Geometry (LoG), Level of Information Need (LoIN), Level of Cost Item (LoCI), and Level of Work Item (LoWI) (see Fig. 4).

The following data and information structures constitute the common denominator for the proposed framework: (1) Product Breakdown Structure (**PBS**), partially aligned with the facility structure; (2) Cost Breakdown Structure (**CBS**), derived from the cost parameter or item structure; and (3) Work Breakdown Structure (**WBS**), organized by the construction condition (new construction, demolition, reuse). The construction condition is a leading parameter for the primary allocation of cost items.



Cost Class	cost framework	budget cost estimate	definitive cost estimate	construction cost control
LoG:	2D geometry	3D building objects	3D building objects	As-built 3D building objects
LoIN:	project type characteristics incl. facility units	characteristics of system components	characteristics of building components	characteristics of constructed and billed building components
LoCI:	1.Hierarchie level (facility unit + construction activity)	2.Hierarchie level (system component + construction work)	3.Hierarchie level (building component + construction work)	As previously
LoWI:	1.Hierarchie level (activity: new construction, demolition, reuse)	2.Hierarchie level (activity + discipline of construction works)	3.Hierarchie level (activity + work process of construction works)	As previously

Fig. 4

Concept of cost-related information and knowledge development.

Fig. 5 presents an overview of the framework for cost-related information and knowledge for small-scale railway stations. In developing the proposed knowledge model, findings from previous studies (Liu et al., 2016; Im et al., 2021; Cassandro et al., 2023; Signorini et al., 2025) were consolidated and transferred to the context of station projects, taking into account the perspective of public clients and the requirement specifications of the new framework. In defining the classes and subclasses of the new ontology-based framework, existing structures were either adopted (e.g., *product, system component, scope, construction work, activity, work, elementary* *resource, labor/equipment/material resource, property/characteristic*) or adapted (e.g., *facility unit, building component, cost item*).

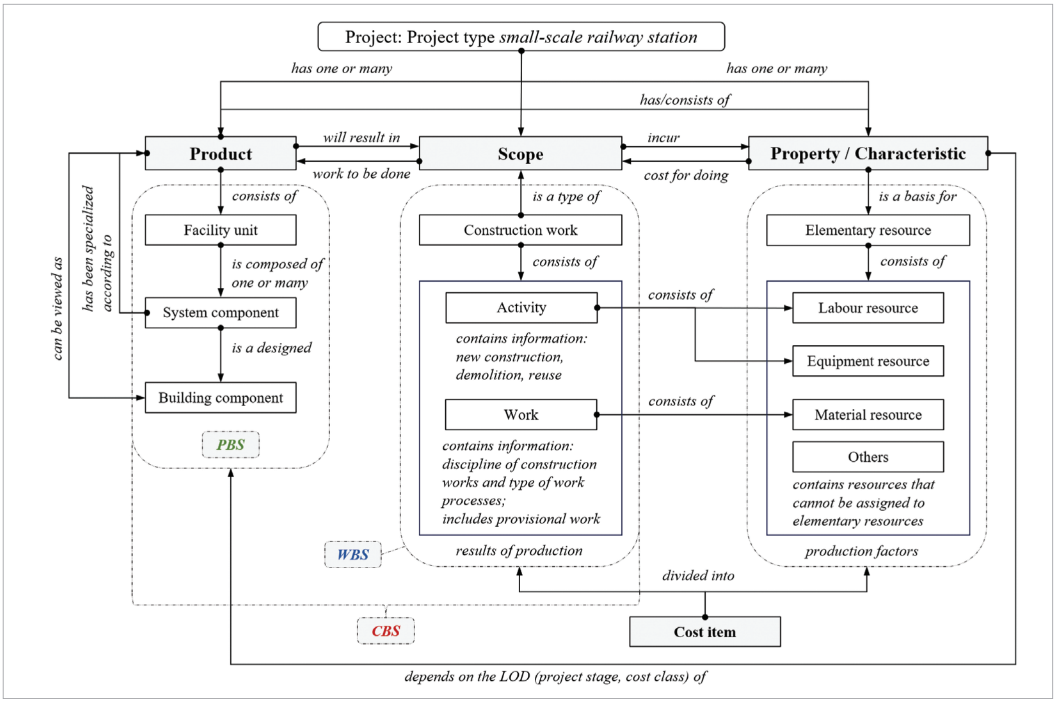


Fig. 5

Proposed model for cost-information and knowledge structure.

B. *Taxonomies and properties*

The proposed model establishes an explicit linkage between products, scope, and cost analysis via product properties. The taxonomies for products, construction works, and costs are illustrated in **Figures 6–8.** The figures show exemplary extracts of these taxonomies.

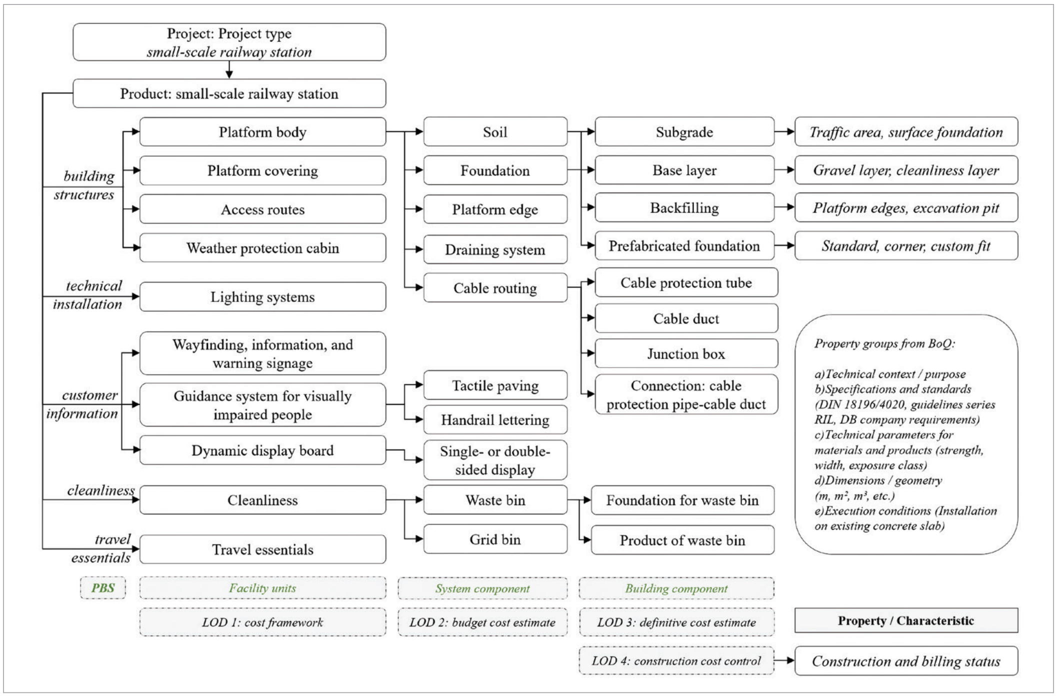


Fig. 6

Overview of taxonomy for products (exemplary extract).

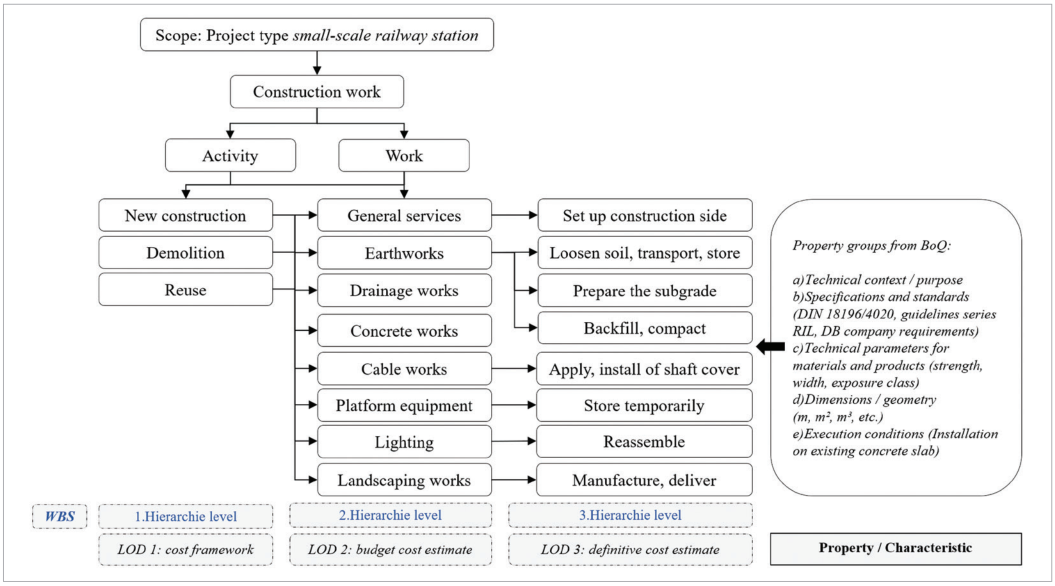


Fig. 7

Overview of taxonomy for construction works (exemplary extract).

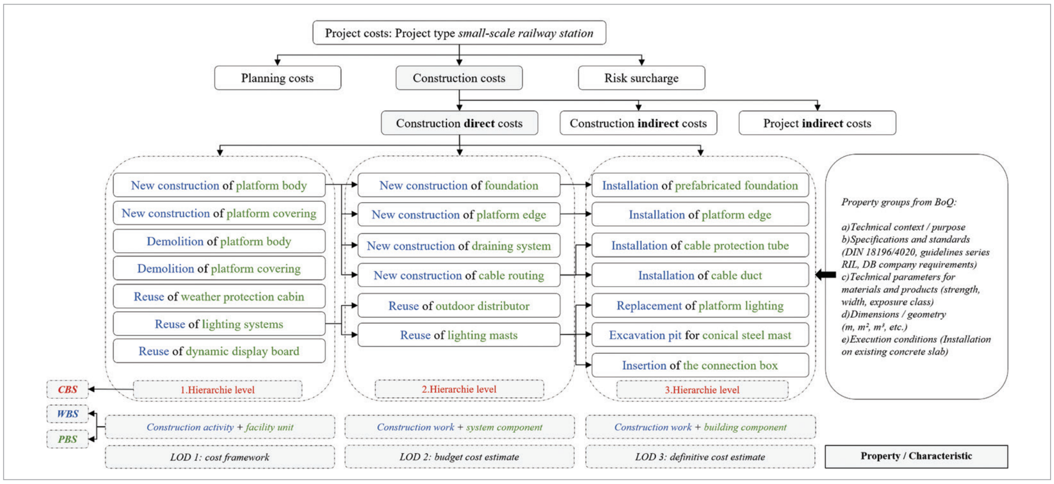


Fig. 8

Overview of taxonomy for costs (exemplary extract).

Project represents the defined project type of small-scale railway stations. *Product* is an object formed or modified through one or more work processes. It comprises three subclasses: facility unit, system component, and building component. *Building component* denotes a physical product that is part of the facility; it can be classified by multiple criteria (e.g., material, location, function). *System component* refers to an assembly of building components and/or specific mechanisms that together constitute a product. *Facility unit* represents higher-level functional units within the station (e.g., weather protection cabin, lighting system). Cost-related information may be associated with any of the three product subclasses. *Scope* corresponds to construction works and comprises activities and works. An activity is the action to be performed to execute the construction work and consists of labor and equipment resources. A work is the physical outcome delivered by the construction work and consists of material resources. Labor, equipment, material, and other resources are elementary resources that contractors must account for when pricing construction works. *Property/Characteristic* encapsulates cost-relevant information typically found in the BoQ and replaces it as a structured, ontology-based carrier of attributes. All classes and subclasses possess their own properties and characteristics, which can be used to further specialize items, specify detailed requirements, or compile attribute lists. This class also supports the integration of geometric data derived from BIM. Together, these definitions ensure consistent alignment of product characteristics with scope (construction works) and cost items, enabling traceable cost analysis across the taxonomy layers.

C. Implementation and application of the proposed model

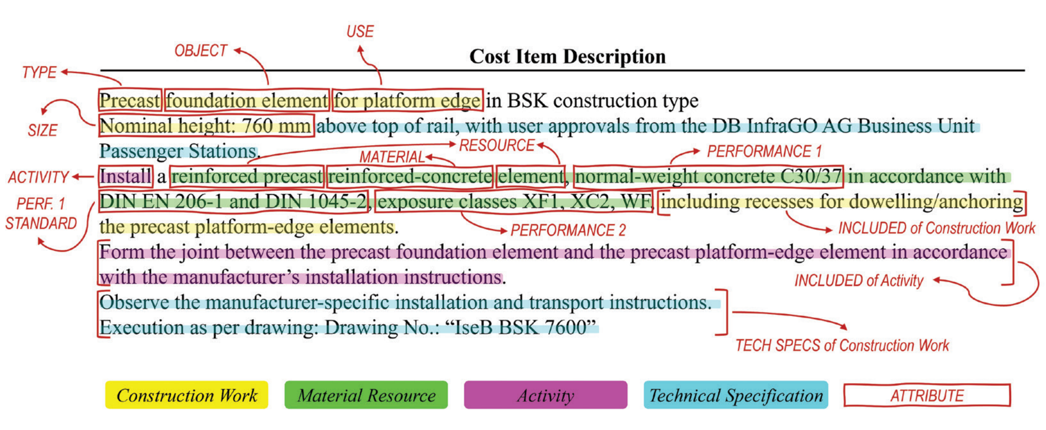
The proposed model was implemented for the **definitive cost estimate (LOD 3)** in order to assess its applicability to cost management in small-scale railway station projects. The approach was applied to a focused subset of the BoQ items. Specifically, five representative cost items were selected, covering three key construction elements that are fundamental to most railway station projects and include both construction and demolition activities: the precast foundation element, the precast platform edge (see Fig. 3), and the precast corner element. Although only a few cost items were analyzed, the selected elements are standardized and recurrent in railway station projects and therefore suitable for an initial assessment of the approach's applicability and transferability.

The experiment comprised two main steps: (a) semantic analysis and structuring of the selected cost-item descriptions; and (b) the integration of cost and geometric data. For data integration, existing ontologies were reused, and the resulting unified cost-geometry graph was queried to examine the relationship between modelled construction elements, semantic classifications, and cost information.

D. Semantic structuring of cost items

As shown in Fig. 9, cost-item descriptions often contain heterogeneous information on construction work, material resources, activities, and technical specifications within a single unstructured textual entry. Following the ontology-based approach proposed by Signorini et al. (2025), these cost items can be decomposed into semantically distinct components, such as *construction work object* (e.g., precast foundation element), *activity* (e.g., installation), *material resource* (e.g., reinforced precast element), *technical and performance specifications* (e.g., compliance with manufacturer-specific instructions).

This semantic structuring highlights recurring weaknesses of conventional cost-item descriptions, particularly semantic overlap, implicit assumptions, and ambiguities between objects, processes, and requirements. By making these distinctions explicit and representing the information through clearly defined attributes, such as object, type, material, use, and performance, the ontology-based approach improves the consistency and transparency of cost-items representation. At the same time, it preserves the original meaning of the descriptions and enables their machine interpretability.



Cost Item Description

Precast foundation element for platform edge in BSK construction type
Nominal height: 760 mm above top of rail, with user approvals from the DB InfraGO AG Business Unit Passenger Stations.
Install a reinforced precast reinforced-concrete element, normal-weight concrete C30/37 in accordance with DIN EN 206-1 and DIN 1045-2, exposure classes XF1, XC2, WF, including recesses for dowelling/anchoring the precast platform-edge elements.
Form the joint between the precast foundation element and the precast platform-edge element in accordance with the manufacturer's installation instructions.
Observe the manufacturer-specific installation and transport instructions.
Execution as per drawing: Drawing No.: "IseB BSK 7600"

Fig. 9

Semantic structuring of cost item *Precast foundation element for platform edge.*

E. Establishing cost – geometry linkage

To establish semantic links between cost and geometric data, three ontologies were used: *ifcOWL*, to generate an RDF (Resource Description Framework) representation of the IFC model and access geometric objects and their properties; the *Cost Item Ontology*, to formalize cost items based on the semantic structuring described above; and the *Construction Resource Ontology*, to define explicit relationships between geometric objects and cost items.

By integrating these ontologies, a unified knowledge graph is created in which cost items are linked to their corresponding geometric objects (see **Fig. 10**). This enables automated quantity take-off from IFC-derived data and its consistent assignment to cost items within a shared semantic framework. As a result, quantities, cost-item definitions, and unit prices are integrated into a single machine-interpretable model. This supports the generation of a computable and extensible BoQ, in which cost values can be updated or compared across scenarios.

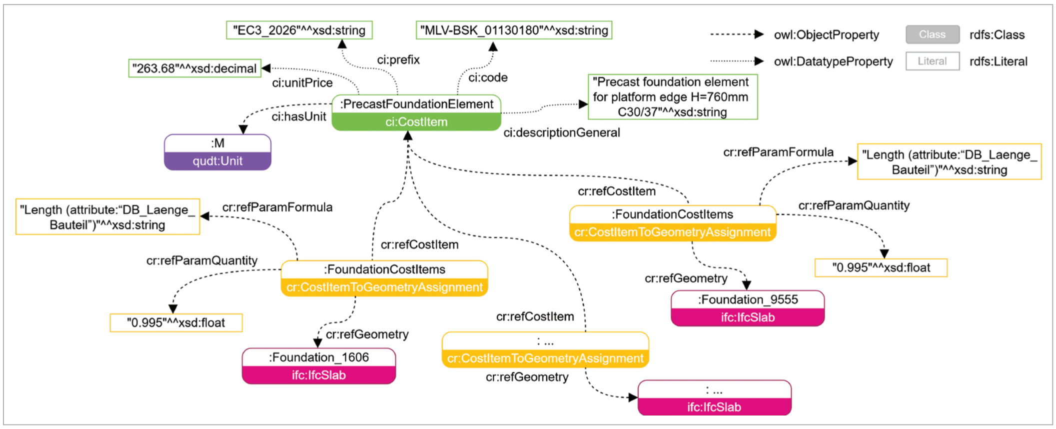


Fig. 10

Unified knowledge graph for precast foundation element.

Finally, the resulting knowledge graph is queried using SPARQL. The queries serve as a verification mechanism for the internal consistency and operational applicability of the ontology-based model rather than for statistical analysis. The query results consolidate each cost-geometry association in a single row, linking the construction object to its cost item, quantity reference, unit price, unit of measurement, and calculation formula. Ordered by construction object, the dataset supports systematic inspection and validation. The results show that cost and geometric information can be consistently retrieved from one integrated model.

Discussion and Conclusions

As Collison and Parcell (2005) emphasize, knowledge itself cannot be managed; rather, only the environment that enables its creation and sharing can be managed. In construction, semantic interoperability is a prerequisite for such an environment, particularly in cost management where data fragmentation is prevalent. The proposed ontology-based framework provides a structured and semantically consistent foundation for managing cost information. It reduces subjectivity in cost estimation, improves the comparability of bids and price analyses, and establishes explicit links between early-stage cost estimates and actual construction performance. Moreover, implementing ontologies outside native systems enables the integration of heterogeneous data sources and thereby supports a more holistic perspective on cost management.

This paper focuses on a specific use case, namely a small-scale railway station project. Compared with previous studies, this research (1) addresses a new, concrete subdomain of infrastructure construction; (2) seeks to overcome transferability and generalizability limitations through the use of widely adopted terminology and classification systems; (3) integrates and verifies existing ontology-based approaches; and (4) covers the development of cost-related information across the main project stages.

The case study draws on real project data and describes cost management processes at a comparatively high level of detail. The analysis proceeds from general, broadly applicable processes to the specific procedures required for the selected project type. The contribution of BIM models to the overall cost management process is illustrated, and the results show how BIM-based geometric and semantic information can support cost calculation, while the exact LoG and LoI requirements remain context-dependet. The study constitutes an application-oriented validation rather than a full-scale technical evaluation of the proposed model. In the experimental part, the relationship between geometry and cost information is demonstrated on the basis of selected BoQ items.

Remaining challenges concern stakeholder consensus on terminology and classifications, as well as the integration of the ontology-based cost management approach into existing digital ecosystems – such as BIM platforms. Unlike CCI, which primarily provides a standardized classification and reference designation structure for lifecycle-consistent identification, the ontology proposed in this study focuses on the semantic integration of component-, process-, and cost-related information for BIM-based construction cost management. Nevertheless, alignment with CCI/RDS appears promising for improving interoperability and lifecycle stability and is an important direction for future research.

By embedding structured knowledge into infrastructure delivery processes, this research contributes a further building block toward more transparent, efficient, and sustainable management of public infrastructure projects. Future work will include a prototype platform implementation and expert validation to further verify scalability and usability.

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Nomenclature table

Abbreviation	Description	Abbreviation	Description
5D BIM	Building Information Modelling for cost estimation	*ISO*	International Organization for Standardization
AEC	Architecture, Engineering, and Construction	*OWL*	Web Ontology Language
BCF	BIM Collaboration Format	*LoCI*	Level of Cost Item
BIM	Building Information Modelling	*LOD*	Level of Development
BoQ	Bill of Quantities	*LoI*	Level of Information
BPO	Building Product Ontology	*LoG*	Level of Geometry
BSK	Platform edge component	*LoIN*	Level of Information Need
CBS	Cost Breakdown Structure	*LoWI*	Level of Work Item
CCI	Construction Classification International	*MVD*	Model View Definition
CI	Cost Item Ontology	*NBS*	National Building Specification
CR	Construction Resources Ontology	*PBS*	Product Breakdown Structure
CSI	Construction Specifications Institute	*QTO*	Quantity Take-Off
DiCon	Digital Construction Ontologies	*QUDT*	Quantities, Units, Dimensions and Types Ontology
DIN	German Standardisation Institute	*RDF*	Resource Description Framework
GAEB	Joint Committee for Electronics in Construction	*REB*	Regulations for electronic construction accounting
IDM	Information Delivery Manual	*Uniclass*	Unified Construction Classification
IEC	International Electrotechnical Commission	*XML*	eXtensible Markup Language
IFC	Industry Foundation Classes	*WBS*	Work Breakdown Structure
ifcOWL	IFC Ontology		

Use of AI Tools in the Preparation of the Manuscript

During the preparation of this article, the authors used ChatGPT (OpenAI; GPT-5.4 Thinking) to support language editing and improve text clarity. The authors reviewed and revised the content independently and assume full responsibility for the accuracy and integrity of the work.

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