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ENHANCING CONSTRUCTION SAFETY MANAGEMENT: STRUCTURING AND INTEGRATION OF DATA THROUGH IFC

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Abstract

Estimating and managing construction site safety costs remains a critical issue within the construction sector's digital processes. Despite the adoption of Building Information Modeling (BIM), safety-related cost items are still in natural language and commonly handled using spreadsheets and unstructured PDF documents, resulting in documents containing disjointed data and unrelated to the information model and temporary site elements. This research proposes an innovative methodology to structure and standardize safety cost data using the Industry Foundation Classes (IFC) schema, enabling their integration into the digital model. Unlike prior work focused on general construction costs, this study applies IFC-based structuring specifically to safety-related costs, a rarely addressed domain. It develops a specific data architecture for safety elements, such as barriers, signage, scaffolding, and personal protective equipment, characterized by granular attributes and semantic relationships. The method was tested through a case study of an urban construction site using IFC-compliant models. The results highlight the feasibility and benefits of integrating safety costs into the BIM model, improving traceability, accuracy, and the potential for automation in managing safety costs. The study addresses a significant gap in current practices and paves the way for structured and interoperable management of safety costs and geometry data in construction and civil engineering projects.

Keywords: Safety Cost Estimation, Construction Safety, IFC, Structured Cost Data, Interoperability.

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1. Introduction

Estimating and managing safety costs is a central issue in the design and planning of construction sites, particularly concerning protecting workers' health and safety, and compliance with regulatory obligations. In the Italian context, these costs are defined as the set of expenses necessary for the implementation of the prevention and protection measures provided by the Safety and Coordination Plan (PSC), as indicated by Legislative Decree 81/2008 [1] and Ministerial Decree September 9, 2014 [2]. These costs are quantified analytically using the regional cost catalogue (price list). At the European and international level, the situation is more heterogeneous. Although Directive 92/57/EEC [3] imposes an obligation to draw up a safety plan, there is no uniform regulatory constraint to distinguish and structure safety costs formally. In other jurisdictions, such as in the United Kingdom [4] or according to the ISO 45001 standard [5], the focus is on “resource availability” and risk management, but no technical criteria are defined for the economic representation of security interventions. The introduction of Building Information Modeling (BIM) has opened new opportunities for the digitization of design and management processes in construction. However, most BIM implementations focus on geometric elements, leaving data belonging to different domains in the background, including project costs and/or safety costs. Such information is often still managed disjointedly through static and fragmented files, with no possibility to relate the data within them (Excel, PDF) and in natural language, preventing systematic analysis, traceability, and validation [6]. To address this gap, this study proposes an innovative methodology for construction management, involving the representation and integration of safety costs within the digital information model, leveraging the Industry Foundation Classes (IFC) standard. The aim is to exploit the potential of IFC to structure not only geometric data but also cost information, ensuring full interoperability across domains. This approach shifts from static document-based practices to a

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dynamic, queryable information model (IM). Cost items become structured entities within the model, enabling validation and informed decision-making. The method proposed was tested on a case study, related to an urban construction site phase in Italy, employing models compliant with the IFC4 standard and open-source tools for data processing, such as the *IfcOpenShell* Python library, data querying, and validation.

2. Literature Review

Construction site safety cost management represents an area that has still not been explored in the digital streams of the construction industry. Despite the growing popularity of Building Information Modeling (BIM), cost items associated with safety elements or construction site resources are often unstructured, expressed in natural language, and processed through heterogeneous and noninteroperable tools such as spreadsheets and PDF files [6]. Numerous studies have explored the link between BIM and safety management, but with approaches that rarely go as far as semantic and interoperable encoding of Costs. Lu et al. [7] propose a system based on fuzzy logic integrated in a BIM environment for risk assessment at construction sites. Although methodologically interesting, the work does not include a structured representation of costs or their direct association with information objects. Similarly, Fang et al [8] use a knowledge graph to map hazards at construction sites, contributing to the theme of semantic formalization, but leaving out the economic and quantitative aspects. A cross-cutting contribution is made by Charef et al. [9] who systematically analyse the advanced dimensions of BIM (4D-7D), highlighting the usefulness of 5D BIM for integrating costs into the information model. However, the analysis does not distinguish between general and security-specific items, which remain absent in the architectures proposed by the research. In parallel, Shoar et al. [10] discuss the automation of cost estimation in engineering services using machine learning, focusing on forecasts and cost overruns, i.e., discrepancies between forecast costs and actual costs incurred, but ignoring the semantic structuring of the data and its integration into the model. Turner et al. [11] offer an integrated view of Industry 4.0 technologies on construction sites, including Digital Twin, IoT, and Cyber Physical System (CPS). The latter represent integrated systems in which physical and digital components interact in real time, enabling automated monitoring and control of worksite activities and resources. However, the work of Turner et al. does not propose concrete tools for the formal representation of cost items. Therefore, despite the increasing number of studies on cost estimation and safety management in construction, a clear methodological gap persists in the digital structuring and integration of safety-related cost items within BIM-based workflow. Existing approaches often limit themselves to general cost domains or rely on natural language descriptions, lacking semantic formalization and interoperability across platforms. Moreover, current implementations of 5D BIM tools typically offer static and fragmented associations between geometric objects and cost data, without supporting real connections between data and a subsequent automated validations or traceability of cost-object relationships. Although recent contributions have proposed the use of IFC entities such as *IfcCostItem* for representing unit cost elements [6, 12], these efforts predominantly focus on construction works and resources, leaving safety-related costs largely unexplored. Consequently, no established methodology currently exists for the standardized encoding, association, and verification of safety cost data within the IFC schema. This study addresses this gap by introducing a novel approach for the semantic representation and integration of safety-related cost items in the digital model, enabling structured, queryable, and verifiable cost data to support enhanced safety planning and management in construction projects.

3. Methodology

The proposed methodology leverages the IFC schema to develop an IM that integrates both geometric and cost data, enabling their relationship and extraction in a structured and interoperable format. This integration supports the generation of a safety-related cost estimation from IM, ensuring full traceability and consistency across data domains. The absence of structured data for construction sites and safety cost management within digital IM is a major critical issue. From this gap emerges the main objective of this research: application of an innovative approach for the representation and integration of safety costs in IM. The main aim of the research is to develop an innovative approach for generating a digital safety-related cost estimation directly from the Construction Site Information Model (CoSIM). To this end, the IFC schema is used to define structured cost objects that are explicitly linked to the geometric elements of the model. The approach adopted consists of several operational steps, each represented graphically in Figure 1. In the first phase, identified as Step 1.a, the identification of information objects within the IFC model was carried out, to develop a cost estimation prototype geared toward the management of equipment and construction site elements that are also useful for site safety. Due to the limited scope of the article, validation was conducted on a limited number of selected elements (shown in Figure 2), such as weighted mesh panel, construction site boxes, including offices, meeting rooms, dressing rooms, access control room, and toilets, and tower crane included as an operational support element. Consequently, as illustrated in Figure 1 at "Step 1.b," the cost items structured in IFC format according to the structure developed by the research group [6, 12] were defined starting from the price list of Lombardy Region (Italy). The result of this step was the creation of a dedicated database containing the cost items formalized according to an ontological structure, consistent with the IFC data model. The second step, illustrated in "Step 2" in Figure 1, involved the integration of geometric and cost information through entity relationships. In this phase, the IFC model was queried to extract the geometric entities (IfcElement) for defining the cost estimation, while the cost item database, previously structured IFC, was queried to identify the cost entities. The main objective was to define explicit semantic relationships between geometric objects and cost objects. These associations were made through the *IfcRelAssignsToControl* entity, which allows an object (*IfcProduct*) to be linked to a cost item (*IfcCostItem*) in the same information model. Finally, the last phase, illustrated in Step 3 of Figure 1, involved the definition and extraction of cost estimation views through the aggregation of previously structured cost item entities. These views were formalized through the *IfcCostSchedule* entity, which allows the configuration of both "global and partial cost estimation views", focused on specific functional elements or categories. The "partial views" were obtained by filtering entities based on semantic links to cost items, thus enabling the production of thematic economic frameworks directly integrated into the information model. The resulting *IfcCostSchedules* are associated with the project (*IfcProject*) and are dynamic cost estimations integrated into the information model according to the specific needs of the designers. The testing of the proposed methodology was applied to the CoSIM phase of a school project in the Lombardy region of Italy. The construction site phase analysed refers to the completion of the excavation works. Figure 2 shows the BIM model phase highlighting the elements considered in the proposed method, created using ACCA Software®'s CERTUS-HSBIM and exported in IFC 4 ADD2 TC1.

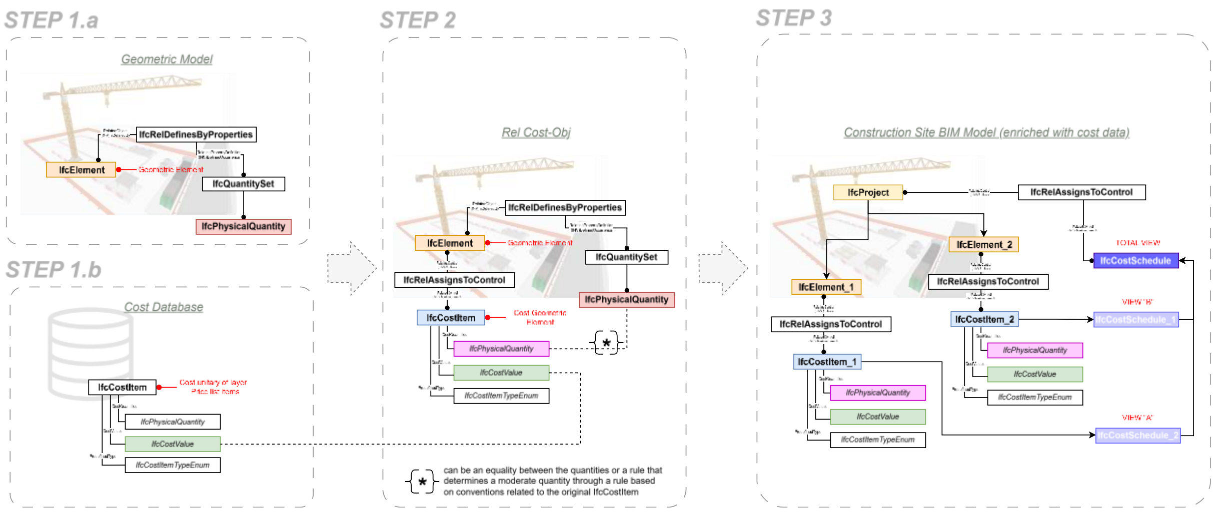

Figure 1 - Methodological workflow for integrating security costs into the IFC information model

4. Results

The analysis of the IFC model produced several significant results useful for verifying the effectiveness of the association process between geometric entities and cost items. The version of the case study model was verified and confirmed as conforming to the IFC4 standard. Then, information regarding the units of measurement used in the model was extracted to ensure consistency in quantitative and economic calculations.

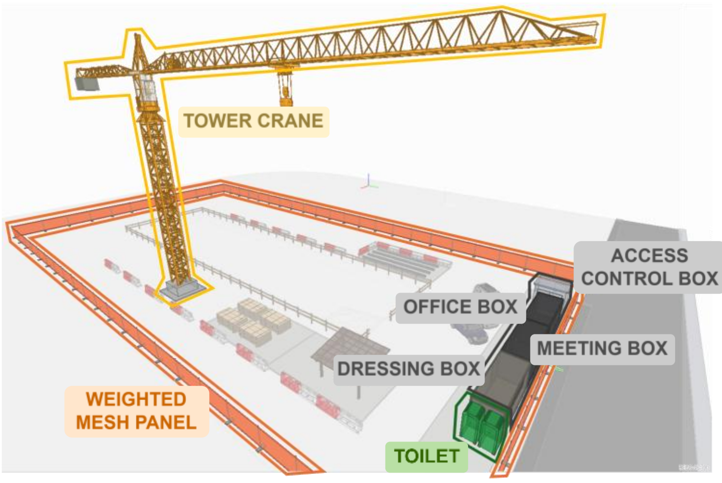

Figure 2 – IFC model of the case study with identified construction site elements for cost estimation.

The analysis covered only specific entities belonging to the *IfcProduct* hierarchy, as they represent any object referring to a geometric or spatial context. Specific objects are selected within this category. This selective choice made it possible to optimize the process, reducing information "noise". The focus was on the *IfcBuildingProxy* and *IfcRailing* classes. Thirty-seven objects belonging to the former class and 3 to the latter were detected. The use of *IfcBuildingProxy* was necessary due to the lack of specific IFC classes for modeling certain site elements, currently unsupported by the standard. For each instance, the PredefinedType attribute was analysed, and where this is valued as "UserDefined", the "ObjectType" attribute was extracted. Identifying the specific type of information object is crucial for accurately interpreting its role and characteristics within the model. All the information collected was organized into indexed data structures, enabling subsequent visualization, filtering, and association of the entities with their respective cost items in the database. After the geometric entities identification, the phase of quantity definition to be used in the cost estimation was initiated. The quantity definition was selected according to the unit of measurement provided for each price item (e.g., meters, number of elements). They were related to the duration of use (as meters/month to define the price for the first month of rental and for subsequent months, or per cad/month) to identify the correct quantity useful for cost estimation. The entire process is designed in an iterative form: multiple cost items can be associated with each item if required by the composite nature of the item or by differential computation needs (Figure 3).

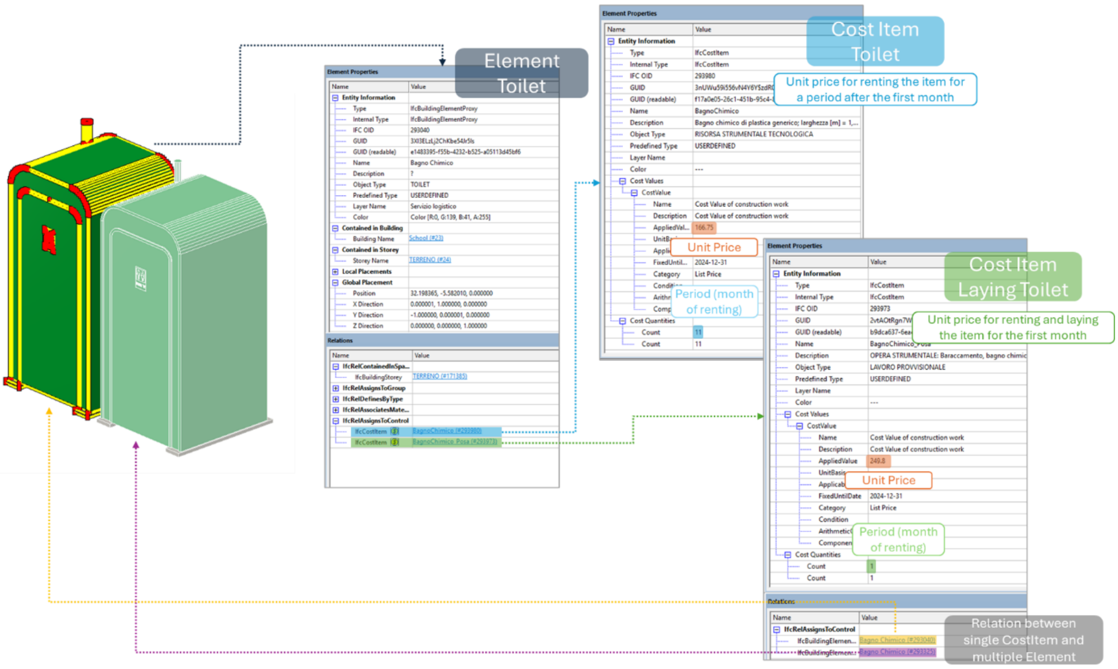

Figure 3 - IM with geometrical and cost data; example of linking a site element to multiple cost elements in the IFC environment.

Otherwise, the process continues to the next object. At the end of this phase, a BIM model is obtained enriched not only with geometric and functional information, but also with structured economic content, ready for automated extraction of the cost estimation views (Figure 4).

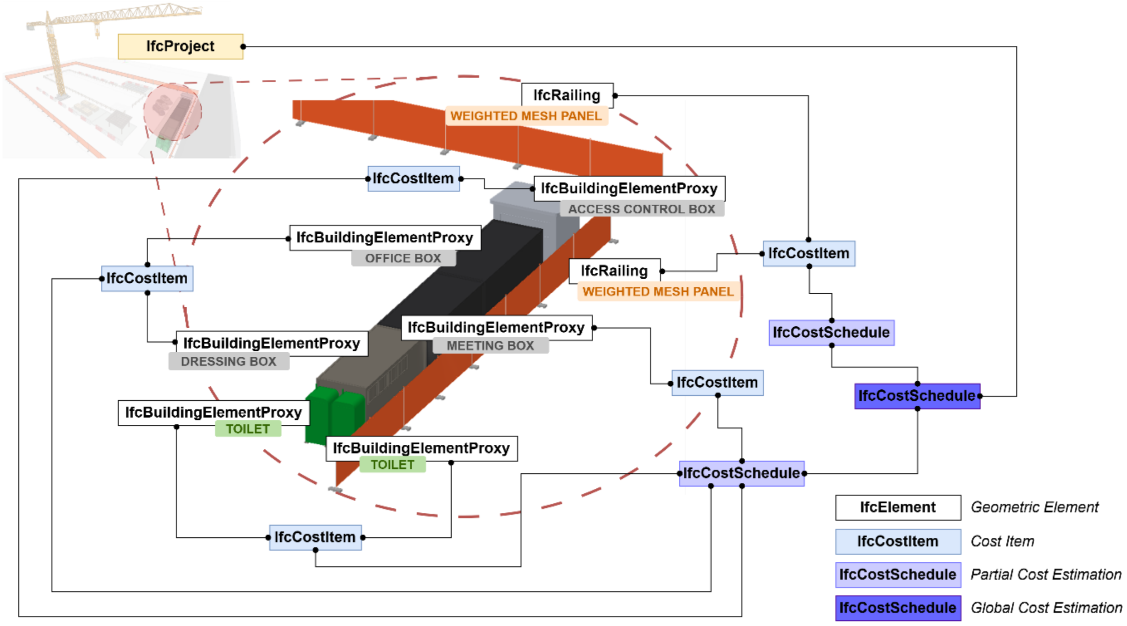

Figure 4 - IFC-based model association of site elements with multiple cost items and schedules.

5. Discussion and Conclusions

Considering the gaps identified in the literature, the proposed methodology offers a concrete opportunity to optimize the process of creating safety-related cost estimates, starting from an integrated information model. This process is still commonly carried out using static document-based tools such as spreadsheets (e.g., Excel or Google Sheets), where quantities are manually multiplied by unit prices from the cost catalogue. Furthermore, the use of current 5D BIM tools provides only fragmented and non-dynamic links between geometry and cost data, lacking mechanisms for automated data extraction, validation, or traceability. As a result, safety cost management remains disconnected from the information model, limiting integration within the overall digital workflow. The integration of safety and yard costs within the information model represents a significant step toward more structured, transparent, and interoperable construction site management. The validation results confirm how the IFC format makes it possible to overcome the traditional fragmentation between geometric, economic, and documentary content, centralizing, historicizing, and structuring the information in a single coherent and queryable digital environment.

In this way, their future validation is envisioned as the relationships between data and entities allow the development of automated/semi-automated verification procedures. The capacity to associate structured cost items (*IfcCostItem*) with the geometric elements of the model made it possible to make explicit relationships between objects and costs. This approach has proven effective not only in the automated generation of cost estimation but also in reducing errors resulting from manual operations on disjointed documents such as Excel or PDF sheets. Furthermore, by minimizing manual operations and automating the procedures for defining the cost estimation, it also decreases repetitive error-prone procedures. The adoption of a semantic, IFC domain-compliant language ensures traceability of information and the ability to perform verifications based on specific attributes (type, material, function, quantity). The use of open-source tools, such as the *IfcOpenShell* Python library, has demonstrated how it is possible to build customized and automated operational flows without having to depend on proprietary software. This is particularly relevant from the perspective of scalability and reproducibility of the method in different project contexts. The resulting model, enriched by entities such as *IfcCostItem* and *IfcCostSchedule*, supports the extraction of targeted cost estimation views, which can be configured by functional categories, time phases, or site zones. The result is a greater ability to plan and control, even in a comparative perspective between different design assumptions. The validation, although limited to a subset of construction site objects, has shown that the proposed approach is also applicable to complex domains with high information variability, such as safety on a construction site. In conclusion, an information model enriched with multi-domain data not only increases the accuracy and management of cost data but also emerges as a strategic tool for integrated site planning, management, and control, enabling automation, consistency, interoperability, and traceability. Prospects include the introduction of cross-validation and verification mechanisms between geometric and economic domains through automated consistency and congruence rules. Such developments may further strengthen the potential of the openBIM approach in managing specific costs, including site safety, making the information model a reliable and certifiable reference for the entire project lifecycle.

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