Linked Data for a Construction Big Data Platform

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Abstract

In the challenge towards a data-driven vision of the construction sector, companies are facing the criticalities of complexity and volume of data produced, shared, and elaborated during the distinct phases of a project. This research presents a solution to these issues, proposing a construction big data platform based on Linked Data to organize and integrate information related to the different disciplines. The Linked Data approach is critical for this process because of the ability to create connections between multiple data models – as the ones adopted in each discipline – providing a homogenous formalization of data and making it available for different applications and analytics.

Keywords

General Contractor, Construction big data, Linked Data, Information ontologies

1. Introduction

Nowadays construction companies are facing critical challenges in effectively managing the transition of this complex industry towards a fully data-driven vision, intended as a new way to drive their decisions, strategies and operations relying on a complete and structured set of information derived from current and previous projects. The complexity of data, heterogeneity in sources and representation, and the amount of information elaborated in a construction project are key factors that hinder the effective access to and use of data in construction, keeping this industry still managed in knowledge silos with limited and often on-demand only information sharing. Many disciplines and aspects – often increasing depending on the peculiarities and requirements of each project – needs to be represented through datasets while much data is often cross-needed and interpreted from different perspectives depending on the discipline and objective of its use [1] [2]. This does not mean that the construction industry is not aware of how to manage data and of their potential and we can say that its data landscape is quite diversified: some disciplines rely on well-structure data organization, often promoted by the early adoption of applications with their data models, while other disciplines rely on internal data templates tailored accordingly to the specific needs of the company, in some cases focusing more in how to manage values rather than providing agreed-upon definitions of entities. In other areas such as Building Information Modeling, some standards and classifications are in use but variations in clients' requirements make it difficult to use a unique data schema such as the IFC while other disciplines show limited adoption of standardized data and rely on document-based representations and limited reuse of information. This is a generalized scenario that can sensibly vary depending on contractors, market sectors, and main activities. What we can say is that the larger the scope of activities of a general contractor and its portfolio, the more difficulties arise in having a unified approach to data management able to optimize and exploit a large amount of information and knowledge developed daily in construction. In this context, this paper discusses the adoption of a Linked Data approach to ensure an effective and scalable solution to progressively drive the transition of a large general contractor towards the extensive use of integrated data in both bidding activities and construction projects.

The specific gap that this work investigates resides in the lack of data unification approaches that can support the development of a construction company knowledge base acting as a single source of truth. The overall demand is to move from an on-demand business model, where each actor requests

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information, to other specialists with evident limits of traceability and reuse, to a centralized knowledge-based one, where data are organized and made reusable even after the completion of a project. In particular, the proposed solution aims to solve the key issues that emerge in this process: 1) the necessity of an integrated, rigorous, and scalable data model that can act as a reference for the formalization of each data and 2) the ability of the platform to manage the high volumes of data produced by different projects.

Considering a first group of disciplines related to the technical areas of a contractor, the presented approach relies on the use of existing information ontologies, data models and internal standardization to depict and organize the data landscape, mapping entities and relationships that can act as connections or overlaps between different disciplines. Where applicable, existing ontologies have been used to generalize the schema or to provide an agreed-upon reference on entities, while in a few cases, domain-specific ontologies have been developed and integrated with the other datasets. In some cases, the use of data models derived from applications was so consolidated that the data organization has been just reconstructed from the referring databases. The Linked Data approach demonstrates its full potential and applicability to this kind of scenario, where applicability to real projects and processes is critical and where different data sources are already in place.

2. Literature Review: Linked Data and big data approaches for general contractors

Since the introduction of different information systems in the context of construction, the inability to incorporate all kinds of information related to the Architecture, Engineering and Construction (AEC) world has been a critical issue. The diversity of domains and disciplines has quickly highlighted the importance of an interoperability-based approach – rather than a centralized one such as in BIM – like the one provided in the World Wide Web by the use of semantic technologies [3]. On this basis, a plethora of discipline-specific ontologies and data models have progressively been introduced in the construction field, embracing various aspects such as planning, cost monitoring, quality assurance and control, quantity take-off, health and safety, contracts management, etc., often without actual attention to the topic of interoperability. At the same time, in some disciplines, multiple ontologies have been developed, while in others there are still no ontologies available. For instance, in construction planning and 4D modelling, Soman presented a method based on Linked Data formalization to support Constraint Checking to validate construction scheduling and to capture the construction knowledge created during look-ahead meetings [4]. In a strict relationship with construction planning, Zheng [5] presented an ontology for logistics operations in the construction industry to integrate the information transferred from contractor's partners and material suppliers with the project-specific information, while Sauter [6] introduced two ontologies (Circular Exchange Ontology and Circular Activities and Materials Ontology) to support material classification and circulation in the constructions sector. In the area of Health and Safety in construction, Zhang reported on ontology-based semantic modelling of construction safety knowledge, proposing a dedicated ontology integrated with Construction Product and Process models [7]. In terms of structuring information from different disciplines and systems, Werbrouck [8] discussed as Semantic Web approaches can be used to federate datasets relying on modular domain ontologies without the need for a centralized server, while Simeone [9] focused on the use of knowledge graphs to integrate information models in a Common Data Environment.

The issue of linking or integrating ontologies in the construction field has emerged contemporarily to the proliferation of domain-specific models, and some research has focused on identifying strategies to connect them to manage the complexity of the multi-faced representation of buildings or construction projects. Rasmussen presented the general BOT ontology using topology to connect different disciplines related to buildings representation [10]. Carrara [11] and Elshani [12]both discussed the use of central ontologies to bridge knowledge between different domains to improve collaboration among actors. These approaches have shown potential during the initial design phases, while there is a lack of research work focusing on the detailed design and the construction phases, where the number of disciplines and the amount of data to be elaborated increase.

The gap related to the integration of knowledge domains in the construction sector was also identified by El-Diraby [1], who proposed the development of a construction domain ontology for semantic exchange in this industry [13]. Nevertheless, the attempts to provide a single, fully comprehensive ontology are showing limits compared to the increasing complexity of the construction scenario as a whole and in each domain. The other issue to be faced is the heterogeneity of the large volumes of data from construction projects. Big data techniques are nowadays still being experimented with in this industry, in particular to process a large amount of data, structure them and extract useful insights and patterns [14]. Yan [15] elaborated on the use of data mining in construction big data, highlighting that Data Mining techniques are more widely used in analyzing building energy performances, usually based on data collected by sensors, or produced by IoT systems. Big data are also considered relevant for environmental control in the construction business [16] and for construction waste monitoring and management [17]. Data from construction sites can also be elaborated through big data techniques to generate analytics on construction safety and to fuel automated classification and prediction systems [18]. Kagan [19] elaborated that traditional ways of processing information presented in the form of relational databases are not able to work with unstructured data, such as free text or data coming from analogue sensors, and that Big data analysis can reveal opportunities for improving various aspects of design, construction and operation.

In this scenario, limited applications exist of big data techniques elaborating horizontally interoperable data from different domains – in projects or tenders -, while a large part of them are dedicated to discipline-specific analytics on data collected.

3. Methodology

This research is functional to the development of a prototype of a big data platform to support the operations of a general contractor, using a Linked Data model as a reference for the structure the data lake is built upon. For this reason, we chose to refer to the NeOn methodology, considering in particular scenarios 2 and 5, respectively focusing on re-engineering non-ontological resources and on reusing and merging ontological resources [20]. The use of the NeOn methodology was considered particularly applicable to our case because of the strong focus on industrial applications and the necessity of dealing with different situations depending on the domain to consider. In some cases, we already had consolidated ontologies while in others, ontologies need to be re-engineered from data models already in use. In this project, the development of the integrated view is just part of the process, which requires the implementation of the data lake and the validation through a test in specific projects. In this context, the main steps of this process are:

1. *Definition of requirements* of the platform: among the others, the big data platform is required to operate and relate data produced during pre-construction activities (such as tendering or design and planning phases) and collected/elaborated during projects' execution (such as production rates, work progression monitoring, costs variation, resources involvement). Another important requirement is the scalability of the platform, intended to progressively embrace other disciplines and sectors.
2. *Selection of key domains* to be included in the prototype and analysis of the use of existing data models. In the first phase, we considered some major disciplines such as design (BIM), quantity take-off, construction planning, and work monitoring.
3. *Research and assessment* of existing ontologies applicable to the selected domains, and comparison with data models already adopted by the Contractor.
4. *Development of missing ontologies* for those domains that do not rely on a standardized data structure or when existing ontologies are neither available nor far from the general contractor practice.
5. *Linking data* from different ontologies and data models to provide an interconnected system of information representing the data managed and elaborated by the contractor, as well as the overlapping knowledge and concepts between the different disciplines.
6. *Implementation of the data lake*: the integrated data model derived from the Linked Data schema is used as a base to implement the structure of the "gold" area of the data lake, where data are organized and made available for analytics and elaborations.

7. *Assessment and validation* of the data model, through comparison and integration with data managed by discipline-specific applications.

From a Linked Data perspective, the definition of a unified data model is performed with both top-down and bottom-up approaches: in the top-down process, ontologies (existing or new ones) are used to shape the data model; in the bottom-up, existing data structures already present in systems adopted by the general contractor are made abstract and integrated into the Linked Data structure. In this case, a result is a hybrid approach where ontologies – formally conceived – are integrated with data models and application schemas adopted in the actual practice of the Contractor, organizing data in a way that is adherent to the requirements and operations of the different specialists involved in tenders and projects.

4. Linked Data for knowledge integration in a general contractor.

Intervening on existing procedures for data management in a contractor is a delicate action that requires balancing improvement and critical revisions of the data models and the necessity for a pragmatic adaptation to other aspects such as the Contractor's organization, its business model, its data accessibility policies, etc. In this context, the Linked Data approach is particularly suitable because of its focus on interlinking, connecting data derived both from structured or unstructured systems and making it accessible with queries and computable. In the operativity of a general contractor, where availability and organization of data vary from discipline to discipline – and in some cases from project to project – the Linked Data approach ensures a context-aware action that makes more efficient and exploitable a set of data that is already collected and elaborated by the different teams within the general contractor. In this project, the first two steps of the methodology were useful to perform an analysis of the state of the company regarding data management in the different disciplines as well as the use of data models.

Following the NeOn methodology, a requirements report has been produced where we can identify two typologies of requirements: *domain-specific* and *integration-based* ones. The firsts expressed specific needs such as the homogeneity of quantification methods across different projects or the ability to manage planned and actual critical paths in a construction plan, while the integration-base ones relate to how data is moved from one discipline to another, involving the level of granularity of quantities from Quantity Take-Off (QTO) to Costs, where information regarding resources should be managed, as well as the identification of originators, owners and users of each data typology, to avoid duplication and misalignments. In this first phase of the project, a set of disciplines has been selected to assess the actual potential of Linked Data in this context. This knowledge core is composed of the following domains: BIM (intended to represent the design solution), QTO, construction planning, 4D modeling and cost modeling. These disciplines were selected because of their mutual interoperability and the fact that, nowadays, they usually exchange information on demand in a distributed schema without a centralized single source of truth and with a limited federation of models. In addition, these disciplines were considered relevant because their presence is almost continuous from the preliminary design stages until the construction and the handover of the building or infrastructure.

The initial analysis has shown that, while Building Information Modeling has the optimal capability for data integration because of the availability of existing ontologies and standards (i.e., the ifcOWL ontology), other disciplines rely more on consolidated data structures usually derived from the applications that are more diffuse in the construction industry. Although the process is still ongoing and the knowledge base is under a process of extension, table 1 shows the main disciplines and the existing ontologies that have been used. Even in the case of ontologies developed from scratch, alignment, and reuse of concepts from other existing ontologies were critical to have a consistent and interoperable data model.

Table 1
Construction knowledge domains and the adopted reference data models

Domain	Reference Data Model	Note
Product (building or infrastructure)	IfcOWL	Other ontologies adopted: BOT, DiCon
Project Framework	Contractor existing model	Revised and aligned with E-Cognos, DiCon
Quantity Take-Off	QTOn ontology	Developed from scratch, aligned with DiCon
Construction Planning	ConPla ontology	Re-use/alignment with Dicon, Construction Scheduling Ontology
Cost Modeling	Contractor existing model	Detailed model interoperable with QTOn and ConPla ontologies

In the case of Construction Planning, for instance, construction companies usually refer to data schemas from applications such as Primavera P6, Tylos, or Microsoft Projects that, although originally conceived for project planning, have been progressively customized by companies for their needs. This discipline is emblematic because comprehensive ontologies are not publicly available, and ontologies such as DiCon [21] or the Construction Task Ontology [22] show limited coverage. In this case, we develop an ontology by a process of abstraction of current planning processes, extensively relying on inheriting concepts, attributes, and relationships from existing ontologies and focusing on the interoperability with other data models such as those dedicated to 4D modeling (figure 1).

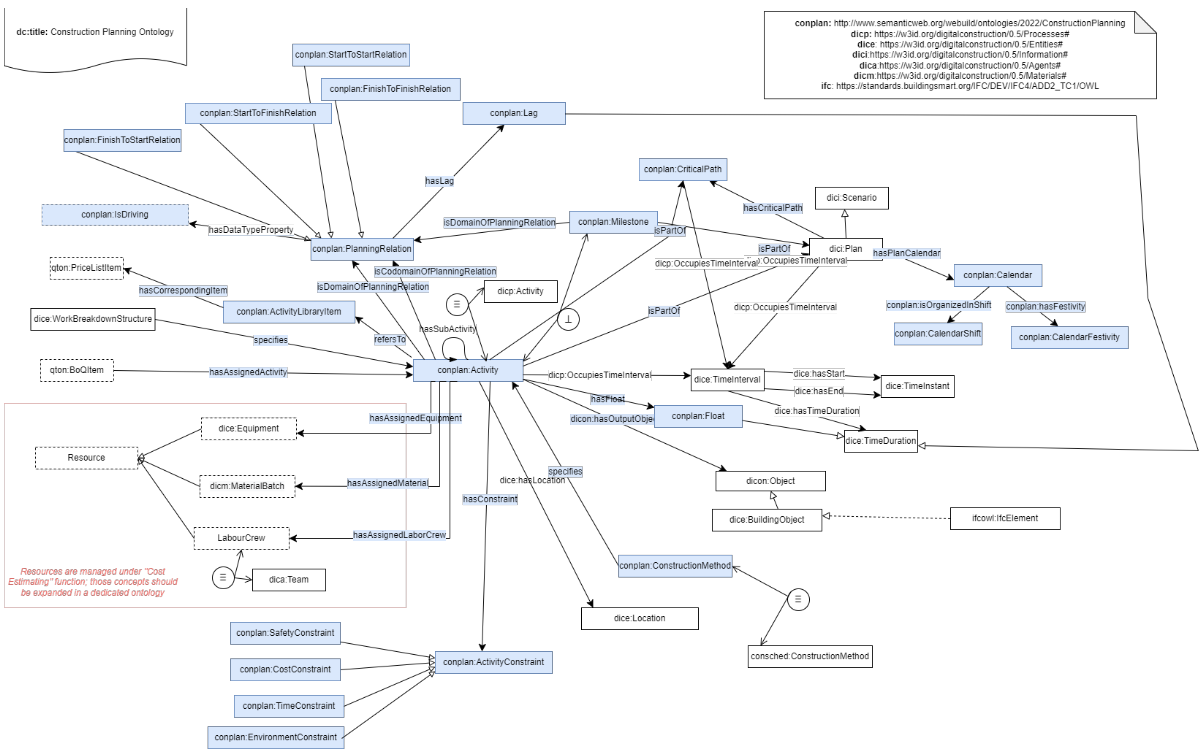

Figure 1: The Construction Planning Ontology schema (under development) conceived to be interoperable both with different data models of the construction company and with existing ontologies such as DiCon.

In the case of cost estimation, the Contractor had already an accurate and consistent data model based on a mapping between work items and job analysis – managing different elements such as materials, workers' number and typologies, machinery typologies and productivity, indirect costs, contingencies – and relying on specific libraries and parametric indices, that we considered it not effective to develop a new ontology, but we clarified the data schema to allow integration with other disciplines (figure 1).

Quantification Take-Off is another activity where no ontologies are currently available, with partial data models applied following the specificness of the project and the relevant phase (bidding, design assessment, project monitoring). In this case, we developed an ontology relying on the data usually managed by a construction company and integrating it with the DiCon ontology and others such as the IfcOWL and the QUDT (figure 2).

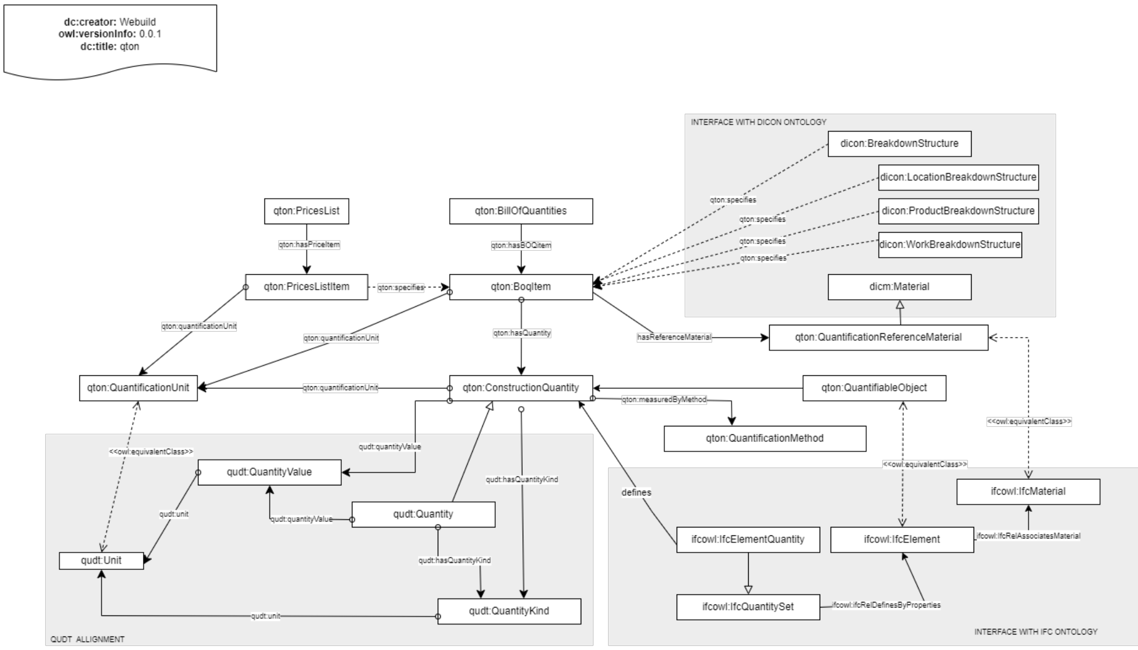

Figure 2: The Quantity Take-Off ontology – under development - aligned with DiCon, QUDT and IfcOWL ontologies and integrated with the other data models of the project.

Alignment and integration of ontologies and data models is another key element of the development of a data lake based on ontologies. In our case, we chose to start by mapping interaction between disciplines considering:

- Information that is shared by one discipline to another and is used as input.
- Concepts that are common between two or more disciplines and mutually influencing their definitions.

After this mapping process, different alignment strategies have been adopted:

- Lexical Matching: in some cases, meeting between different actors highlighted that the same concept was labelled differently in the two domains.
- Structural Matching: by looking at two data models or ontologies in some cases patterns in terms of hierarchy, attributes and relationships emerged, alerting us that two distinct entities were referring to the same concept.
- Semantic matching: meanings of intended concepts were compared to verify if they were semantically similar. In this case, a similarity relationship has been used to keep the two concepts distinct in the two domains, without renouncing the specificness of their interpretation in the different contexts.

Analysis of current data flows between applications (for instance between QTO platform Vision CPM and the construction planning application Oracle Primavera P6) suggested to us the key concepts and entities that are at the base of the interoperability between different data models adopted. Those were particularly critical because a mismatching definition of the relationships would have hindered the data exchanges in the current operations of the construction company.

In usual data lake definitions, a three layers structure – bronze, silver, gold – is used to define distinct levels of data refinement and quality. In our implementation, a Linked Data model has been used as a reference for the data organization in the gold area, where data is fully refined and processed, and it is considered ready for use in critical decision-making processes. The bronze area- where the raw data ingestion occurs- still allows for non-correctly formalized data to be introduced in the data lake while the silver layer is where data is translated, aggregated, and elaborated to fulfil the representation structure provided by the Linked Data schema. The three layers architecture is particularly relevant for our purpose because it allows data extracted by different systems with their datasets to be ingested (bronze layer), reorganized/cleaned (silver layer) and formalized in a homogenous way (gold layer). The gold area contains data that has been transformed, cleaned, and enriched to the highest quality possible to support both direct interactions with platforms and direct data analysis, even involving data from multiple disciplines at the same time (figure 3).

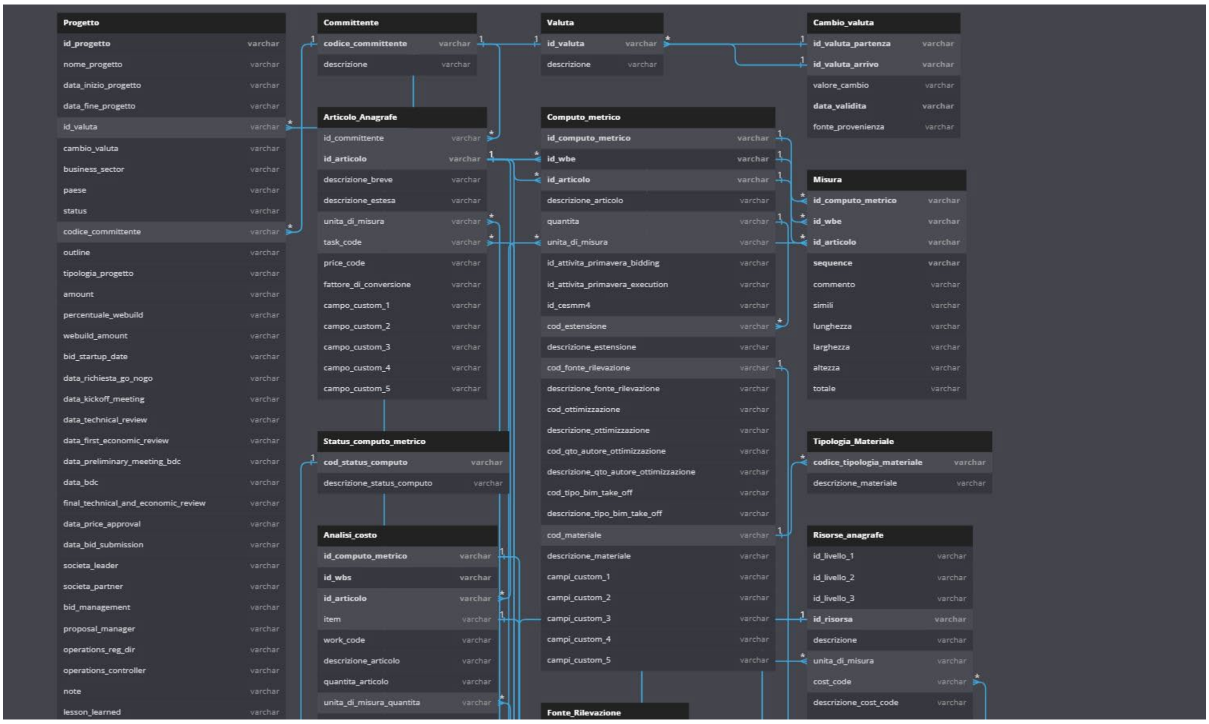

Figure 3: Part of the gold area of the Construction data lake, represented through an entities-relationships schema.

While in the pre-construction processes this workflow is useful to re-organize data and information produced by different systems and sources, in the construction phase the same progressive elaboration can be used to manage high volumes of data produced by IoT systems such as sensors, cameras, LiDAR, cleaning and aggregating them before their formalization in the gold area.

5. Experimental data integration and reuse

The Linked Data approach we are currently working on is conceived to function as a reference model for data organization in the big data platform, ensuring that the data produced by the different actors is formalized homogenously in a centralized environment. In this way, data related to a project is organized and integrated and, because of the clarity of the data model, can be accessed and exploited both by humans and systems. At the same time, the use of a big data platform allows one to still be able to manage that data once its amount increases, due to the progression of a project or the increasing number of projects in a portfolio.

As discussed, the aim of this project is not only to formalize data in a centralized environment but also to assess how effectively it can be exchanged with the major applications currently in use in a general contractor. Depending on the disciplines and the related systems, different modalities of interoperability between the data lake platform (developed in the Microsoft Azure environment) and the specialistic applications have been evaluated. For Construction Planning, an existing API has been selected to ensure the bidirectional connection and update of data in the application and the data lake. For other applications – for instance, those dedicated to the quantification of projects or works estimating – a set of tables has been used as a bridge relying on importing tools for CSV files.

In terms of integration between BIM and the Data Lake, two pipelines have been conceived depending on the nature of the models. An existing tool has been used to transfer data from IFC models into areas on the data lake relying on the IFC and thanks to the integration of IfcOWL concepts in the data model. For native models developed in the Autodesk Revit authoring environment, a Dynamo script has been implemented to extract data from a Common Data Environment – developed in the Autodesk Construction Cloud – and write them in specific tables in the data lake. In this experimentation, Linked Data provided a coherent and consistent data model that allowed for better exploitation of data elaborated in previous projects. At the same time, the use of the data platform improved the standardization of data exchange among different actors in the same project, moving from a distributed approach where information is shared one-to-one on demand to a centralized data hub, reducing the risks of uninformed actors or the sharing of out-to-date information. The centralized, homogenous formalization also allows for the development of new applications to enable business intelligence and analytics on project data, even in comparison with previous projects' historic information.

6. Conclusions

In this paper, we presented an ongoing R&D project that aims at developing a Linked Data model to integrate information elaborated in a construction project and use it as a reference for the implementation of a big data platform to support operations and decisions of a general contractor. The objective of the Linked Data model is to provide a clear and well-organized structure of data that can be applied to a construction firm portfolio to ensure a homogenous representation of data. The experimental application of the data model as a reference for the implementation of a construction data lake is intended to contribute to the management of complexity and volume of the information produced and elaborated in construction projects. This ongoing experiment investigates if and how this approach can represent a solution potentially enabling construction companies to use data management to capitalize on knowledge rather than consider it as an additional burden.

A particular advantage of Linked Data application to data integration in construction is related to the scalability of the model, allowing it to progressively include new disciplines or data sources without losing the coherence and consistency of the previously formalized project. This aspect is critical for a general contractor because it enables a modular process flexible enough to adapt not only to the requirements of each project but also to the context evolution over time. New knowledge domains – such as those related to sustainable processes and ESG parameters – can be integrated into the existing Linked Data model without losing control of the complexity of a project data representation. From an implementation perspective, the ongoing assessment of this prototypal big data platform is showing potential in supporting collaboration among actors and a high capability of making reusable knowledge produced in current and past projects, capitalizing on the incredible amount of data and information developed by a construction company during the years. At present, the prototype focused on a limited number of disciplines and is dedicated to supporting decisions during the tendering and pre-construction phases, but ongoing implementations are now dealing with data collected on-site through IoT systems, elaborated, and formalized in the data platform to allow for useful comparison between planned and actual performance.

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