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CON-TEND: AN ONTOLOGY FOR KNOWLEDGE REUSE IN CONSTRUCTION TENDERING

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ABSTRACT

In construction tendering, the ability to successfully manage and capitalize technical knowledge is a competitive advantage for a general contractor. In this context, we present Con-Tend, a flexible, high-level ontology conceived to formalize information and knowledge produced in projects and tenders and make it reusable during tendering processes. The Con-Tend ontology is under development from a general contractor perspective and shows how linked data approaches can ensure homogenous, computable knowledge bases for powerful, data-driven strategies by a general contractor.

INTRODUCTION

The relevance of decisions support in construction tendering

For a general contractor, tendering is a delicate phase, dense of critical multidisciplinary decisions and impactful for the following execution of the project (if awarded). Especially in large international projects, the offer includes large technical parts where the tendering Contractor is required to propose and assess construction methodologies, planning optimization, managing procedures and, in some cases, improvements to the design.

The preparation of these proposals requires a major effort from the Contractor (or the Joint Venture) in terms of decisions making and assessment of different approaches, opportunities, risks. In this context, the capability of the general contractor to rely on previous data and knowledge relevant to the project is crucial for the successful tailoring of the proposal and the right estimation of the final bid.

A key resource of the tendering action is the technical knowledge - introduced, elaborated, and shared within the tendering team – and its efficient management can positively impact collaboration in the process and quality of the tendering proposal.

In construction tenders, a competitive advantage is provided by the ability to effectively manage knowledge (Kivrak, Arslan, Dikmen, & Birgonul, 2008) - even when such a resource is not explicit but resides in the minds of involved specialists. A precise knowledge formalization is also important to prevent excessive use of tacit, personal knowledge from the different team members, avoiding bias or subjective judgement that can lead to unfair, incomplete and poorly constructed results (Sauter & Free, 2005).

On these bases, this paper discusses the ongoing research aimed at developing a high-level ontology, named Con-Tend, to formalize the technical knowledge that can drive or support decisions in construction tendering.

In this research scope, the Con-Tend ontology development represents an exploratory experiment by a general contractor towards more extensive use of information ontologies as a way to drive technical knowledge formalization to capitalize data and experiences, improve solutions explorations and assessments, and increase the ability to operate in competitive scenarios.

Knowledge management criticalities in the construction tendering process

Tendering is a challenging activity for a general contractor, and the presence of different hindering factors highlight the necessity of a linked data approach that can support decisions. Time is undoubtedly one of the more hindering factors that affect the quality of the technical proposal of a tender. Usually, a short period is granted by the tenderer organization to develop and submit the proposal, and this forces the proposal team to try to access as much as possible construction data, from different sources, to act as a reference for new decisions.

Specificity and uniqueness of construction projects is another hindering factor: differently from other industrial sectors, knowledge reuse is difficult because interpretative context may vary, reducing the reliability of previous data. Often, blind use of correct data from other projects can even hinder the tender assessment.

Variation of the tender team is another obstacle to knowledge reuse: variations usually occur both in terms of companies involved in the tender (i.e. the partners of a Joint Venture) and within the same company in terms of specialists and people involved. In this case, it is particularly difficult to access tacit knowledge, usually provided by the main project leaders for each discipline.

In large contractors' operations, often data and knowledge are collected and used along large periods and it is difficult to avoid data and knowledge loss during the time, especially regarding tacit knowledge that often is held by people that may leave the contractor or retire.
This brief description of some of the difficulties related to knowledge in tender activities shows how relevant is, for a contractor, to have nowadays some digital approaches, processes and tools to collect, structure and reuse knowledge for tendering purposes.

KNOWLEDGE FORMALIZATION IN CONSTRUCTION TENDERING: A STATE OF THE ART

Data re-use in tendering: limits of databases

Data usually used as a reference in construction tenders is derived from a vast domain of sources, both internal or external to the general contractor organization, such as:

- Previous projects (internal);
- Lesson learned reports (internal);
- Previous tenders' estimations (internal);
- Data provided by other JV members, sub-contractors and suppliers (external);
- Consultants and specialists (external);
- Available literature, patents, methods (external);
- Tacit knowledge of team members (internal);
- Norms and regulations (external);
- Client reference data (external);
- Other sources (external).

With the advent of digital approaches for data management in the AEC domain, the industry has shown a progressive transition from a document-based approach to data retrieval to the adoption of live databases to organize history and reference data.

Because of the high competitiveness, each general contractor has investigated, conceived and developed its database structure, often encountering the same formalization issues and without metrics for its validation.

Although databases for tender data retrieval have represented a great improvement if compared to the previous reliance on the tacit experience of specialists and organized documents, some of their limits have progressively emerged, leaving the aspect of knowledge reuse in tender phases still poorly supported by digital support systems.

A first limit to the adoption of the database resides in their intrinsic complexity and difficulty in understanding its construction logic by a user that is different from its creators. The second limit is the rigidity of a database structure, based on primary and secondary keys, that limits data entries and impose several restrictions to ensure efficient information access and management (Martinez-Cruz et al., 2012).

Relationships, that are crucial when formalizing complex knowledge as that re-used in construction tender decisions, are also quite limited in current databases structures: they ensure data integrity and allow the database normalization and scalability, but do not provide a sufficient interpretative context for a full comprehension of the data stored (Sir and Bradac, 2015).

This introduces the main issue of the adoption of databases for the formalization of knowledge in construction tendering: the low level of semantics representation. While databases are good in ensuring the integrity of simple data with few relations to other entries, they are inadequate in representing more structured semantics, showing difficulties in providing useful knowledge regarding concepts, ideas, methodologies that require for their comprehension a more structured system of information (Simeone et Cursi, 2017).
Also, after the initial conceptual definition of the database structure, the organization logic and approach are lost, limiting the following possibilities of evolution and making unclear its modelling principles.

Linked data for knowledge representation in construction

With the progressive development of the semantic web, some research has been started investigating the possibilities of relying on a representation framework different from databases for construction data.

Much effort has been particularly spent on investigating construction representation from a product perspective, interfacing BIM, IFC and information ontologies. Some research (Belsky and Sacks, 2016) explored the theme of interoperability through the development of new models and methods of representation and possible evolutions of IFC-based representation schemes to downsize the errors and reworks and improving efficiency and productivity in creating, using and reusing knowledge throughout a project lifecycle.

More recently, the introduction of the Linked Data approach has shown the potentialities of the introduction of semantic web technologies to improve representation and information management in building information processes

As well described by Pauwels (2013), the analogy between the representation schemes for the building (eg. IFC) and the description logic of semantic networks (RDF and OWL), has encouraged the creation of informative ontologies in the AEC sector, usually in combination with the IFC schemes and the Express rules, opening new possibilities for the semantic enrichment of BIM.

In 2005, Beetz (Beetz et al., 2005) has introduced an embryonic version of the future IfcOWL, an ontology that can be considered the first step to extending the structured AEC information to the world of semantic ontologies.

In 2008 Jeong (Jeong, 2008) investigated the use of ontologies for semantic sharing in multidisciplinary design. In the same period, Carrara (Carrara et al., 2009) interprets the ontology as a way to move towards knowledge-based models to improve collaboration in the

AEC processes. Integration between BIM and semantic web technologies is also at the core of the enrichment platform presented by Simeone and Cursi in 2017.

Such approaches rely on the use of semantic networks, systems of concepts and logical relationships (usually represented in graphs as nodes and oriented arcs) to decompose and make computable knowledge in a certain domain (Gruber, 1993).

Information Ontologies for construction tendering

Although extremely relevant for the adoption of linked data in the AEC industry, the previously mentioned research is only partially applicable to the scope of the tendering phase because it essentially focuses on the product domain, while knowledge elaborated in construction tenders usually involved a larger representation domain that includes construction planning, logistics, management, methodologies and so on.

In the construction sector, ontologies adoption is related more to knowledge representation rather than reasoning and normally complemented by databases or artificial intelligence tools to be effective in supporting decisions in AEC processes (El-Diraby & Osman, 2011).

The E-Cognos Project (Lima, 2004) is recognized as a leading research project that led to developing an open and flexible system that can encourage collaborative and coherent knowledge management in the construction sector and that can be a reference structure for proprietary tools that are easily accessible and suitable for the operational needs of end-users to allow the creation, capture, indexing, retrieval and dissemination of construction knowledge. Later, El Diraby et al. proposed its extension with the BCTaxo (El-Diraby & Zhang, 2006), shifting from the product-oriented taxonomy of the E-Cognos Project to a process-oriented one. While the use of information ontologies is now a consolidated practice in knowledge modeling for specific construction domains, the sector is facing an increasing and challenging demand of project-wide integration approaches for construction and infrastructure (Costin & Eastman, 2017), and for higher-level ontologies able to support multi-task holders project development processes, relying on integration and interoperability among existing formalization frameworks. This requirement is even more important if we consider the perspective of a general contractor, used to face large complex projects where the specific domains views have to be accompanied by a higher control of the relevant project data and their integration.

THE CON-TEND ONTOLOGY

Development methodology

As often happens in research related to information ontologies approaches in construction, the underlying methodology is essentially constructive (Lukka, 2003), relying on the prior research in knowledge representation in construction using information ontologies to solve the key problem of effective knowledge reuse and capitalization for contractor tendering activities, and resulting in both a practical solution (the knowledge-based system to be adopted in the contractor tendering activities) and a theoretical contribution to the field (the Con-Tend ontology). It is also important to state that the proposed ontology framework relies upon and includes concepts and relationships developed in other ontologies described in the background section, rather than "reinventing the wheel" by recreating from zero a new ontology. Besides the impossibility of recreating from zero an ontology for such a vast knowledge domain, this choice allows reaching adequate flexibility in connecting to more detailed ontologies, usually discipline-specific, ensuring a good level of adherence to the evolution of technical knowledge in this field.

As shown in figure 1, the first step in the Con-Tend Ontology development has been the definition of its scope and the identification of the different knowledge areas involved, based on the contractor necessities during tendering and its portfolio (both tenders and projects).

Once the knowledge areas have been defined, in each domain some high-level ontologies have been developed and later integrated, also considering the potential connection with other existing ontologies. Eventually, the ontology is validated by its application to tender case studies (verifying its formalization capabilities) and by direct feedback from domain experts, to assess its coherence and consistency.

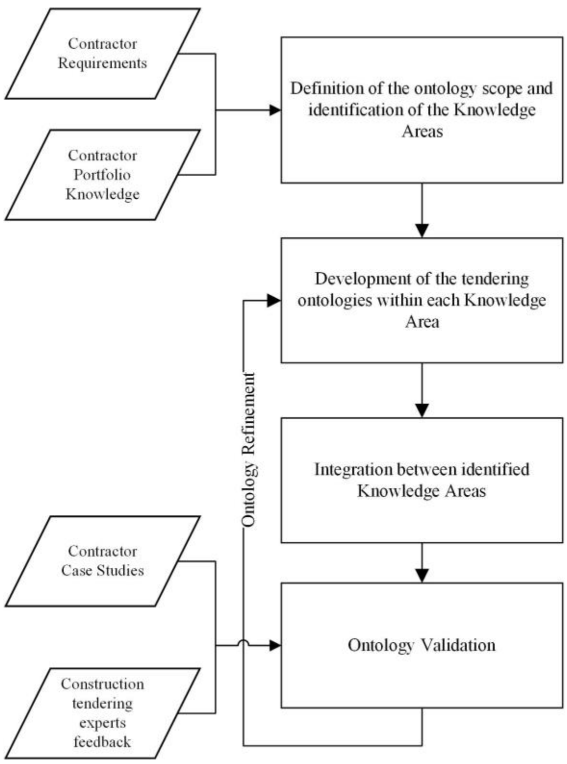

Figure 1:The Con-Tend Ontology development methodology.

The presented methodology is partially based on the methontology development processes (Gomez, 1996), although revised to suit the specific operative context of a general contractor. Although the used methodology can be considered less rigorous than the ones usually available in the semantic web field, it allows to:

1) Involve different specialists within the general contractor technical department, stimulating them in shaping the data model;
2) Spread in the general contractor the culture of attention to data formalization and of re-usability of information.

The Con_Tend ontology has been mainly developed in the ontology editor Protegé (version 5.5.0) (Musen, 2015) while OWLGrEd (Liepins, 2014) has been used for online visualization and sharing with the different technical specialists.

Knowledge areas

Looking into the contractor tendering portfolio and considering the knowledge shared and produced during the development of a technical offer, we identified three main areas -potentially incrementable and extendable – that embrace the high-priority technical knowledge and ensure the possibility to develop, within each of them, a dedicated ontology.

The *Project Framework Knowledge* (PFK) includes all the information that is necessary to fully understand the context of each project as well as its major characteristics. Usually, contractors already store some of that knowledge in updated lists of tenders and projects, although without an actual formalization of classes and relationships.

The *Project Reference Knowledge* (PRK) includes the information that is independent of the project but that can be referred to during the development of the technical offer. This area includes major expertise, norms, and those technical elements that can drive decisions.

The *Project Definition Knowledge* (PDK) focuses on the actual representation of the project as well as the results of technical decisions, including all its physical components, intended or applied construction methodologies, construction and logistics measures, and so on.

In our ontology development, these areas act as high-level knowledge containers that favour knowledge management and integration of existing ontologies (where applicable and necessary). For instance, within the Project Definition Knowledge, it is possible to adopt ifc-owl ontology when dealing with physical components of the building or infrastructure, to ensure direct interoperability with building information models, while other discipline-specific ontologies can be applied in all the knowledge areas. This has two major advantages: 1) it allows to avoid the "reinventing of the wheel", relying on already established definitions, relationships and so on, and 2) it makes immediately available a lot of knowledge formalized in public ontologies for many domains, reducing the big effort of populating the ontology, and this represents a major obstacle to DSS application in tender phases.

To interrelate these major classes we introduced three major *intra-areas* relationships that have the scope of organizing all those more detailed relationships that occur to provide cross-references among these three knowledge worlds. Those relationships are (fig. 2):

- *refers_to* (Project_Definition entities -> Project_Reference entities);
- *placed_in* (Project_Definition entities -> Project_Framework entities);
- *involves_in_the_scope* (Project_Framework entities -> Project_Reference entities).

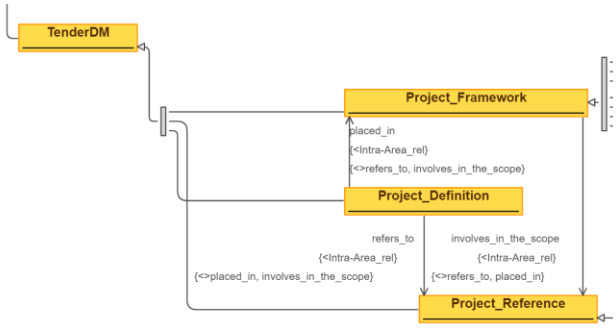

Figure 2: The high level classes and their intra-relationships: [Project_Definition], [Project_Reference], [Project_Frame-work] as children of Tender Data Model.

For instance, at a very high level, a *Road* (PDK) is *placed_in UK (PFK)* and has as client *Highway_England* (PFK). Client and Country (both PFK) involves_in_the_scope *HE_norms* (PRK). Then, *Bridge* refers_to *HE_Norms*.

This small example shows how these high-level classes and relationships, even if extremely general, not only act as references to start organizing knowledge elements but also provide context for interpretation of decisions performed during the project.

Project Framework Knowledge

In an international general contractor environment, a draft ontology is often implicitly available in simple databases (or at least project lists), providing a general overview of the projects and tenders portfolio. Nevertheless, the process of depicting a clear formalization of the concepts and their relationships and properties highlight patterns and hierarchies of the project context, improving its full comprehension. Among the others, some of the classes implemented in this knowledge area are:

- *Project*: qualifies, within the contractor operation, the project in terms of three subclasses: *Pre-qualification*, *Tender* and *Construction_project*. Each project has a set of data properties that express features of the instance such as project-code, year, if awarded, cost, etc.

- *Procurement_route*: qualifies the typology of procurement intended for the project, such as *design&build*, *design-bid-build*, *design-build-operate*, etc.

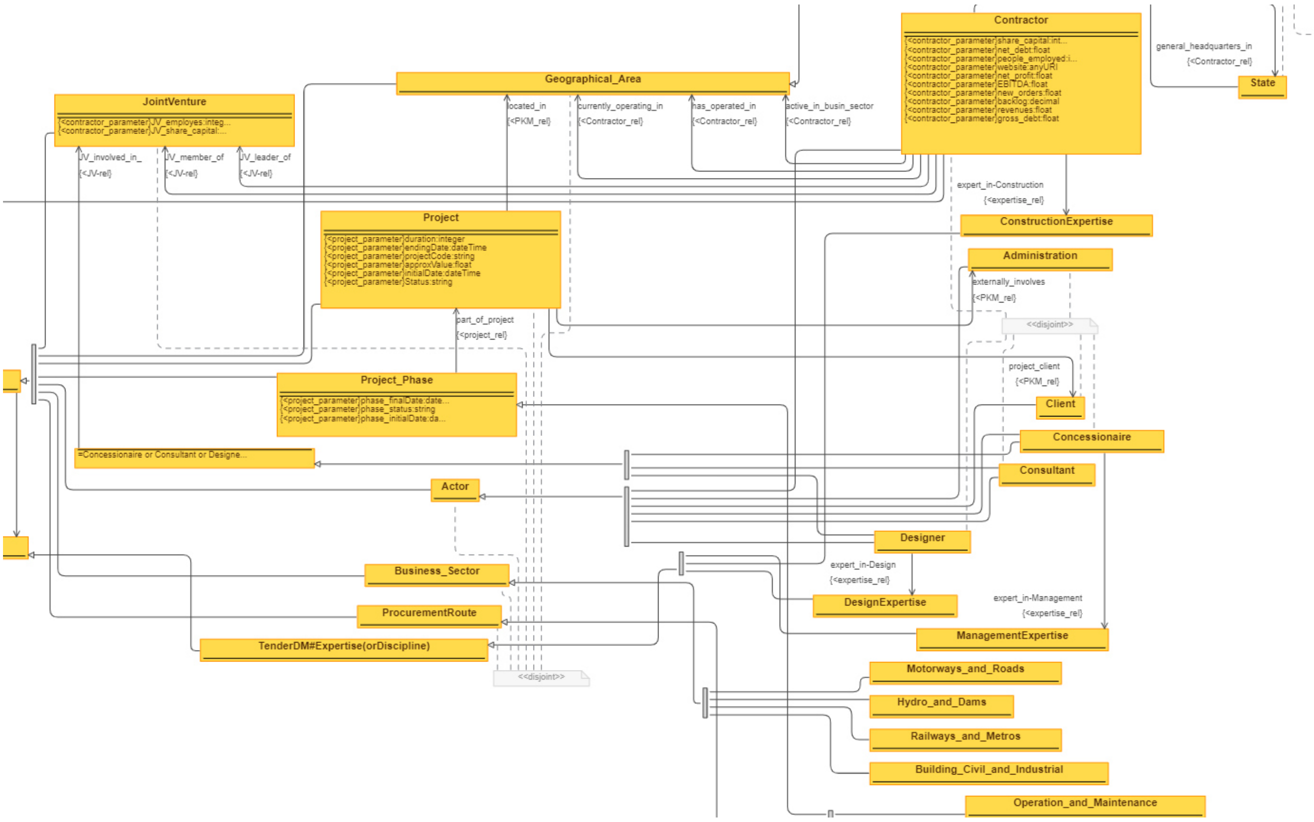

Figure 3: A part of the Project Framework Knowledge Ontology.

- *Business_sectors*: for a general contractor that acts at the international level, it is important to define the scope of action of each tender following its main business sectors. Main business sectors include *Buildings*, *Hydroeletric&Dams*, *Motorways&roads*, *Railways&metros*. Subclasses are then used to further depict the specific business sectors.
- *Country*: this class support the identification of the geographical context of the tender project. This is particularly relevant to assess decisions on construction methodologies or logistics following actual national and continental context.
- *Actors*: The actors class is intended to formalize the different stakeholders involved in the project. In this phase, we recognized a simplified scenario where actors are divided into *JV_members*, *Client_team_member* and *External_administration*. Multiple subclasses are then conceived to indicate specific roles in the project.

Project Definition Knowledge

The Project- Definition Knowledge domain includes all relevant information and the technical decisions that are made within the tender activities for a project. Following the main disciplines and team involved, we categorized the knowledge related to the area in the following macro-classes:

- *Issues*: representation of issues related to construction, is beneficial for knowledge re-use if considered as a dynamic part of the semantic network. By controlling relationships between issues and project-dependent contents it is possible to better understand or clarify decisions.
- *Constraints*: similarly to issues, also a description of the constraints of a project clarify the motivations behind decisions. Constraints related to different aspects such as context or production play a key role in the definition of the key_performance_indicators of a project.
- *Construction_methods*: the topic of construction methods is one of the most relevant aspects to be carefully tailored during tender development. In this class, different sub-classes are indicated for the main typologies of methods used for the different work classes such as *excavation*, *concrete structures*, *tunnels excavation methods*, etc.
- *Work_typology*: in the projects portfolio of an international general contractor, often a single project includes several work typologies that should be faced with a combination of construction methodologies. For instance, road projects can imply viaducts parts, at-grade parts and different typologies of tunnels. In this initial ontology, a categorization of different work typologies has been included as subclasses of this domain.
- *Logistics*: this class includes the concepts and entities related to the logistics and all the site elements necessary for the completion of the project. Main sub-classes include site_installations (offices, gates, fences, site networks, machinery, etc.), concepts of materials supplies such as *access_roads, temporary_roads,*

querries, production_sites, etc., and *transportation_vehicles*.

In the PDK, for the part regarding the subject of the project (meant as the building or the infrastructure and its parts), we chose to adopt a two-level approach: a higher-level representation has been conceived using concepts such as *Works* or *WBS* to formalize major parts of the project, while for a more granular and detailed representation of the design ifc-owl classes have been used. The *IfcElement* class (and its subclasses such as *IfcBuildingElement*, *IfcCivilElement*, etc.) are replicated in the Con-Tend ontology and some relationships – i.e. *part_of* – may connect them to high-level concepts. We also conceived a specific set of relationships, defined *onto_bridge*, to connect concepts between different ontologies and express the meaning of those relationships (such as *same_as*, *domain-oriented_specification_of*).

A specific object property – *ontosource* - has also been introduced to depict entities replicated from other ontologies.

The choice between the use of *onto_bridge* relationships and *ontosource* property essentially depends on the actual necessity of relying on an entire domain-specific ontology or just refer to a selected set of concepts from it. As a matter of fact, "pruning" criteria represent an open issue of the majority of knowledge bases and, at least for the moment, we chose to keep it flexible to fulfil the knowledge requirements of the tendering processes.

Project Reference Knowledge

As previously, described, the PRK aims at formalizing external knowledge, provided by different sources, that influences and act as a reference for different decisions during the construction tendering activities. This domain is probably the most open of the three major areas previously presented since it extends to potentially include all the reference knowledge necessary for each project, also by the specificity of each project. Among the different classes that compose this domain, we can mention some of the most meaningful:

- *Reference_data*: this class organizes knowledge related to aspects given as a reference for tender decisions in different sub-classes such as *requirements*, *planning_parameters, production_indexes, performance_indicators* and so on.
- *Norms&regulations*: many constraints that have to be considered in a project related to the presence of norms, regulations and similar elements of control of the construction and its impacts.
- *Protocols*: this class formalizes the different protocols that can be applied to a project for the different aspects. For instance, all the projects considered specifically referred to as *Environment_protocols*, L*abour_protocols*, etc.
- *Good_practices*: rules for execution of works are often formalized in external sources such as books, manuals, patents, etc. reference to those information carriers should be made clear for a better comprehension of the adopted or discarded methodologies.
- *Materials_data*: information about materials and their features can be both project-dependent and project-independent. For the latter, we considered those values that can be considered as fixed and reference for all the projects.
- *Machineries_data*: features of machinery are often provided by suppliers and vendors. That information can be assumed as independent from the project and help in the homogenization of different knowledge elements such as productions, efficiencies, maintenance requirements etc.

Con-Tend implementation and testing

Once the Con-Tend ontology reached a sufficient level of definition, and after some coherence testing performed using a reasoner in the Protegé environment, we started the process of testing the ontology in some real construction tenders with the intent of 1) progressively refine the ontology and 2) assess potentials and limits of its application, even by receiving direct feedback from the different specialists involved in the tendering activities.

Some of the initial tests implied the direct modeling of knowledge related to case studies directly as a semantic network of individuals in the ontology editor, with the objective of immediately calibrate the ontology even by performing consistency checking through built-in reasoners. As shown in figure 4, this approach is particularly useful during the ontology development and allow to correlate specific project decisions (in this case the adoption of a Slurry Shield TBM) with parts of the project (Adit Tunnel) as a consequence of the presence of an issue (non-cohesive soil). Although this example can be considered simple, it is clear how it improves comprehension of the technical decisions, providing (and formalizing) not only the result of the decision but also the informative context necessary for its full understanding. By horizontally applying this ontology to multiple projects, it is possible to collect and map several solutions and, at the same time, allow different actors to access previous projects knowledge and capitalize it in new tenders.

In a second phase (still in progress), we decided to test graph databases as a way to formalize knowledge more extensively in projects and tenders. In this experimentation, the Con-Tend ontology acts as a data model for the project graph, providing a reference set of classes, attributes and relationships to adopt to make algorithms and rules applicable in the knowledge base of the project. Currently, our experiments are running through the Neo4J platform [neo4j.com] integrated with Bloom visualization tool to share the graph DB with other actors in the tendering process.

In the use of graph databases as a formalization methodology for the project knowledge, we are

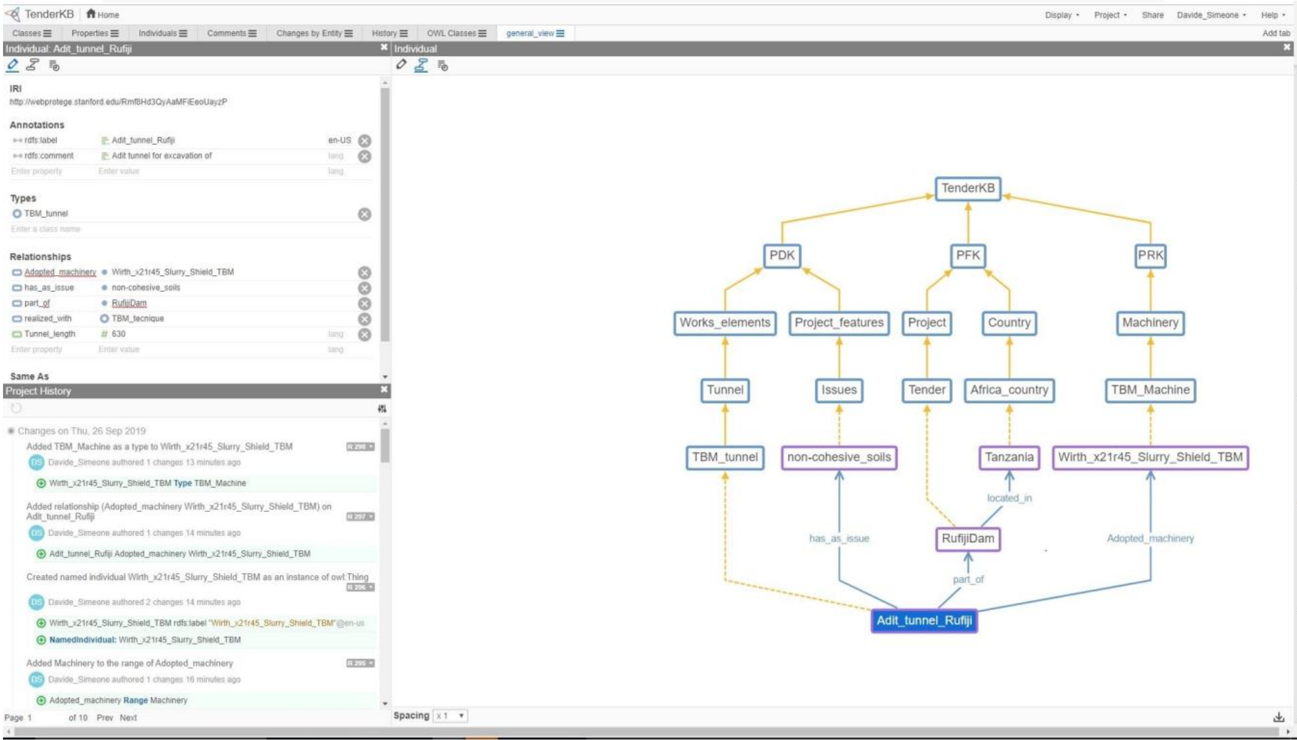

Figure 4: Con-Tend ontology testing in tendering decisions formalization such as the selection of a Tunnel Boring Machine due to context and soil nature.

discovering some advantages such as flexibility and actors' involvement. Graph databases allow for customization of the database by addition of new classes, attributes and properties, introducing new knowledge elements that are necessary for the full comprehension of the technical decisions even if those are not yet considered in the reference ontology.

The second aspect is related to the accessibility of knowledge by the different actors involved in the project. Combining a visualization tool and natural language processing it is possible to actively involve technical specialists in the knowledge base development, allowing them to successfully and easily retrieve information during the technical offer development.

CONCLUSIONS

This paper has presented the ongoing development of the Con-Tend ontology, a structured formalization of knowledge produced and shared in construction tendering for a general contractor. The objective of the Con_Tend ontology is to organize and support the capitalization of knowledge produced by contractor's teams during the development of technical offers and projects, favouring its potential re-use in new projects and tenders. Technical data, information and knowledge can play a decisive role in highly competitive contexts such as construction tendering, and their reliability may affect successfulness and profitability of a project.

The Con_Tend ontology is the first that is conceived from a general contractor perspective and, although still under definition, it shows great potentials in supporting decisions in tendering processes, allowing solutions explorations and increasing contractor competitiveness.

Although the Con-Tend ontology still presents some criticalities and ambiguities in some areas, and it still works at a high level of definition, its progressive adoption is already demonstrating how linked data approaches can be the right path to follow to manage the complexity of technical knowledge produced in a contractor portfolio.

Also, the graph database technology is emerging as a way to implement a general contractor knowledge base and, primarily, to collect information during the tender processes.

To improve the efficacy of the Con-Tend ontology, refinement activities are still necessary, focusing in particular on the integration with other existing, domain-specific ontologies.

In particular, after the initial conceptual model definition, current research activities are focusing on cataloguing and assess existing ontologies, for selected domains, that could be integrated or used to refine definitions and data structure.

To conclude, it is important to state that the Con-Tend ontology – and the derived knowledge base – fulfils only part of the information necessities of a general contractor during tendering activities; a Decision Support System, able to select, elaborate and quickly suggest decisions to the technical teams may be further investigated to enhance the shifting towards fully data-driven tendering processes.

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