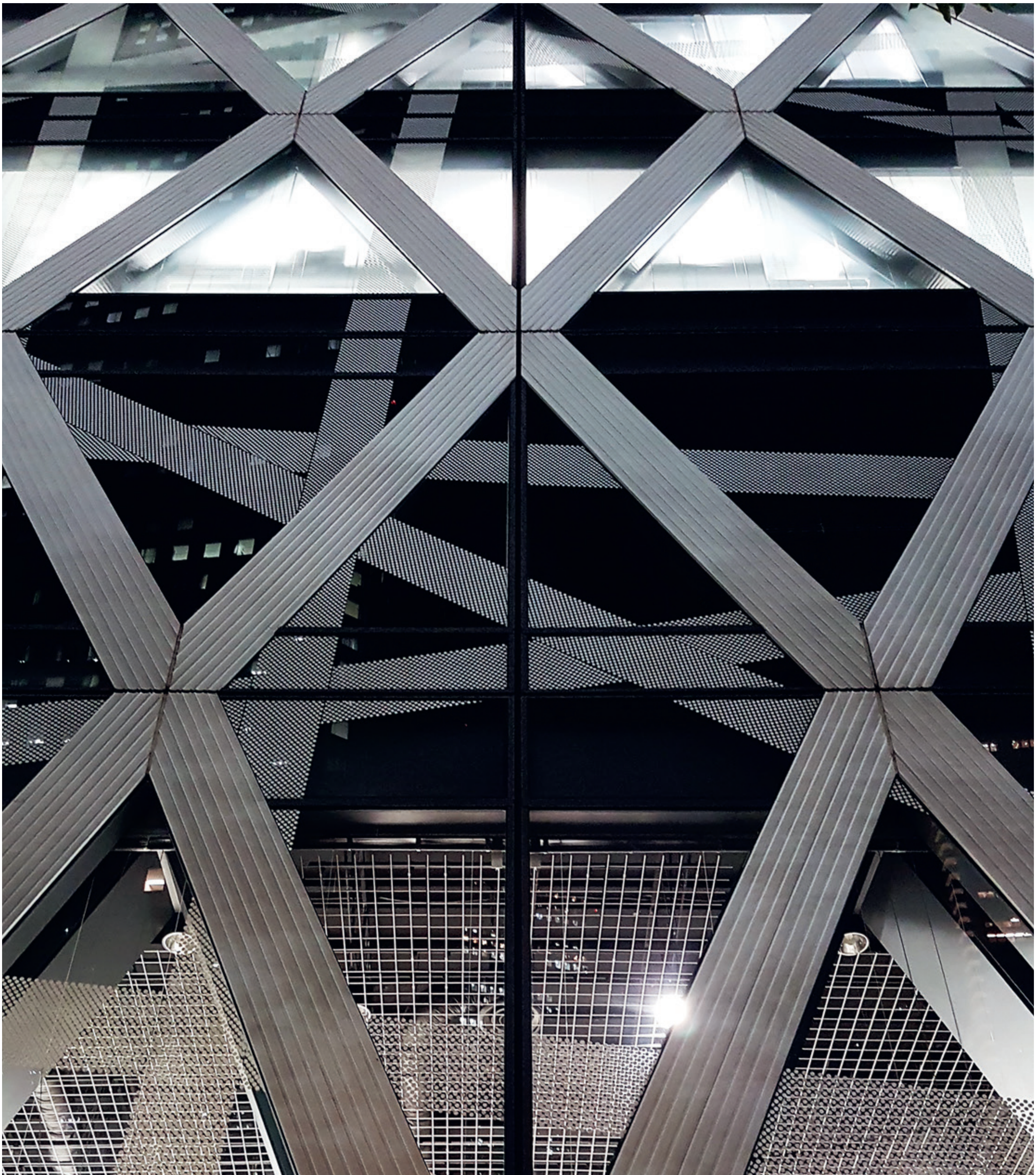

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CONSTRUCTION AND ITS INTERCONNECTIONS

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Cover illustration: Mode Gakuen Cocoon Tower in the Nishi-Shinjuku district (Tokyo, Japan) by Kenzō Tange, external view. © Riccardo Gulli, 2018

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A LINKED DATA APPROACH FOR QUANTIFICATION AND PLANNING OF CONSTRUCTION PROJECTS

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Abstract

In construction projects, the quantification of works and the related planning are critical, interdisciplinary tasks often performed through data extraction from design information models of the building or infrastructure. This paper elaborates on the development and use of a linked data model specifically designed to represent and clarify the information necessary for Quantity Take-Off and Construction planning activities. The model is developed based on existing information ontologies and is designed following the analysis of Quantity Take-Off and planning processes in engineering firms and general contractors. It intends to serve as a reference for both quantification and planning applications and processes. The resulting linked data models are designed to be interoperable with each other and with other construction ontologies such as ifcOWL, DiCon, etc., ensuring coherence with other project information, promoting standardisation of Quantity Take-Off processes, and supporting automated quantity extraction from IFC models.

Keywords

Information ontologies, Construction works, Quantity Take-Off, Construction planning, BIM.

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1. INTRODUCTION

Quantification and construction planning are complex activities that are now considered critical for feasibility analysis, the design process, and the actual construction of a building or infrastructure. They enable the estimation of key aspects of the current construction industry – costs and time – and can be used as tools to optimise capital expenditure (CAPEX) management as well as the logistics of construction investment.

Quantities Take-Off (QTO) is a process that aims to determine, calculate, or predict the amounts of resources (materials, objects, workforce, distance, etc.) required to support various tasks, such as cost estimation, construction planning, logistics optimisation, environmental assessment, and safety management. Although the term QTO is often applied across all phases of a construction process, more precise definitions tend to confine this activity to the tendering and pre-construction phases, differentiating it from the activity of quantity surveying performed during construction activities.

This process requires a relevant number of specialised resources and a lot of time, and it is usually conducted through a deep, integrated analysis of drawings, reports, project specifications, direct measurement and calculations, and usually produces a Bill of Quantities (BoQ) that acts as a base for the estimating and planning tasks. While traditionally this process was conducted manually, the advent of Building Information Modeling (BIM) has introduced automated or semi-automated protocols for the extraction and calculation of materials' quantities, and some modules dedicated to QTO have been developed within major construction project management platforms.

On the other hand, construction planning is a process that aims to define the intended process of realising a building or infrastructure, considering all the activities necessary for the successful delivery of the project. In this process, tasks are typically organised using various temporal and logical relationships, and, depending on the design or construction phase, they are represented at a specific detail level. For construction tasks, quantity estimation is crucial because it enables the calculation of the duration of each activity based on the amount of work to be executed.

Integrating construction planning and information models represents a significant evolution of this activity. However, the complexity of data on both the planning and BIM sides requires a considerable effort in organising and modelling information.

Although the impact of these tasks on the outcomes and profitability of construction projects, there is no evidence of complete and dedicated information ontologies that can act as a reference for standardisation of QTO processes and construction planning processes, and favour interoperability between systems that produce data for QTO (i.e., authoring tools) or that exploit the resulting BoQ in construction planning. As a result, existing software essentially relies on simplified assumptions rather than robust data models, shared definitions are not available, and interoperability is quite limited, causing a proliferation of *ad hoc* (and often unstable) applications.

In this context, this work presents the ongoing process of developing an ontology specifically focused on QTO and construction planning processes that can guide the development of data models for QTO applications in the tendering phase. The QTOn and ConPlan ontologies are designed to be compatible with the ifcOWL ontology and with other major ontologies (such as DiCon), relying on the extensive reuse of existing concepts, attributes, and relationships but reorganising and integrating them to fulfil the information requirements of QTO activities. After describing the resulting ontologies, this paper presents their adoption to demonstrate how the data schema can be useful in providing standardisation and efficiency in the construction quantification within the tendering activities of a large general contractor.

2. RELATED WORKS

2.1. BUILDING INFORMATION MODELLING, WORKS QUANTIFICATION, AND CONSTRUCTION PLANNING

Since the introduction of Information Technology in construction, the accuracy of quantification activities has progressively improved due to the increasing use of BIM-based design to facilitate intelligent extraction of data from building components and the development of BIM-oriented cost estimation software. Nevertheless, while many research and development efforts have focused on automating the extraction of data from information models, the crucial activity of classifying the extracted data into construction products and assigning them to cost items is still conducted manually [1]. The use of specifications such as Uni-format, MasterFormat, or CESMM4 within BIM models facilitates this process only partially, as it still requires a manual and error-prone activity of formalisation, and often these specifications are not fully aligned with the BoQ-identified items. To add complexity, design and estimations are often performed by different parties (i.e., in design-bid-build processes), making it challenging to coordinate specifications in advance. In fact, between the data extraction from models and their formalisation in the Bill of Quantities, measurement and interpretation rules must be applied according to specific guidelines and norms, such as the RICS NRM2 [2]. At the same time, the IFC standard has contributed to providing some references to work quantifications in construction projects, at least from the model side: Ruano-Ruiz [3] developed a method that relies on IFC data structure and eCOB standard to support elements filtering rules in quantification programs, while IFC can be used as a base to apply semi-automated quantification and cost estimation, decomposing models into building products according to specifications [4]. In various BIM-based approaches to work quantification, it becomes apparent that information models must be properly structured for quantification purposes. Usually, this process cannot be fully automated, but the use of standardised model templates favours the adoption and reusability of quantification algorithms and rules [5].

In recent years, digital construction sequencing of works – commonly referred to as 4D Modeling – has enhanced the processes and capabilities of planning teams, both during the design and construction phases. The introduction of applications such as Synchro 4D, Bexel, or Navisworks in the construction sector has driven the adoption of 4D processes. These applications have already been developed for integration with major planning tools, including Oracle Primavera P6 and Microsoft Project, and can import BIM models through the IFC open format. While the process is quite consolidated, the insufficient data standardisation in project schedules and models makes the production of this representation mainly manual, slow, and subject to errors.

2.2. INFORMATION ONTOLOGIES FOR CONSTRUCTION WORKS QUANTIFICATION AND PLANNING

In this direction, some research has investigated the use of semantic web technologies and information ontologies to represent the different concepts involved and to support automatic reasoning in assigning quantities to the correct BOQ items.

Staub-French [6] proposed an ontology-based approach to represent estimators' rationale for connecting building products and cost information, based on construction activities. In contrast, Ma and Liu proposed an ontology-based framework to associate objects with item prices, following specific specifications and construction methods [1], and an application to semi-automatically estimate costs, relying on the IFC data model [7].

Abanda [8] studied an ontology focused on New Rules of Measurement (NRM) that uses Semantic Web Rule Language queries to associate NRM catalogue items and IFC-defined objects (and attributes). Some research has also focused on using ontologies to relate estimations, products, and construction methods, thereby supporting contractors and owners' decisions [9]. Among others, Cassandro [10] has highlighted the importance of structured data models for cost estimation, particularly within the framework of the IFC schema.

Two significant areas emerged from this brief analysis of existing literature: on one side, QTO data models are often integrated as an appendix to larger cost estimation ontology-based approaches, and on the other, much research focuses on utilising knowledge-based systems to enhance quantity calculations from BIM models, given specific measurement indications. In both areas, no ontology has been publicly available, and applications are primarily focused on building design, with integration with existing ontologies and data models typically limited to data extraction from the IFC schema. At the same time, the construction industry considers quantification and cost estimation as two distinct but correlated domains, each requiring specific competencies and processes. Some concepts of Quantification, for instance, were also specified in the DiCon Ontology, although very briefly defined to provide context to the representation core of the ontology [11]. Integration between information ontologies and BIM environments has also been demonstrated by Simeone and Cursi [12, 13].

In construction planning, a similar quest for data models is ongoing. The DiCon ontology involved a partial representation of the planning domain [11], while some attempts have been made to frame the main concepts and relationships for specific purposes. For instance, Sigalov used graph-based knowledge representation to identify reusable process patterns [14], and Zhong developed a framework for the use of information ontologies for technical plan definition and verification [15]. The use of information ontologies and data models is then necessary to automate specific processes, such as the planning of concrete works [16] or the look-ahead planning in lean management of construction sites [17]. Information ontologies are then used to enhance collaboration [18] and to identify and mitigate risks and hazards [19].

In this context, it is then still necessary for dedicated and homogeneous ontologies for Quantity Take-Off and construction planning, able to define and organise concepts, attributes and relationships necessary for the correct management of information during the quantification and planning activities, and acting as a reference also for interoperability with other knowledge such as design, constructability, Quality Assurance and Control, cost estimations and the information models of the infrastructure.

3. RESEARCH METHODOLOGY

3.1. ONTOLOGY DEVELOPMENT

The QTOn-ConPlan ontology has been designed and developed following the Linked Open Terms (LOT) methodology [20] mainly because of:

- its effectiveness in integrating and reusing existing ontologies;
- the presence of an ontology requirements specification activity;
- its strong orientation towards industrial applications.

The first feature ensures the intended ontology's ability to be integrated with other data models corresponding to different domains in the construction process. The second one, the collection of ontology requirements, was particularly effective in shaping an ontology that adhered to the QTO processes of a general contractor and fulfilled the information needs of the different specialists involved. The industry-focused methodology also contributes to the development of customized implementations based on the proposed model, thereby facilitating its standardized adoption in quantification processes. Preliminary objectives and scope definition were crucial to identifying the ontology requirements. Conceptualisation and development have been performed using diagrams.net, enhanced with Chowlk Visual Notation, and the ontology editor Protegé, respectively. Once validated, the consequent data model has been implemented, tested, and assessed in Vision CPM, an application that supports quantifications from IFC-based models.

Ongoing research projects in the context of ontology engineering, such as DiCon [11] and COGITO [21], served as relevant methodological references for this research.

3.2. ONTOLOGY REQUIREMENTS SPECIFICATION

In construction processes, the QTO and construction planning activities involve different experts, who receive input data (i.e., models, specifications) and produce output data that affect other activities, such as cost estimating, planning, and design.

Due to its pivotal role in tendering, specialists from the following disciplines were involved in the definition of the ontology requirements, following their expertise domain:

- Quantity Take-Off;
- Building Information Modelling (authoring and analysis);
- Estimating and methods;
- Planning;
- Procurement;
- Technical coordination.

After defining the general framework for the development of this ontology, a group of experts operating in the general contractor industry was interviewed to derive a set of information requirements, as described in detail in the Ontology Requirements Specification Document (ORSD) (Tab. 1).

3.3. EXISTING ONTOLOGIES REUSE

Following the modularity principles defined by the Linked Building Data group, this research relies on the extensive reuse of existing ontologies to improve interoperability among different knowledge domains and to enable the general contractor to later build its data integration solution, relying on consolidated data models that already drive existing platforms for QTO, planning, BIM, etc.

Research on existing ontologies has been mainly conducted through both literature reviews of published papers in the AEC area and the use of online libraries and collec-

Discipline	Code	Requirement (summarized)
QTO	QTO-01	Distinguish BOQItem, price item and measures
QTO	QTO-02	Versioning of BoQs, Price Lists, measures
QTO	QTO-03	Measurement units based on international standards
QTO	QTO-04	Distinguish materials and quantity typologies
QTO	QTO-05	Measurements/estimations from different information carriers
BIM	BIM-01	Interoperability with IFC
BIM	BIM-02	Identification of quantified elements and attributes
Estimating	EST-01	Include classification systems (CESMM4, NRM2)
Estimating	EST-02	Methods of measurement and/or calculation
Estimating	EST-03	Adopted construction methods
Planning	PLA-01	Relationships with WBS for activities duration
Planning	PLA-02	Possibility to relate quantities and locations
Technical coordination	TEC-01	Quantities aggregation at high-level representation
Technical coordination	TEC-02	Actor providing the quantity value (client, consultant, QTO specialist, etc.)
Procurement	PRO-01	Quantities extracted as per BOQItem specifications

Tab. 1. *Ontology requirement specification (extract). The information requirements were obtained through interviews with specialists from various domains. © 2024, Author.*

tions. The search for existing, potentially related ontologies has been conducted using two approaches: 1) research narrowed to the subjects of construction works quantification and construction planning, and 2) broad research on information ontologies for construction projects, to find general ontologies that involve the QTO domain. For the narrowed search, the keywords used were: "Quantity Take-Off", "Construction Works Quantification", "information ontologies and cost estimation", "QTO data models", "Construction Planning Ontology", "BIM and cost estimation", "4D modeling", "5D modeling"; for the general search the keywords were: "information ontologies in construction", "linked data in construction projects". Since this research scope has only recently shown an increase in the number of publications and conferences, no specific temporal limits have been established for the literature review. Nevertheless, all the ontologies mentioned in the following table fall within the period from 2010 to 2024. Although some additional research pieces have emerged during the literature review, due to the nature of this literature review, which aims to identify information ontologies to integrate with the QTO ontology, we decided to remove from the list those research works that did not present a complete or clear ontology.

An attempt to identify a reference ontology for each domain has been made, giving preference to those ontologies that: a) are publicly available in repositories such as GitHub or b) are described in detail in the literature, with a clear description of classes, relationships, and attributes (Tab. 2) [22, 23]. In addition to those, some general ontologies have also been considered to provide high-level concepts and relationships.

Domain	Key ontology adopted	Online Availability
Informative Model	ifcOWL	Y
Procurement	PPROC (Muñoz-Soro et al., 2016)	Y
Measurement Units	QUDT	Y
Construction Planning	DiCon (processes + information)	Y
Technical Coordination & knowledge management	DiCon	Y
	IC-PRO-Onto (El-Diraby & Osman, 2011)	N
Ordered Lists	OLO	Y
Time	owl-time	Y

Tab. 2. *Ontology reuse. The list (extract) of the key ontologies adopted for the development of the QTON and ConPlan ontologies. © 2024, Author.*

4. THE INFORMATION ONTOLOGY FOR CONSTRUCTION QUANTIFICATION AND PLANNING

4.1. THE QTON ONTOLOGY AND ITS MODULES

The representation model of the QTOn ontology includes three modules:

- the Quantity Take-off module, where quantities are organised as per project specifications;
- the Quantity measuring module, dedicated to the representation of measures/data extractions performed;
- the Price List module, representing the list of works to be estimated and their specifications.

The Quantity Take-off module formalises the project Bill of Quantities and has at its core the BOQItem class, which declares the elements or materials to be quantified during the tender. Bill of Quantities is usually organised in sections, chapters, and levels based on the quantity specifications of the project and design configuration. This module also includes concepts such as WBS and PBS, enabling direct interoperability with project representation.

The Quantity measuring module includes concepts for tracing measurement information and actions, aimed at associating numerical values with BOQ items. In this module, the core class is Construction Quantity, while other classes contribute to the formalisation of measurement units and quantification typologies. As in the DiCon ontology, the QUDT ontology [24] has been referenced through alignment to provide detailed semantic specifications of units of measure, quantity kinds, dimensions, and data types. A part of this module is dedicated to interoperability with the IFC quantity set (available from IFC 2x3), which allows attaching quantities to construction elements and, consequently, automating quantity extraction from BIM models. We consider this integration relevant, particularly for tendering purposes, as it ensures coherence and consistency between the QTO model and the design model, allowing us to trace the process of quantity extraction from model elements. In this way, it is possible to manage revisions of design and QTO efficiently, solving the known problem of misalignment between design and estimation versioning.

The Price List module is dedicated to providing a representation schema of the lists of works, activities, or services that require estimation, including their specifications and features (such as measurement units). The price list can be provided by the client within the tender documents or developed by the estimating team, based on previous projects. The price list can be considered a "project-independent" set of items to be quantified, which is then mapped with the project representation to form the Bill of Quantities structure.

As shown in the diagram in Figure 1, the QTOn ontology has been designed to have direct interfaces with

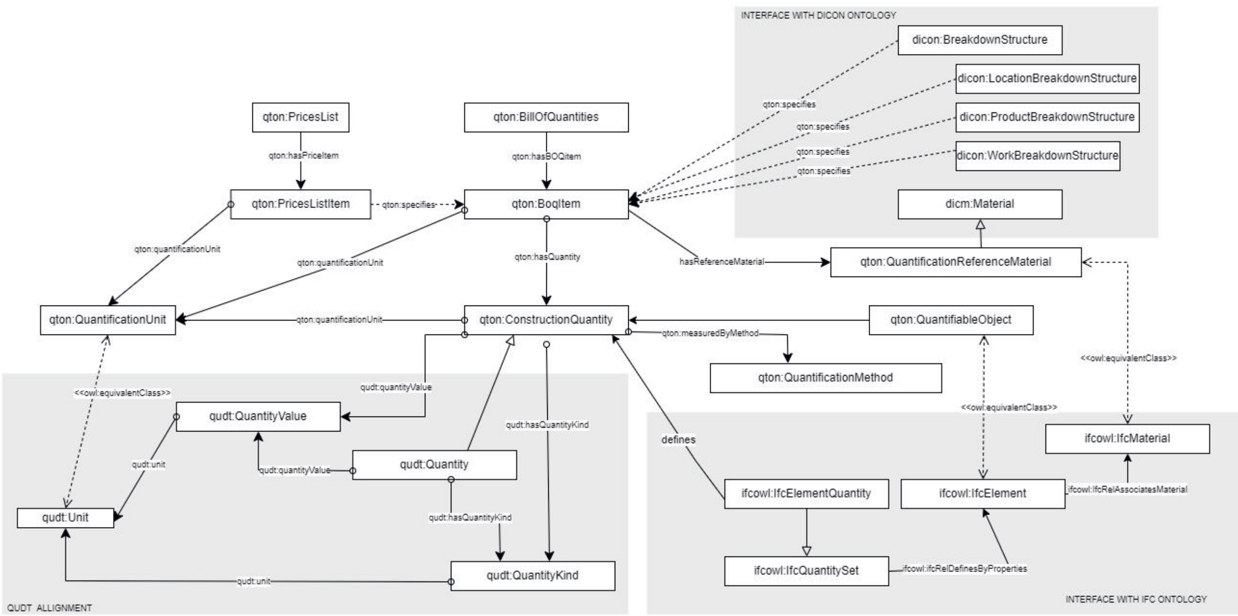

Fig. 1. *The QTOn schema. The ontology is composed of new concepts and a strong reuse of existing ontologies to enable interoperability with other knowledge domains. © 2024, Author.*

IFC and COGITO data models, both to ensure interoperability in terms of processes and to provide QTO information with the proper interpretative context.

4.2. THE CONPLAN ONTOLOGY AND ITS MODULES

As previously mentioned, the ontology for Construction Planning (ConPlan) has been aligned in particular with two major existing ontologies:

- the DiCon ontology and its sub-domains, to ensure interoperability with a general representation of the construction processes, and
- the ifcOWL ontology [25], to ensure interoperability with a standardised and open representation of the building and infrastructure, without relying on any specific data model derived from the authoring platform.

The key concept in the ConPlan ontology is the [Activity], which is the central entity in the different planning platforms, that is the main recipient of information and is used to shape the [Plan] by the formalisation of [PlanningRelation] among activities with the relevant [Lag] and [Float]. The [Activity] is also linked to other concepts, such as [WBS], [ActivityConstraint], and [Resource], which are derived from both the Dicon ontology and the data models currently adopted in practice. The configuration in time is represented through concepts such as [TimeInterval]. During our analysis and tests, we identified the need to incorporate additional concepts to provide context for the interpretation of construction planning: the [ConstructionMethod], the relationships with the [BoQItem], and the reference to a [ActivityLibraryItem], which is an item from the engineering firm's activity catalogue.

To ensure interoperability with 4D planning and, more generally, to allow interaction between planning and works models, the relationships derived from Dicon have been reconstructed in the ConPlan ontology, enabling connection with the [IfcElement] in terms of a process-product representation.

To further detail the construction planning representation, the ConPlan ontology includes some entities designed to represent and manage the [Calendar], including the [CalendarFestivity] and the [CalendarShift].

The ConPlan ontology is represented in Figure 2.

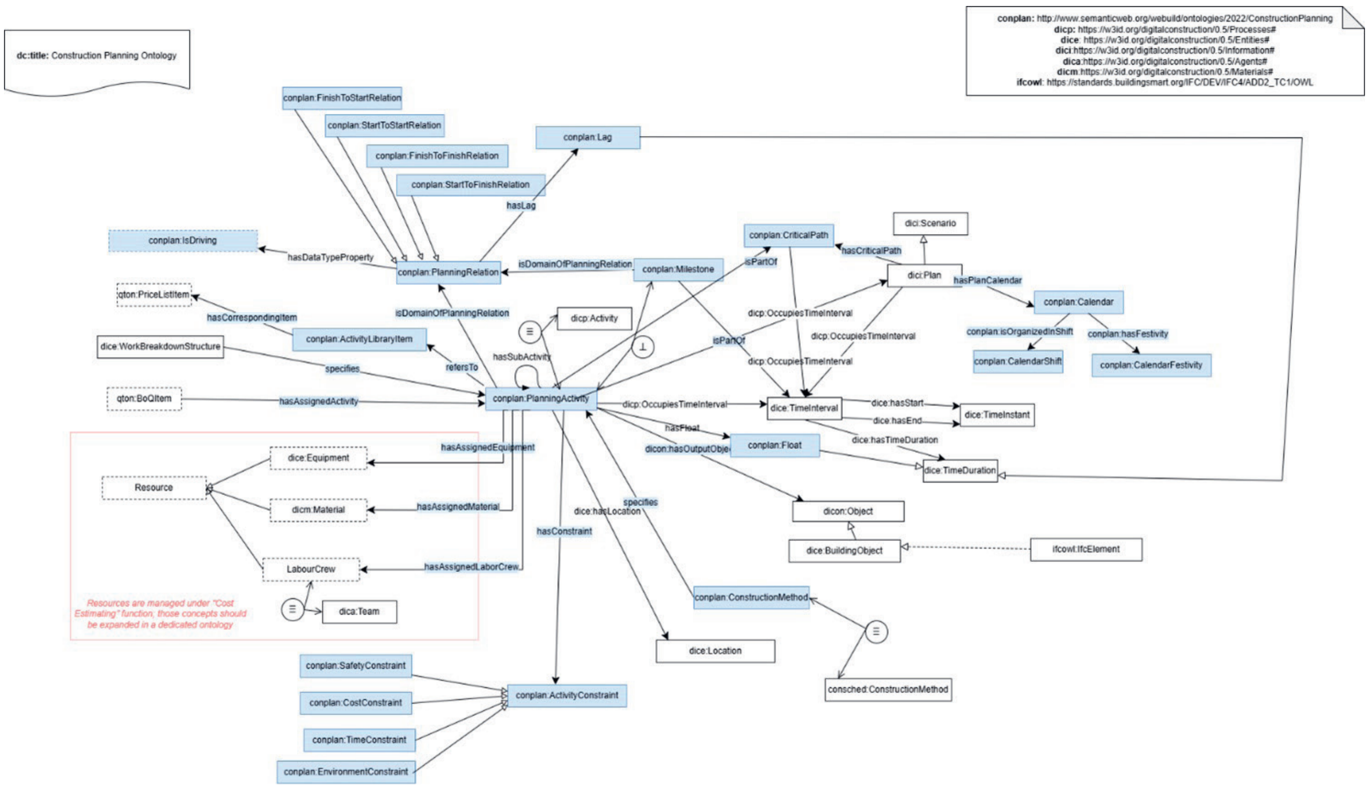

Fig. 2. *The ConPlan schema. The ontology is developed around the key concept of Activity, embedding new concepts and items from existing ontologies. © 2024, Author.*

5. ONTOLOGY TESTING, DATABASE IMPLEMENTATION, AND DISCUSSION

The QTOn – ConPlan ontology has been developed and tested within the operations of a general contractor to assess their effectiveness in forecasting and estimation processes in infrastructural tenders. In particular, the ontologies have been used to drive and refine the representation schema within the quantification environment, developed on the Vision CPM platform, and the 4D construction planning platform Synchro 4D.

Initially, a database has been implemented to organise data across different quantification platforms (Fig. 3). In fact, Vision CPM allows customised data sets and, at the same time, features interface modules with IFC models, ensuring data consistency between design information, quantification, and estimation domains.

By overlapping the QTOn schema with the Vision CPM template, we derived that the key concepts are easily identifiable in the QTO platform – i.e., the PriceListItem, BoQItem, Construction Quantity –, although in some cases with a different label (i.e., construction quantity defined as "measure"), with specific input/editing areas. This demonstrates that the key domain developed in the QTOn ontologies is recognised in the current quantification practice. Units, rates, and other concepts derived from the QUDT are present in the original data schema of Vision CPM. They are managed through a dedicated interface, although simplified as a list of declarative units. Similarly, the ConPlan concepts and relationships shaped the information represented in the activity-based view of a construction plan, enriching the quality of information stored and enabling more powerful queries on the entire portfolio of construction plans.

Project specification concepts – such as the different breakdown structures and classifications – are not formalised explicitly in the application, and no direct link to the external dataset is considered. In any case, the flexibility to add custom attributes to key entities (i.e., BoQItem) partially overcomes this issue, ensuring that this information is stored in lists/tables and recalled during the quantification process. Besides this technical limitation of the platform, we are assessing the relevance of using the QTOn ontology schema, integrated with DiCon, as a way to improve and standardise the design of the necessary attributes, thereby enhancing the quality and accuracy of the project estimation.

Similarly, the ConPlan ontology has been implemented using the Ontology editor "Protegé", and it is currently under validation (Fig. 4).

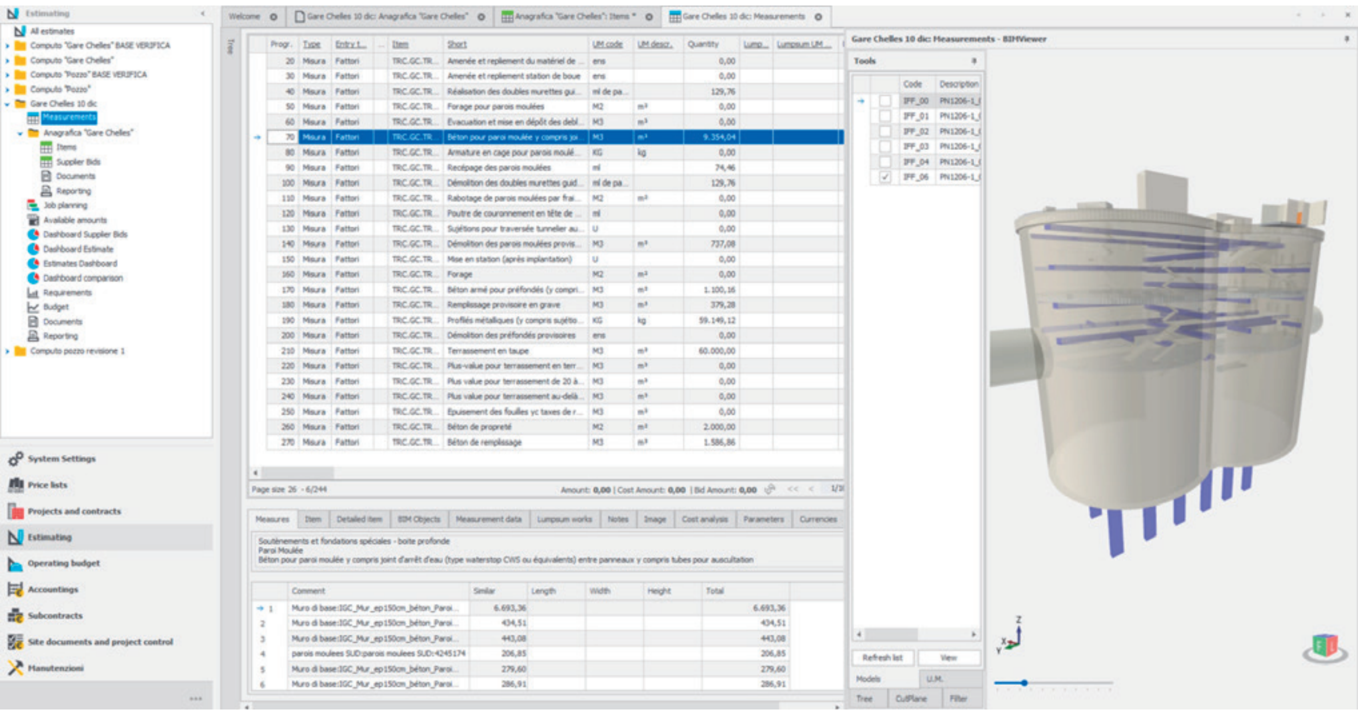

Fig. 3. *Ontology application in construction management platforms. The QTOn ontology is used as a reference to enrich the representation of quantity estimation in the Vision CPM environment. © 2024, Author.*

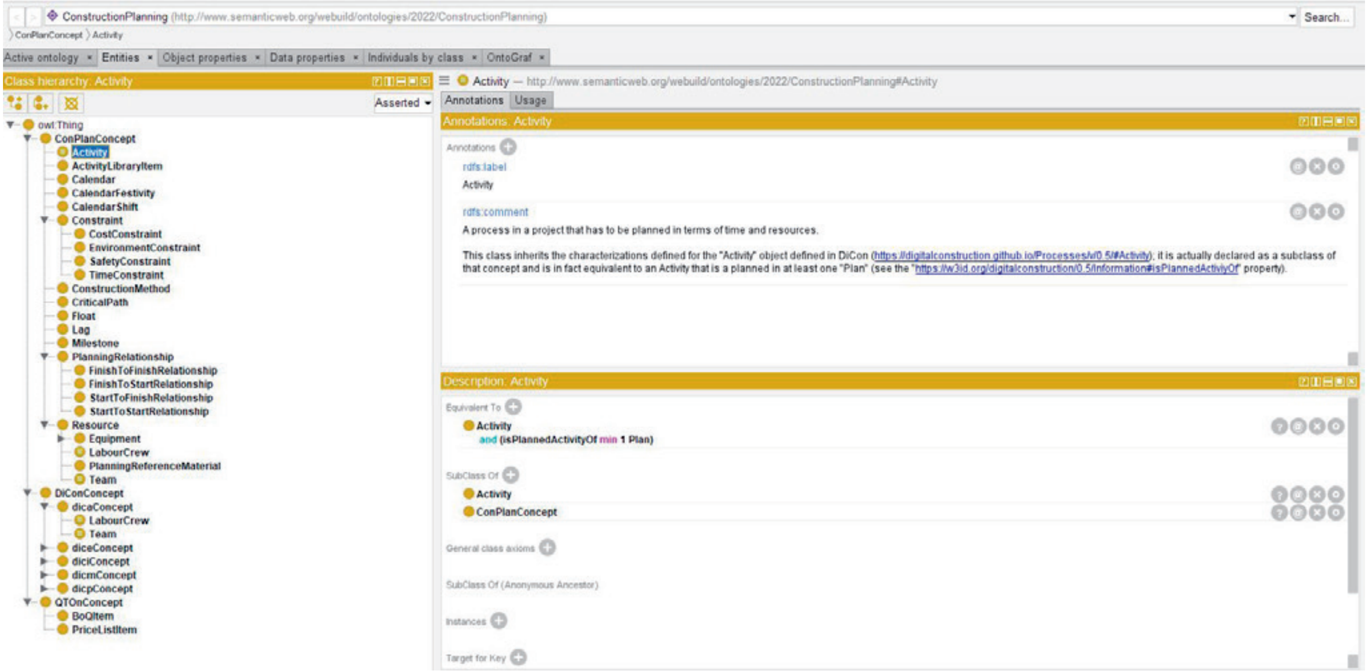

Fig. 4. *ConPlan implementation. The ConPlan formalisation in the ontology editor Protegé, where existing ontologies are included for a complete alignment. © 2024, Author.*

The last relevant part of this test is dedicated to the information flow between IFC models and the construction quantity database. The current Vision CPM interface primarily relies on mapping the information model object ID and its quantity attribute to a Construction Quantity entity, usually performed through a manual selection of the objects. Although some automated rules can be implemented, poor standardisation and high variability of quantification typologies hinder automated quantification processes, favouring manual filter-select-associate actions. In this case, the designed integration between the QTOn ontology and the ifcOWL schema provides an agreed-upon framework for developing quantification algorithm libraries, which are manageable within the Vision CPM interface and reusable. Automated extraction of quantities remains an important feature yet to be fully realised in QTO platforms, as quantification is a key activity on the critical path in tender processes. Any delay or error in this action can lead to incorrect estimations or the inability to successfully present a competitive bid within the deadline.

6. CONCLUSIONS

This paper presents the process of developing an ontology schema dedicated to quantifying and planning works in construction projects. The QTOn and ConPlan ontologies have been developed following the Linked Open Terms (LOT) methodology [20] and tested within the bidding operations of a general contractor to improve information management in BIM-based quantification and construction planning processes. To fully exploit existing ontologies and concepts, and to ensure full interoperability with other data schemas for other disciplines such as design, planning, and estimation, the resulting QTOn and ConPlan ontologies rely on alignment with other consolidated ontologies (DiCOn, QUDT, and ifcOWL), connecting them with some key concepts that represent their core. The ongoing tests of these two ontologies within the quantification/estimation platform Vision CPM have shown adherence to concepts and information usually elaborated during quantification, as well as the ability to organise other data to improve data exchange between models (Costs, BIM, Quantities) and to standardise and automate quantity extractions from IFC models.

The adoption of the QTOn and ConPlan ontologies in general contractor quantification activities shows great potential in improving the efficiency and speed of this complex task, which is often still based on manual measurements, albeit on digital models, and is subject to errors, delays, and a lack of data. Acting as a pivotal data schema during tendering estimation, the proposed ontology integrates information from different areas to provide a comprehensive and accurate BoQ for further estimation and planning activities.

In the general trend of increasing adoption of AI techniques in the construction industry, particularly the use of Large Language Models to support queries and decisions on construction project knowledge, the QTON and ConPlan ontologies represent a scientific contribution that can significantly enhance the quality and efficacy of AI-based analysis. In fact, generative AI is showing great potential, but its reliance on well-structured knowledge to operate represents a significant gap that hinders its adoption in AEC projects. BIM represents a partial solution to this problem and needs to be integrated with knowledge bases that enable generative AI to fully realise its potential. In this perspective, the two proposed ontologies can have a significant impact on the future operations of construction companies. They provide:

1) a clear data model that companies can use to manage and keep in order the data relevant for QTO and Construction planning;
2) a knowledge structure that can be used to drive the use of dedicated software as well as the development of new custom applications or integration between systems;
3) a structured and ordered data set that can enable efficient and accurate AI analysis and prediction within the context of quantification and planning of construction projects.

In a context where construction companies must face the digital impact on their business and operations, the proposed ontologies represent a way to determine which knowledge to manage with the upcoming generation of new AI tools, as well as a way to express how they should be handled and for what purpose. QTOn and ConPlan ontologies can then represent a key step towards real data-driven operations of construction companies.

Currently, the ontologies have been aligned with DiCON, ifcOWL, and QUDT ontologies, while another integration with estimation and procurement schemas is still under development. Further work will focus on this integration, as well as on incorporating project management ontologies to facilitate the quantification of infrastructural projects at higher levels. Other development perspectives include the conception of automated estimating algorithms based on SPARQL definitions and testing of the QTOn ontologies within other quantification platforms.

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