ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

NOVEL FRAMEWORK FOR BIM INTEROPERABILITY FOR SUSTAINABILITY AND GREEN BUILDINGS - AN APPLICATION FOR CONCRETE STRUCTURES

SUBMITTED: June 2022
REVISED: January 2024
PUBLISHED: February 2024
EDITOR: Bimal Kumar
DOI: 10.36680/j.itcon.2024.003

Marina F. Muller, Ph.D.
Florida Gulf Coast University
mmuller@fgcu.edu

Filipe Esmanioto, M.sC.
Pontifical Catholic University of Paraná (PUCPR)
filipe@averbe.com.br

Natan Huber, M.sC.
Pontifical Catholic University of Paraná (PUCPR)
natan@averbe.com.br

Eduardo F. R. Loures, Ph.D.
Pontifical Catholic University of Paraná (PUCPR)
eduardo.loures@pucpr.br

Osiris Canciglieri Junior, Ph.D.
Pontifical Catholic University of Paraná (PUCPR)
osiris.canciglieri@pucpr.br

Aaron Costin, Ph.D.
University of Florida
aaron.costin@ufl.edu

SUMMARY*: The construction industry has a great impact on the environment, therefore sustainable construction presents itself as a growing requirement of society. However, the concern with green buildings must not only be considered during the construction stage, but also during the entire life cycle of the building, integrating all stages from the design up until the demolition. Ensuring that the information permeates this lifecycle without data losses is vital. This way, efficient interoperability can support sustainability, allowing data to feed the process, and promoting the creation of more sustainable buildings. BIM (Building Information Modeling) arises as a means to support interoperability improvements in the AEC (Architecture, Engineering, and Construction) industry, by sharing models through open formats and enabling communication amongst actors. This paper presents a framework for BIM interoperability, with the goal to support knowledge organization and aid users in the decision-making processes. It will allow users to track sustainability concepts throughout the entire green BIM lifecycle and to improve processes in the construction industry toward more interoperable processes, minimizing data loss, and improving communication and efficiency. The framework is presented through process mapping techniques to analyze and integrate sustainability concepts using BIM throughout the lifecycle of a building. This framework considers not only data interoperability but also other aspects such as process, business, and service interoperability. Also, an application of the framework is described, using the case of cast-in-place concrete structures. Research findings identified the critical data points in the lifecycle of concrete structures which can influence sustainability.*

KEYWORDS*: Industry Foundation Classes (IFC), Ontology, Business Process Model and Notation (BPMN), Decision Model Notation (DMN), Green Buildings, Concrete structures, Leadership in Energy and Environmental Design (LEED).*

REFERENCE*: Marina F. Muller, Filipe Esmanioto, Natan Huber, Eduardo F. R. Loures, Osisris Canciglieri Junior, Aaron Costin (2024). Novel framework for BIM interoperability for sustainability and green buildings - an application for concrete structures.Journal of Information Technology in Construction (ITcon), Vol. 29, pg. 40-57, DOI: 10.36680/j.itcon.2024.003*

1 INTRODUCTION

Building Information Modeling (BIM) enables the management of the lifecycle improving interoperability and allowing for more efficient and sustainable buildings (Wong and Zhou, 2015). The lifecycle of a building is constituted of five stages: design, construction, operation and maintenance, and demolition. Each stage presents different challenges for sustainable construction and influences it in different ways. For example, the impact of the use of concrete structures is not relevant during the operation stages, however, it impacts the demolition stage largely, since concrete residues have a great environmental impact (Mehta, 2001). Therefore, the information must permeate the lifecycle without data losses, so sustainability data can feed the process, allowing users to create more sustainable buildings.

The impact of the construction sector on the environment can be observed through the energy used. Buildings and construction and operations account for 36% of global final energy use (Global ABC, 2018). The efficient use of BIM can support Building performance analysis (BPA) to achieve more sustainable and energy-efficient constructions, however, Chang and Hsieh (2020), state that this field of research still needs further research and development.

Important designations of sustainability are denoted by green certifications, such as LEED (Leadership in Energy and Environmental Design) which was developed in 1998 by the U.S. Green Building Council (USGBC), to provide the construction industry with a framework for identifying and implementing green buildings. Other certifications such as Building Research Establishment Environmental Assessment Method (BREEAM – United Kingdom) and Green Star (Australia) are also relevant (Oti et al., 2015), but not as relevant in the academy as LEED, since the term appeared more frequently on the literature (Muller et al., 2019). Not only that, LEED is a worldwide well-established standard in the AEC industry (Costa et al., 2018, Ma and Cheng, 2017) and the LEED elements support the processual nature that the BIM lifecycle must consider. However, Muller et al. (2019) highlights the gap for a comprehensive framework for BIM interoperability in sustainability, since most of the literature focuses solely on one stage of the building's lifecycle (usually design and construction), suggesting the need for a broader approach. Also, the need for this more comprehensive approach is seen in studies related to interoperability and sustainability, since most studies tend to focus on one aspect only.

BIM arises as a means to solve interoperability issues in the AEC industry, by modeling objects, sharing them through open formats, and facilitating communication amongst actors (Eastman et al., 2011). However, along with the use of BIM, other interoperability issues emerge, and measures must be taken to reach higher interoperability maturity levels (Succar, 2009, Muller et al., 2017). Wang and Chong (2015) highlight the importance of BIM evolving in integration with other technologies, improving the efficiency of projects at all stages of their lifecycle.

The ISO/IEC 33001:2015 Standard defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged". Interoperability can be studied through many different views, such as Chen et al. (2008) enterprise interoperability framework (EIF), which divides interoperability issues by barriers, concerns, and approaches. However, interoperability in BIM-based computer systems will forever be an endemic problem, thus the use of shared representations and linking subsets of data models together will be required (Costin et al., 2022). There are a few methods to mitigate interoperability issues, such as open application interfaces (APIs), translators, and exchange models (Costin and Eastman, 2019). In each of these, it is important for each use case to identify the data requirements needed to be passed in the end systems (Costin et al., 2021), which can be achieved by a standard methodology or framework for that specific use case.

This study presents a framework for BIM sustainability in an interoperable environment. Interoperability works as a structuring element to provide a model for BIM sustainability. This framework considers the construction lifecycle as well as interoperability concerns, integrating these two areas with sustainability markers. To provide semantic requirements for the "data" concern, an ontology layer was created to organize the knowledge and feed the processes (Liao et al., 2016). The process and services concerns were structured into a Business Process Model and Notation (BPMN), to organize the information flow. This ontology is connected to the process by semantic annotation. Finally, the process´s decision points are influenced by standards and certifications, which are aligned in the business layer of the framework, structured in a DMN (Decision Model Notation) connected to the process models (OMG, 2019), enriching a process model decision-wise (Bazhenova et al., 2019).

The objective of this paper is to present a propositional framework for BIM interoperability. This framework suggests a method to map tasks and important concepts in a field within the construction and convert them into an ontology annotated process. This is demonstrated through an application of this framework for sustainable buildings. Concrete structures were chosen to illustrate this application. They were chosen because structural elements are responsible for the greatest carbon emissions in a building (Gan et al., 2018), and among structural materials concrete is the most used worldwide, also having one of the biggest environmental impacts (Global ABC, 2018).

2 BIM AND SUSTAINABILITY THROUGH THE LIFECYCLE

This section will present the literature related to BIM interoperability for sustainable structures and will describe the referential foundation for the development of the framework structure.

The lifecycle of a building tends to be quite complex. Buildings take a few years to be planned and built, and decades to reach the point to be demolished and recycled. Special needs arise from this extended lifecycle. To improve the transferring of information, all stages can be developed by BIM methods to ensure more sustainability and interoperability in the process (Wong and Zhou, 2015). This section provides a description of interoperability concerns, sustainability categories, and their influence on the building's lifecycle. Finally, an integrated overview is presented, describing how sustainability concepts influence the lifecycle of a building.

There is more to interoperability than the concerns related to software and technical issues. For interoperability to occur efficiently, not only technical issues should be solved, but also processes must be well structured, and companies must commit to it. These different areas are called interoperability concerns (Chen et al., 2008), and Muller et al. (2015) present their relationship with BIM:

- Business: This is concerned with interoperability at the strategic and organizational levels. It relates to standards, guidelines, and certifications. These can be linked to BIM by aiding users to create methods of working and standards.
- Process: This is related to the requirements to align processes for the building’s entire lifecycle. By using BIM, companies change not only their way of designing but also alter the entire process of building and operation.
- Service: Service interoperability describes the concern of an enterprise to consume services of external sources. It focuses on the necessity to make services from diverse companies work together. In BIM this is exemplified by the role of suppliers who need to provide detailed and well-structured information about their products.
- Data: This refers to the need for different platforms and systems to work together. Digital resources and documents in the AEC (Architecture Engineering and construction) lifecycle need to be usable and available to all stakeholders, preferably through BIM. This concern is addressed by Building Smart through their open format, the Industry Foundation Classes (IFC) (Eastman et al., 2011).

BIM interoperability frameworks such as Ren and Zahang (2021) present the importance of observing data interoperability, as well as the role process mapping could play in establishing a framework for BIM interoperability. Other BIM frameworks also highlight the importance of BIM interoperability in the Business layer (standards and regulations), as described by Mzyece et al. (2019). Other BIM sustainability frameworks highlight concerns with the interoperability of BIM environmental modeling programs. Such programs often are not able to recognize building components and material properties, making it necessary to check simulation models to eliminate errors and avoid information loss. The need for a data schematic framework to enable BIM mapping between such systems is also demonstrated (Gan et al., 2018). This shows that there is a concern in literature with BIM interoperability and BIM-based sustainability, however, BIM interoperability for sustainable constructions is still a novel approach.

U.S. Green Building Council (USGBC) developed LEED as a standard for building sustainable constructions. Araszkiewicz (2016) highlights the fact that BIM can influence sustainability and aid companies to score higher in LEED´s main categories: Energy and Atmosphere; Innovation; Integrative Process; Location and Transport; Materials and Resources; Regional Priority; Indoor Environmental Quality; Sustainable Sites; Water Efficiency. BIM can aid users to keep track of points and perform simulations, choosing the most sustainable solution.

Sustainable construction practices should be considered within the lifecycle of the building. For example, if the designer decides to increase the thickness of exterior walls, this leads to greater quantities of structural materials and embodied carbon, however, this has a mild impact on operational carbon emissions. Nevertheless, when the layer of thermal insulation is thickened, the operational carbon in the building can be substantially reduced. (Gan et al 2018). Muller et al. (2019) also provides insight into how sustainability concepts weigh differently during the stages of the BIM lifecycle. For example, water efficiency has a great influence on the operation stage, however, it has little to no influence on the construction or demolition stages of a building’s lifecycle.

Even though all stages should be considered for mature interoperability and sustainability requirements, most technologies are developed for the earliest stages. A building´s lifecycle consists of four main stages: design, construction, operation and maintenance, and demolition.

- Design: When considering sustainable aspects in buildings, designers must consider the building profile, geographic location, and climate characteristics and then develop designs. After that, BIM can be used to develop analysis. If sustainability requirements are not met, new designs must be developed (Jie et al., 2014).
- Construction: BIM can aid professionals to reduce construction and operational costs, minimizing resource consumption (Wang and Zhai, 2016), and developing lean construction methods (Gordon and Holness, 2008).
- Operation and Maintenance: Green BIM models generate great amounts of data. This data can be used for managing and monitoring the building's performance, therefore, improving sustainability (Wong and Zhou, 2015). The need for BIM use emerges in maintenance, since it is a multi-domain issue, encircling financial, human resources, facility management, asset management, and code compliance, affecting all stakeholders differently (Curry et al., 2013).
- Demolition: Adopting sustainable deconstruction strategies such as recycling and reuse may result in economic and energy savings. With BIM, this cost may be estimated more precisely by users.

Also, operation and maintenance appear highly interconnected. Some authors even consider them together (Dong et al., 2014) as one stage for some studies, since they tend to happen simultaneously in the construction industry. Other Authors present them as two separate stages, such as Wong and Zhou (2015). In this study, Operation and Maintenance were considered as one single stage, due to their interdependence.

3 FRAMEWORK METHODOLOGY

This section aims to provide the description of the method used to develop the present framework. The following framework aims to organize and structure concepts of interoperability and sustainability in the construction industry through BIM. A use case in cast-in-place concrete structures for sustainable buildings is used for validation, which was chosen to demonstrate the framework since structural elements are responsible for the greatest impact, being responsible for the highest percentage of carbon emissions (Gan et al., 2018). Also, concrete structures influence a building´s sustainability through all stages, even until the demolition. (Mehta, 2001). The framework is based on well-established researchers within BIM literature, such as Eastman, Azhar, Jalaei, Jrade, Succar, Wong, and Zhow (not necessarily in particular studies, but these authors were strongly referenced as a whole). Also, the terms that are foundational in this framework are relevant keywords in BIM research, such as: Framework, Interoperability, Lifecycle, Sustainability, BIM, and ontology (Saka and Chan, 2019).

This framework presents a disk structure as seen in Figure 1. Each slice represents the stages of the building´s lifecycle: Design, construction, operation and maintenance, and demolition. The transversal layers are structured to organize interoperability concerns as follows:

- Business: The outermost layer presents the standards and certifications used. This information carries decision support factors to influence the process toward more sustainable constructions. In this case, LEED is used as a reference, since it provides a well-structured scoring system, however, any certification or standard can be used. The LEED manual is structured in a DMN matrix with the ontology and connected to the process in the data layer (Tibaut et al., 2017).
- Process and services: Processes can be designed on the center layer and used to structure and bind together the other two layers. It receives inputs from both the innermost and outermost layers, that

feed it with data and information going through different actors and stages of the lifecycle. Also, it is important to establish processes for better decision-making in the construction industry (Abdelhady, 2013).

- Data: The innermost layer is where data is structured through IFC-based ontology, as suggested by Venugopal et al. (2015), ontology can be used to improve IFC interoperability. Ontologies can be an important tool to organize information shared through the process lifecycle. As shown by Liao et al. (2016), processes can use ontologies to create an understanding of the semantics and exchange knowledge to improve semantic interoperability. This layer works as a repository for knowledge that feeds the other layers.

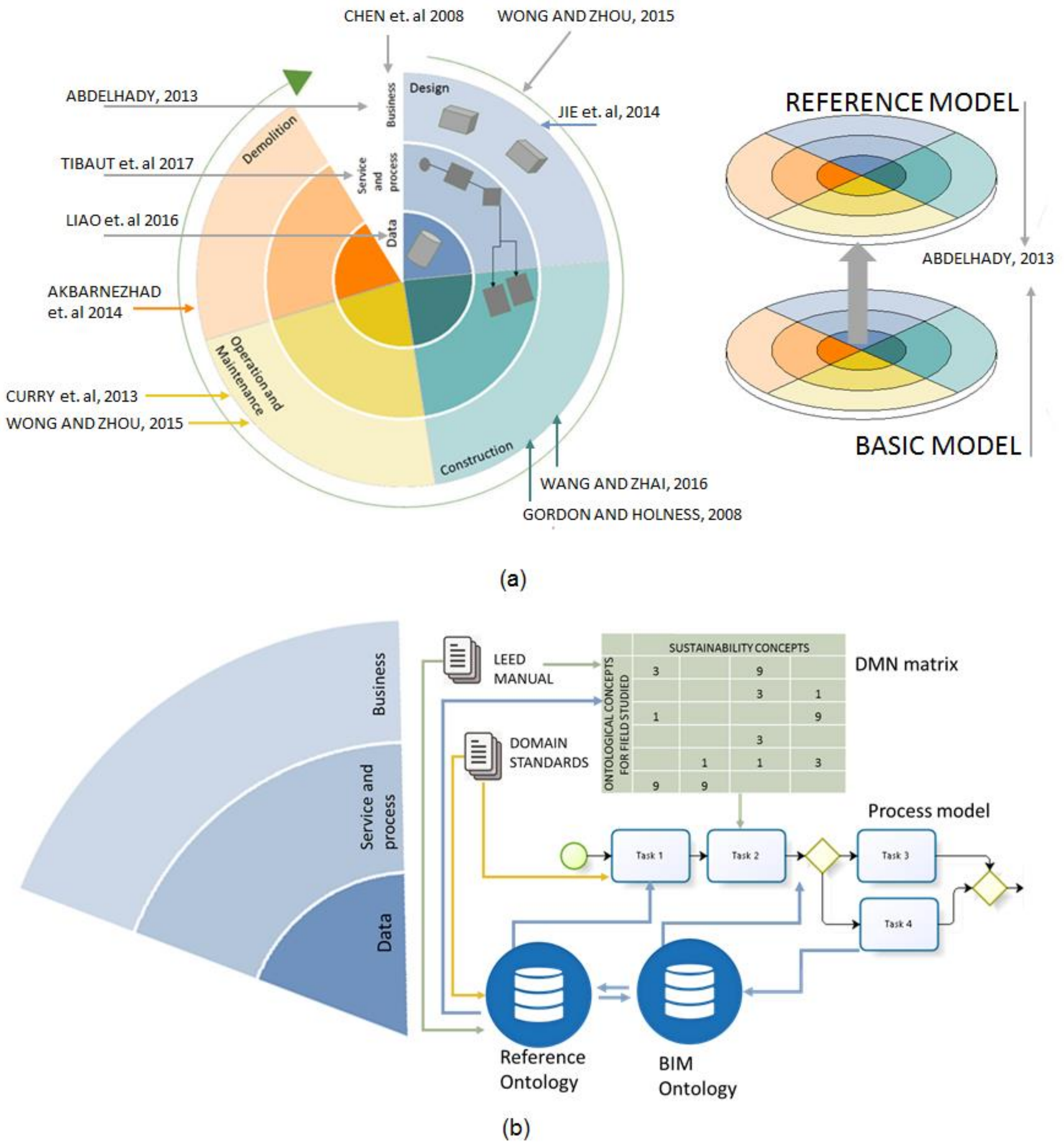

Figure 1: (a) Framework for interoperability in the green BIM lifecycle with references. (b) Framework detail.

The proposed framework presents two phases related to two different moments: A basic and a reference model. First, a basic model is developed, observing companies, and structuring the current state of the AEC industry in the interoperability and sustainability field, considering a pre-BIM or early BIM moment in the industry, when companies don't use BIM or use BIM mainly for geometrical purposes, carrying little information through the lifecycle. After that, a reference model is developed, presenting the scenario with ideal BIM use and efficient interoperability (Abdelhady, 2013), as seen in Figure 1.

The information flow between the stages is one of the main concerns of the framework since it must permeate the entire cycle. This way a central data ontology-based repository supports the other layers acting as a semantical reference. This data allows the semantic annotation of the processes and the Decision Model Notation (DMN) matrix, so it is possible to observe information bottlenecks and analyze LEED's influence on each process task. This DMN relational matrix is based on LEED points and the influence of the ontological concepts used on each task of the process on sustainability. These influence factors can support decision toward the most sustainable options for a building. This structure is demonstrated in Figure 1. For instance: In the design stage, in task "Define slab type", the designer may opt for a plan slab or a waffle slab type. The waffle slab usually creates less residue and presents better thermal insulation for construction, so it would present a higher influence LEED factor, suggesting the designer to follow the path to the task "select waffle slab type".

This framework can be applied to different systems or fields in the AEC industry, such as concrete structures, led lighting, plumbing, etc. The chosen field can then be cathegorized by its own ontology, process, and matrixes. Thereby, companies from specific fields can focus on their interoperability and sustainability goals and compare their status to the ideal, and verify new ways to improve and achieve a higher interoperability maturity level on sustainability.

3.1 Framework development

First, a set of methodological steps must be taken to structure such a framework. The structure is presented for both the basic model and the reference model. To present the framework process, IDEF0 diagrams are used. They show the methodological process and steps of the framework, considering inputs, outputs, programs used, etc. (Cheng-Leong et al., 1999). Then, Figure 2 presents the methodology proposed in further detail.

3.1.1 Basic model

The basic model considers the state of pre-BIM or early BIM. Figure 2 describes the development of processes and ontologies in an IDFE0 diagram. In an IDEF0 model, the arrows entering the boxes horizontally are the inputs and the exiting are the outputs of every stage. The vertical downward arrows are the methods used, and the upward ones represent the tools used.

First, the business layer must be structured. In this case, domain standards are selected and analyzed. In the second step, a preliminary process can be modeled based on literature and standards from the specific field from the business layers. This process is then refined into a final process by an Information Acquisition Instrument (IAI 1), containing questions sent to companies specialized in each of the lifecycle stages. This IAI 1 provides the process modeler with information on tasks, sequences, and professionals involved in each process.

The third step is to develop the ontology for the data layer. This ontology can be extracted from IFC files. First, native BIM files containing elements from the field studied can be exported to IFC. For example: for concrete structures, models such as concrete beams, slabs, and columns were used. These files can be exported as an ontology on the Terse Triple Language (TTL) format, containing elements such as structure types, concrete characteristics, reinforcement bars diameters, etc. These files are readable by ontology editors (Di Mascio et al., 2013) and can be presented in an ontology viewer called ontograph.

3.1.2 Reference model

The reference model considers full BIM use and interoperability efficiency throughout the lifecycle. The process can be developed similarly to the basic process. The preliminary processes are developed based on the basic processes, literature, and standards of the field. Collecting the literature references, data and standards is the first step to developing the reference method. However, for the reference processes the IAI is submitted to specialists, going through Delphi rounds, either until the specialists reach consensus or until a predefined number of rounds (Hsu, 2007). This is the second step for the Reference model.

The third step is to structure the data for the Reference Model. An ontology can be developed based on the literature and standards of the field. The method used was the Seven-Step method, which is an already established ontology development methodology (GAO et al., 2017). The method consists of first, determining the domain and scope of ontology, then considering reusing existing ontologies. If not available, one should list important terms in the ontology and then define the classes and the hierarchical classes. Finally, one should define the properties of the classes, and the rules, and create Individuals.

Systems may present syntactic, structural, or semantic differences. The syntactic question is concerned with the use of different models or languages, the structural issue is related to divergences between data structures adopted by each system and the semantic issue refers to the adoption of divergent interpretations for the information exchanged between the systems (Sheth, 1999).

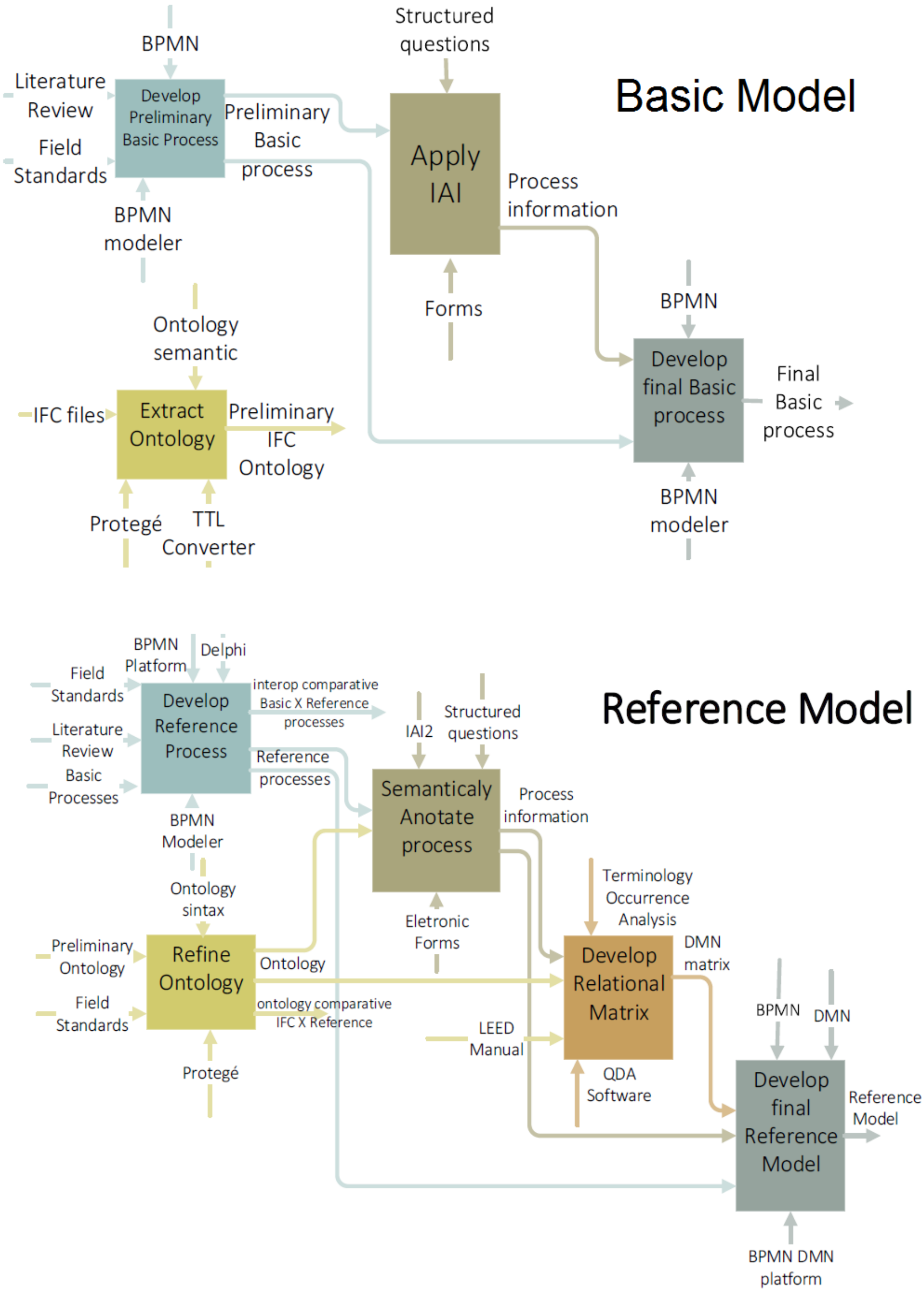

Figure 2: Reference and basic IDEF0 models.

It is possible to enrich process models with semantic annotations from domain ontologies to formalize both the structural and information domain in a shared knowledge base (Di Francescomarino, 2011; Liao et al., 2016). Thus, the fourth step is to add to the process model semantic annotation using the ontology classes, this way, guiding users on the information entry during the process. This process annotation can be supported by a questionnaire, and professionals can inform which information from the ontology classes they use on which task of the process. This information can be stored in a data section of most Business Process Model and Notation (BPMN) modelers to enrich the process semantically.

The fifth step lies within the business layer again. To apply the sustainability concepts to the process, a relational matrix can be developed. A sustainability manual or guideline can be inserted into a QDA (Qualitative Data Analysis) software, and each ontology class term can be configured as a code on the program (Muller et al., 2019). A search is performed, and the relationships between the ontology versus the manual can be quantified. For example, if the number of times the term StructuralElement appeared in the LEED manual section Materials & Resources is higher than in the section Water Efficiency, It means that it might have a higher influence on that field of sustainability.

Finally, based on this matrix, a DMN can be structured. Since the ontology classes used on the semantic annotation of the process and in the annotation of the matrix are the same, the DMN can be linked to the process by this very semantic annotation, this way, it is possible to obtain sustainable guidelines in the process to aid users to make more sustainable decisions. This process is described in Figure 2.

4 FRAMEWORK IMPLEMENTATION

An application case for the framework was conducted by interviewing several companies and specialists, each answering according to their fields of expertise in the lifecycle stages. This example was structured using LEED for the business guidelines and cast-in-place concrete structures as the case for the study. Any sustainability certification and any construction field can be used. This was the first step described in the methodology. Also, the results here presented refer to the design stage, however, all the other stages were also developed with similar results.

4.1 Information acquisition instrument

As the second step of the methodology, an Information Acquisition instrument to be sent to companies and specialists is necessary to develop the process maps. Based on the literature, preliminary processes are developed both for the basic phase as for the reference. Based on these preliminary processes, an information acquisition instrument (IAI) can be structured in two parts. The IAI1 is used to verify the inputs, outputs, and performers for each task of the processes, as well as its sequence, as seen in Figure 3. After the information is acquired, a new refined process closer to reality can be structured. For the reference model phase, the questions can even be structured in a Delphi method as well to refine and improve the ideal model even further.

This instrument can be useful not only to structure the processes but also can support the annotation of the ontology in the data layer developed previously for the processes and the matrix. For each task of the process studied, the consumed information is requested on the IAI 2, so the link between the data and process layers can be made through ontological semantic annotation. This instrument can be sent to companies and specialists via digital media. A simplified example is presented in Figure 3.

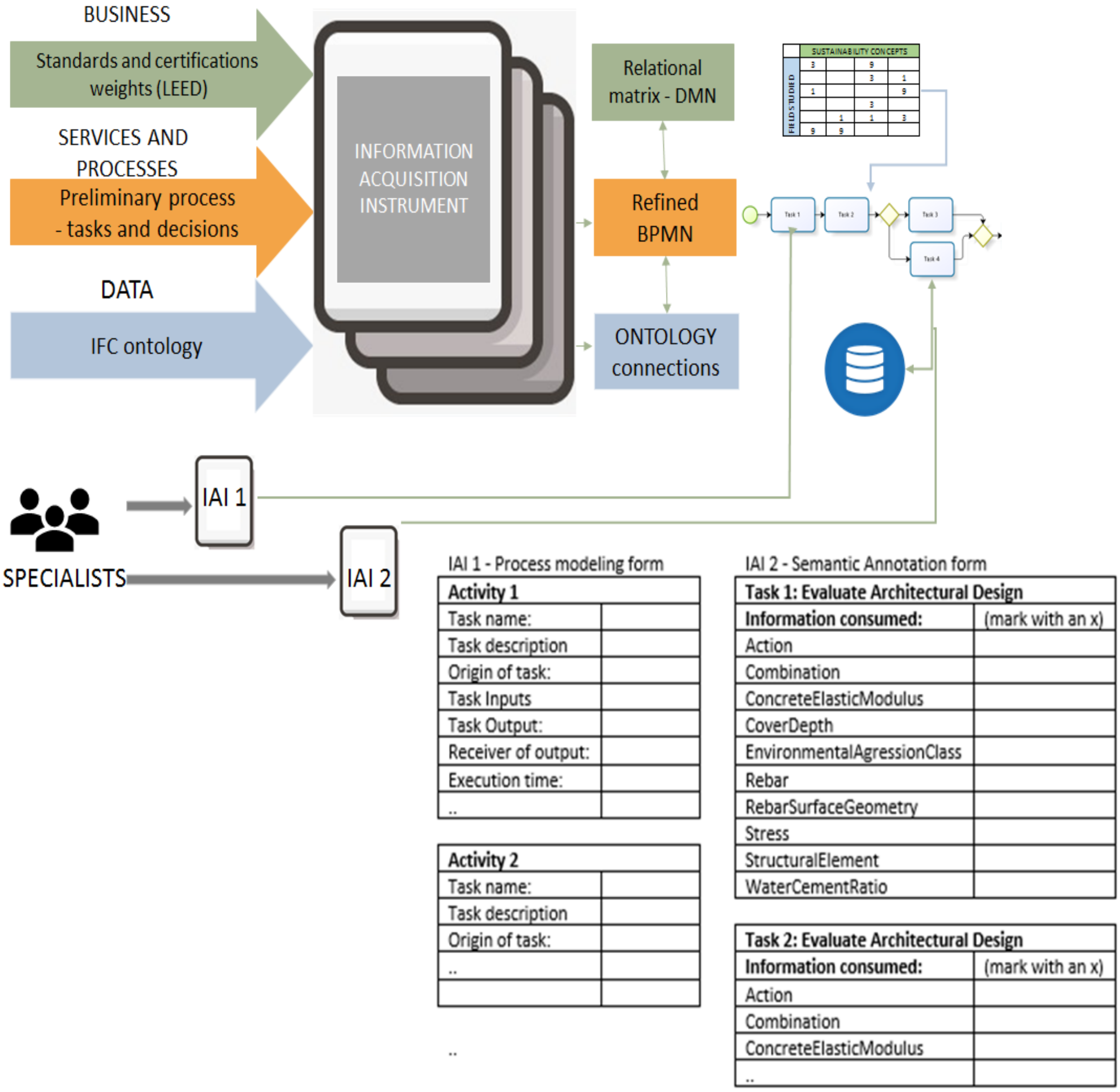

Figure 3: Information acquisition instrument.

4.2 Ontology

The third step of the method includes the development of the ontologies. The preliminary ontology was generated from an IFC model. The system generated a very simple ontology, in which there was no presence of relations between objects and classes, or formal axioms (Figure 4a). The reference ontology was developed from Brazilian cast-in-place concrete standards (ABNT NBR 14931:2004, ABNT NBR 6118:2014, ABNT NBR 5674:2012, ABNT NBR 8953:2015 and ABNT NBR 5686:1977). Figure 4b presents an ontology for the design stage, however, each stage had its ontology development. This ontology presented many classes, axioms, data types, and a more complex structure than the one extracted from the IFC model. A comparative model between IFC ontology and the ontology generated by the standards and manuals can be presented, to aid developers to structure IFC files to support data interoperability, improving interoperability in the AEC industry overall.

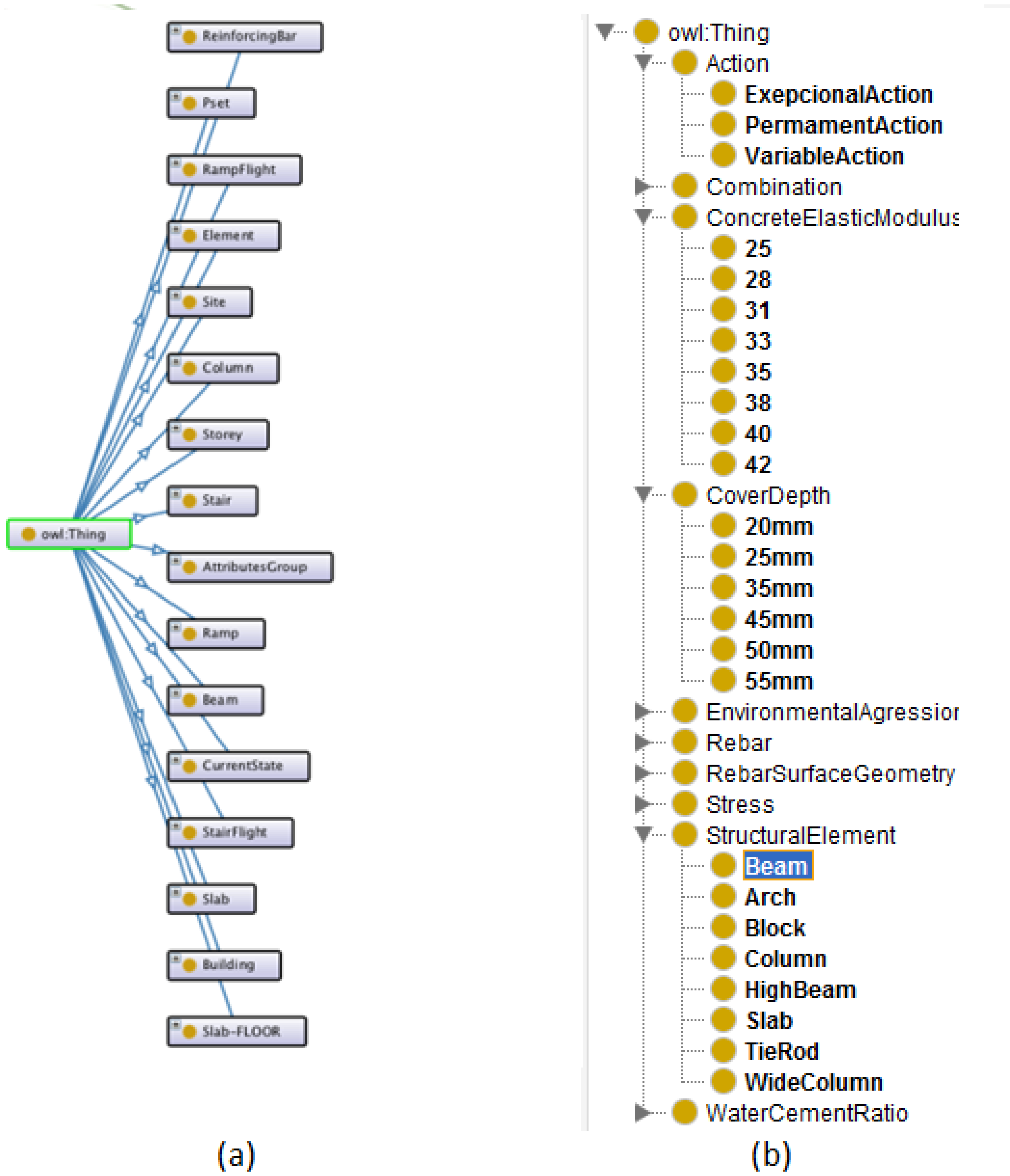

Figure 4: (a) Ontology extracted from the IFC file and (b) ontology developed from the chosen standard manuals.

4.3 Process model and semantic annotation

The methodology adopted in the modeling of the basic processes is based on the ABNT standards. Professionals of companies acting on each stage of the lifecycle of a reinforced concrete structure were, then, individually interviewed. In so doing, these professionals were able to define which tasks belong to the process and what their sequence is. Also, through the interviews, it was possible to map and understand the processes of all stages.

For the reference processes, the Delphi method was used for the validation and improvement of the preliminary proposals. The preliminary processes were developed based on the ABNT standards for cast-in-place concrete structures. After this stage, questionnaires about these processes were sent to the specialists. To do so, a total of 16 interviews were made with 5 specialists from the Design, Construction, Operation and Maintenance, and Demolition areas, and after three rounds the specialists reached a consensus.

Most changes suggested were not related to BIM utilization. From a total of 20 changes recommended by specialists, 6 were related to BIM, and only 2 proposed significant changes – as in the project process that foresees the insertion of a professional called BIM Manager. Figure 5 illustrates a part of the process model of the design stage after the Delphi final round, showing the process tasks (boxes), gateways (diamonds), and lanes (solid lines).

The fourth step in the method is to perform the semantic annotation of the process. The IAI 2 was sent to a company and the data was collected. The information of which ontology classes were used on each task was stored in a small database on each task of the process modeler, thus, annotating the process semantically. The data collected by the IAI2 not only can be consumed by the process modeler, but also can provide important information such as which process tasks utilize more information, and which information is used more often, identifying bottlenecks and crucial information requirements. To better illustrate this, a graphic in Figure 6 was developed showing which ontology classes are used more often by the company interviewed. The class StructuralElement appeared in almost all the tasks of the process. Therefore, the information related to it must be carefully treated, ensuring its interoperability integrity throughout the process.

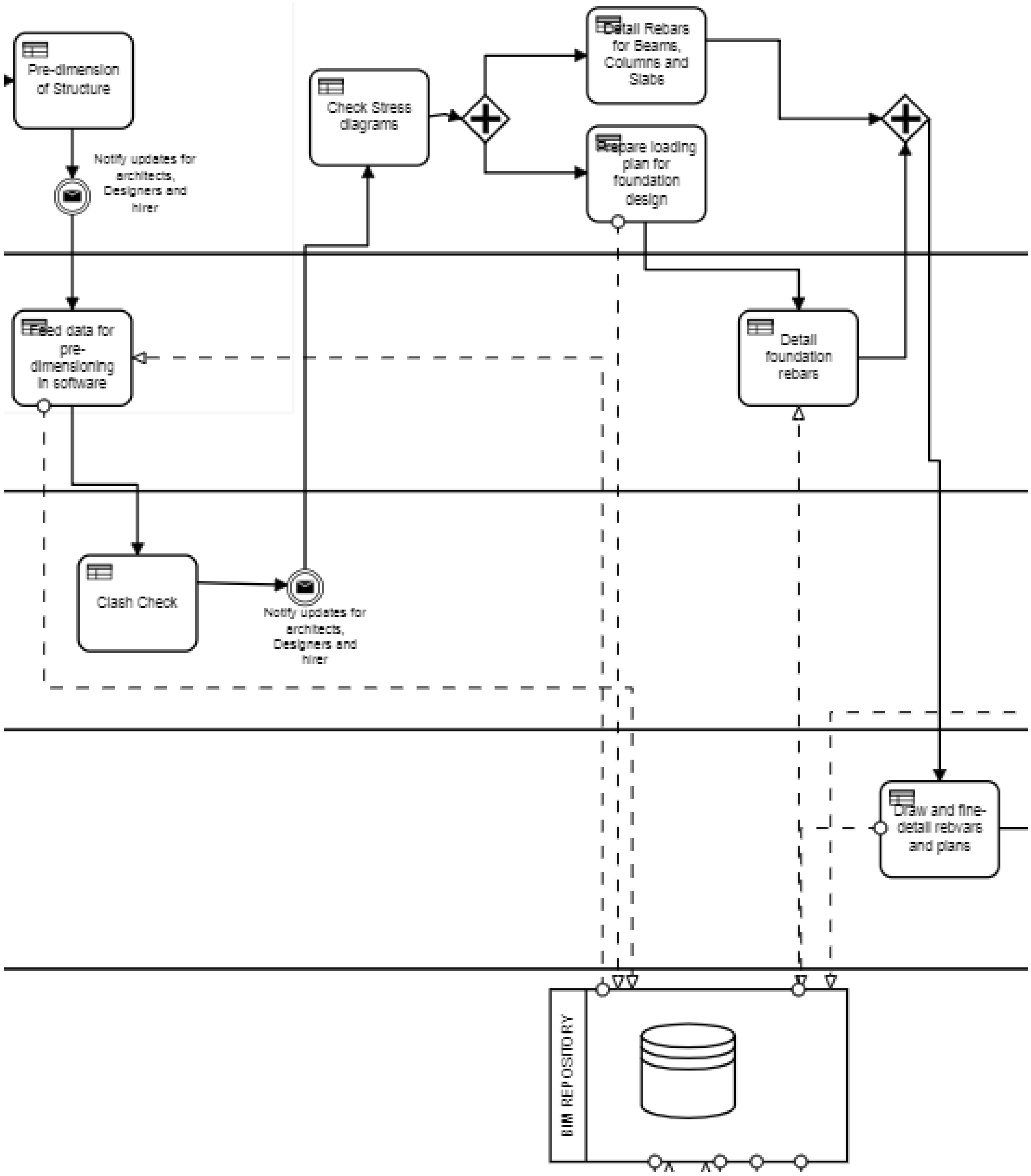

Figure 5: Process model of the design stage after the Delphi final version.

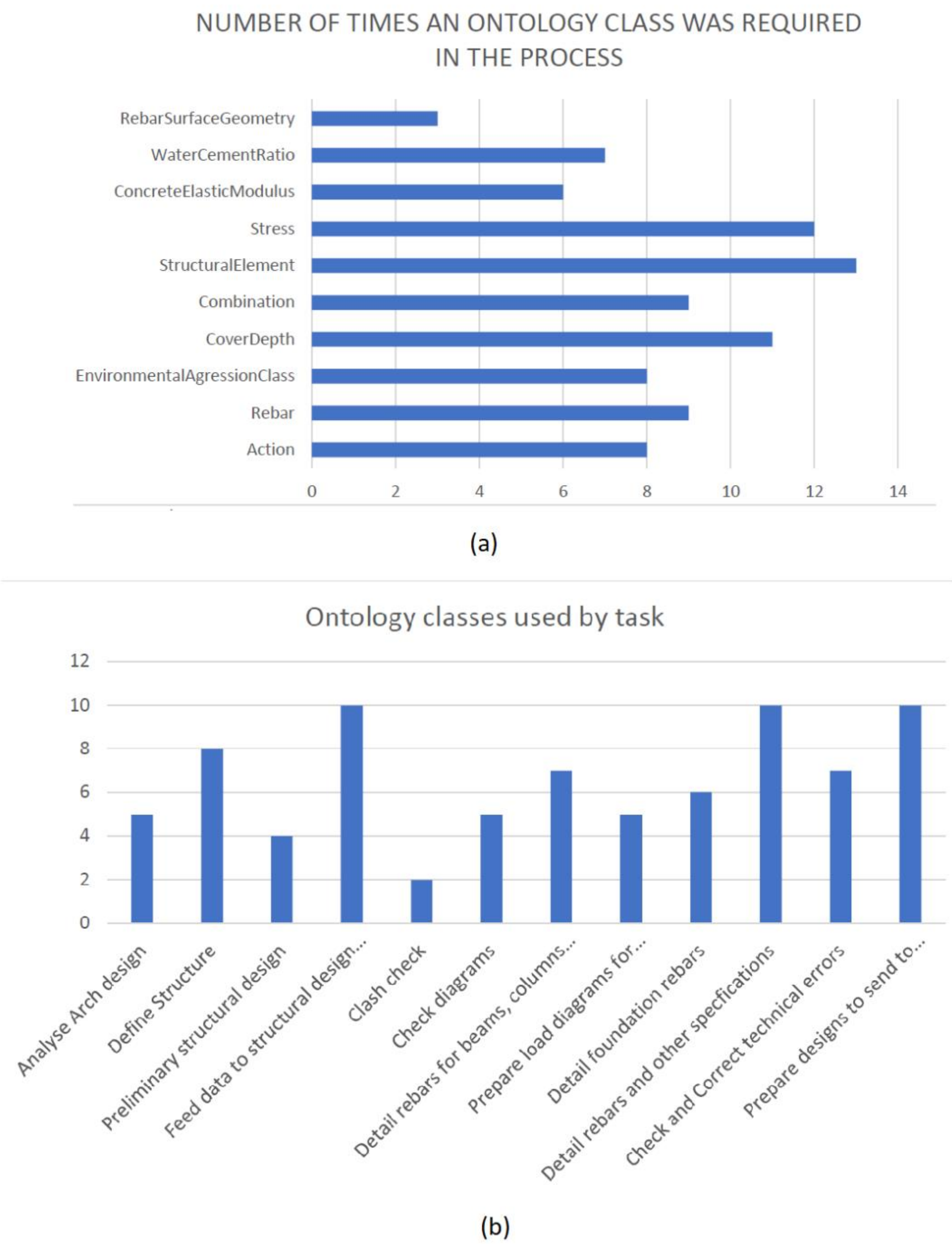

Figure 6: (a) Number of times an Ontology Class was required in the Process and (b) Number Ontology Classes Consumed by Task.

Also, from the data collected from IAI2, an analysis can be developed to show which task consumes more ontological concepts. The results from the design processes can be seen in Figure 6b. It can be seen that both the beginning of the process (performing the preliminary structural design and feeding the data to the analysis software) and its end (Detailing rebars and preparing designs for the construction site) consume a lot of data, therefore supporting the importance of interoperability in the processes, so that the information may be available in the beginning and able to reach the end without data losses.

4.4 Process model and semantic annotation

Finally, to apply the sustainability concepts to the process, a relational matrix was developed. The LEED manual was inserted into a QDA (Qualitative Data Analysis) software, and each ontology class was configured as a knot on the program. A search was performed, and a relation between each ontology class and each LEED field was presented. This process is seen in Figure 7. Which shows the matrix developed, where, a higher number indicates a stronger correlation.

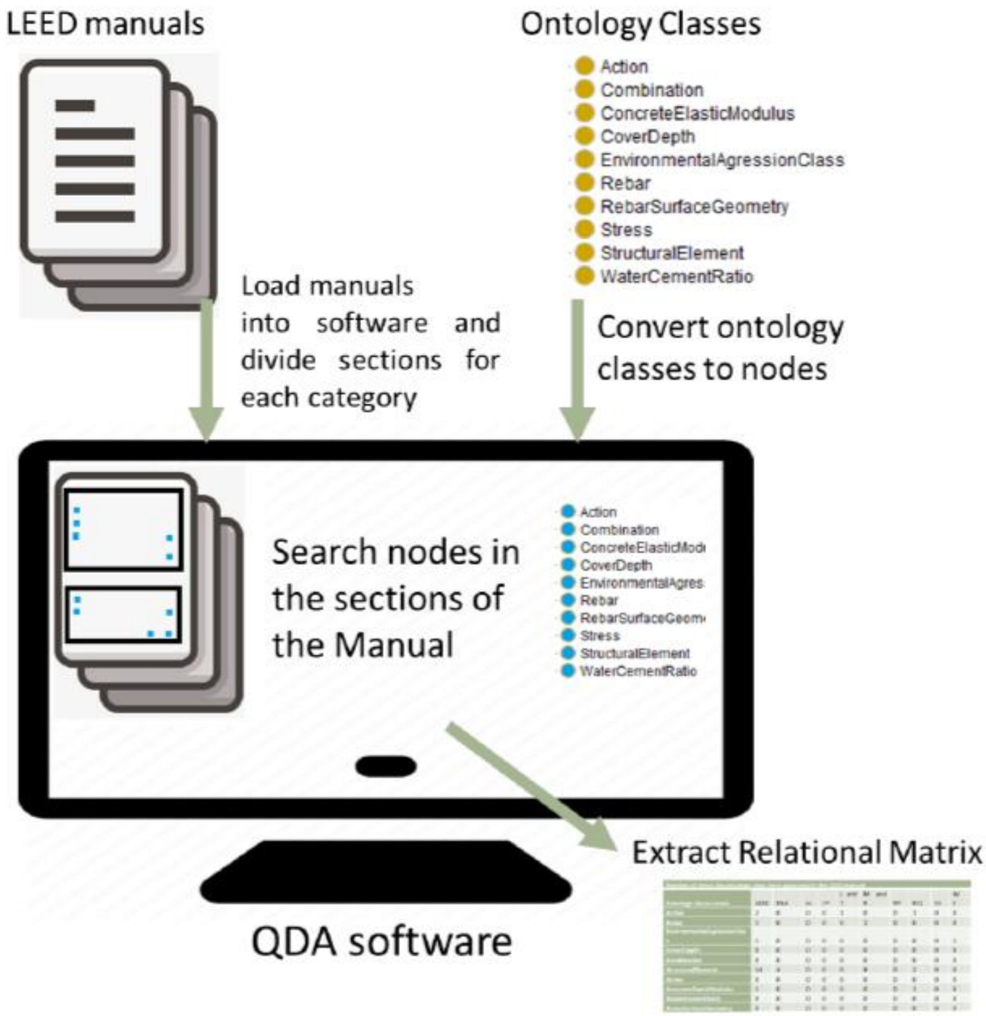

Figure 7: Development of the influence matrix from the ontology and LEED manual and resultant matrix.

Based on this matrix, a DMN was structured. Since the ontology classes were used on the semantic annotation, and in the matrix are the same, the DMN can be linked to the process by the semantic annotation stored in each task of the process, this way, it is possible to obtain sustainable guidelines in the process to aid users to make more sustainable decisions. Figure 8 shows the DMN. Therefore, when the user deploys the process in the BPMN platform he or she can also enter into this platform the terms for the ontological elements in each task. When that particular task is executed, the platform will return the influence in sustainability established in the DMN matrix and the number of possible points LEED points for such category, allowing the user to consider a more sustainable option in that task. In the example shown, when the structural designer starts the task "Detail Rebars", he or she can view which ontological concepts are associated with that task. By entering one or more terms in the platform, the system runs the DMN matrix and returns the LEED influence associated with that concept. In this case "Has low influence in Materials and Resources" is shown, and the system may even check the matrix for the possible points for that category. In this case, the user will know that the rational use of rebars may aid a little to achieve higher sustainability points in the materials and resources LEED category.

It can be seen the "StructuralElement" is the ontology concept that has the most influence on sustainability, and also the term that is more often consumed in the process, therefore, any decision related to structural elements (slabs types, column and beam dimensions, etc.) should be taken with careful consideration for the sustainability influence on the building.

Figure 8: DMN table for sustainability in cast-in-place concrete structures and Input/output of ontology in the process task.

This decision-making model was developed for the design stage of the lifecycle, but can be developed for any stages of the lifecycle, adapting the process model, the ontology, and the sustainability manual if necessary (e.g., LEED has specific manuals for the renovation/maintenance stage). This type of decision support can be significant to aid professionals in the construction industry to make decisions of substantiality more quickly and effectively. Depending on the information used on each task, the process platform can return automatically the influence that task and specific data have on sustainability, reducing the time used to analyze each case according to the manual.

The information collected in the framework application was used to structure three main artifacts. These outputs are consistent with the needs presented in Muller et al; (2019), where an approach that considered the needs for sustainability decision guidelines and interoperability support through all levels and stages of the lifecycle was shown to be in demand. These three main documents seek to structure information based on the data obtained and to aid users to better understand the use of BIM to make decisions seeking improvements in sustainability.

- Ontology: A BIM ontology can be used to structure the information present both in the "data" layer of the cycle, as well as to feed the sustainability matrix and processes. Also may be used by developers to improve IFC interoperability.

- Business Process Model and Notation (BPMN): A process can be structured in a BPMN notation. This process will fill the “process and services” layer, describing activities and connecting both the other layers and structuring the framework.
- Decision support: from the requirements of sustainability, standards, and certifications, a decision support matrix can be developed. This matrix is then transformed into a DMN table and deployed with the BPMN processes. This way, the DMN will return users with decision support on LEED points, so the user may find the best solutions for each project.

These artifacts were developed for both the basic and reference phases, except for the decision support matrix, which considers only the reference stages. These artifacts structure knowledge and aid companies toward a more sustainable and interoperable lifecycle for buildings, providing tools to improve processes, organize information, and improve decisions, considering environmental issues in an interoperable manner.

5 CONCLUSION

The duration of the lifecycle of the construction industry requires special attention when considering sustainability. This is important since there is a need to improve interoperability between BIM sustainability analysis systems (Gan et al., 2018). Since BIM can aid in the management of this lifecycle, a framework was developed to organize knowledge and aid users in decision processes. This framework, which is composed of three layers, is based on interoperability methods to ensure that the information flow is well-structured. The first and innermost layer is an ontology-based data repository. The second layer presents the process used. The third and outermost layer contains the decision support to guide the processes toward more sustainable directions. Other frameworks also highlight the importance of processes and data to ensure smooth BIM interoperability (Ren and Zahang, 2021; Mzyece et al., 2019).

From the sustainability point of view, the use case revealed that “StructuralElement” is the term that has the most influence in the sustainability matrix, and since the term that is more often consumed in the processes, any decision related to structural elements (slabs types, column and beam dimensions, etc.) should be taken with careful consideration for the sustainability influence on the building.

The scope of the application of this study was limited to the interoperability of Cast-in-place concrete structures and its relationship to interoperability. This framework can be applied to any area in the construction industry. Future works can develop a detailed frame for any of these areas. Possible applications are lighting systems, plumbing facilities, air-conditioning, and other structural systems. Also, a comparative model between IFC ontology and the ontology generated by the standards and manuals can be presented, as well as an evaluation of processes improvement in interoperability with the use of BIM. Also, though a study regarding the entire lifecycle was developed, only the design stage is here presented due to space limitations.

One of the difficulties met in the process was finding companies and standards to develop the Operation and Maintenance phases, but especially the Demolition. In the case of the latter, an older and retired version of the standard had to be used.

This framework can be employed by construction industry professionals, organizing and structuring processes, decisions, and data storage. It can also be used by developers, considering the ontology developed as a structure for IFC exportation and importation. Improvements in interoperability were also noticed with the use of BIM, from the Basic model to the Reference model, therefore both professionals and developers should consider the importance of BIM-based processes.

REFERENCES

Abdelhady, I.A.I., Jones, J.R., Grant, E., Carlson, K.D., Schubert, R., Mcginnis, S. (2013). A New Business Process Model for Enhancing BIM Implementation in Architectural Design, Doctoral Dissertation, Virginia Polytechnic Institute and State University.

ABNT - Associação Brasileira de Normas Técnicas. (1977). NBR 5682 - Contratação, execução e Supervisão de Demolições, 41.

ABNT - Associação Brasileira de Normas Técnicas. (2004). NBR 14931 - Execução de Estruturas de Concreto -

Procedimento, 53.

ABNT - Associação Brasileira de Normas Técnicas. (2012). NBR 5674 - Manutenção de edificações - Requisitos para o sistema de gestão de manutenção, 27.

ABNT - Associação Brasileira de Normas Técnicas. (2014). NBR 6118 - Projeto de estruturas de concreto — Procedimento, 233.

ABNT - Associação Brasileira de Normas Técnicas. (2015). NBR 8953 - Concreto para fins estruturais — Classificação pela massa específica, por grupos de resistência e consistência, 3.

Araszkiewicz, K. (2016). Green BIM concept-Scandinavian inspirations. Archives of Civil Engineering, 62(1).

Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I. (2011). Building information modeling for sustainable design and LEED® rating analysis, Autom. Constr., 20, 217–224. https://doi.org/10.1016/j.autcon.2010.09.019

Bazhenova, E., Zerbato, F., Oliboni, B., Weske, M. (2019). From BPMN process models to DMN decision models, Inf. Syst., 83, 69–88. https://doi.org/10.1016/j.is.2019.02.001

Chang, Y. T., & Hsieh, S. H. (2020). A Review of building information modeling research for green building design through building performance analysis, Journal of Information Technology in Construction, 25, 1–40. https://doi.org/10.36680/j.itcon.2020.001

Chen, D., Doumeingts, G., Vernadat, F. (2008). Architectures for enterprise integration and interoperability: Past, present and future., Comput. Ind., 59, 647–659. https://doi.org/10.1016/j.compind.2007.12.016

Cheng-Leong, A., Pheng, K. L., Leng , G. R. K. (1999). IDEF*: A comprehensive modelling methodology for the development of manufacturing enterprise systems, International Journal of Production Research, 37, 17, 3839-3858. https://doi.org/10.1080/002075499189790

Costa, O., Fuerst, F., Robinson, S.J., Mendes-Da-Silva, W. (2018). Green label signals in an emerging real estate market. A case study of Sao Paulo, Brazil, J. Clean. Prod., 184, 660–670. https://doi.org/10.1016/j.jclepro.2018.02.281

Costin, A., Eastman, C., (2019). Need for interoperability to enable seamless information exchanges in smart and sustainable urban systems, Journal of Computing in Civil Engineering, 33(3), 04019008. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000824

Costin, A., Hu, H., Medlock, R. (2021). BIM for Bridges and Structures Case Study: Outcomes and Lessons Learned from the Steel Bridge Industry, Transportation Research Record, 2675(11), 576-586. https://doi.org/10.1177/03611981211018691

Costin, A., Oullette, J., Beetz, J. (2022). Building Product Models, Terminologies and Object Type Libraries, Web and Cloud Technologies for the Built Environment, Pauwels, P. and McGlinn, K. (ed.s), CRC Press.

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., O'Riain, S. (2013). Linking building data in the cloud: Integrating cross-domain building data using linked data, Adv. Eng. Informatics, 27, 206–219. https://doi.org/10.1016/j.aei.2012.10.003

Di Francescomarino, C., Ghidini C.,Rospocher, M., Serafini, L., Tonella, P. (2009). Semantically-Aided Business Process Modeling, Lecture Notes in Computer Science, 5823, 114–129. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-04930-9_8

Di Mascio, D., Pauwels, P., De Meyer, R. (2013). Improving the knowledge and management of the historical built environment with BIM and ontologies: the case study of the Book Tower, 13th Int. Conf. Constr. Appl. Virtual Real, 427–436.

Dong, B., O'Neill, Z., Li, Z. (2014). A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics, Autom. Constr., 44, 197–211. https://doi.org/10.1016/j.autcon.2014.04.007

Eastman, C., Teicholz, P., Sacks, R., Liston, K. (2011). BIM Handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors, John Wiley and sons, New Jersey.

Gan, V.J.L., Deng, M., Tse, K.T., Chan, C.M., Lo, I.M.C. and Cheng, J.C.P. (2018). Holistic BIM framework for sustainable low carbon design of high-rise buildings, Journal of Cleaner Production, 195, 1091–1104.

https://doi.org/10.1016/j.jclepro.2018.05.272

Gao, Wei, Linli Zhu, Yun Guo, and Kaiyun Wang. "Ontology learning algorithm for similarity measuring and ontology mapping using linear programming." Journal of Intelligent & Fuzzy Systems 33, no. 5 (2017): 3153-3163.

Global Alliance for Building and Construction (2018). 2018 Global Status Report Towards a zero-emission, efficient and resilient buildings and construction sector, International Energy Agency and the United Nations Environment Programme.

Gordon, V.R, Holness P.E. (2008). BIM Gaining Momentum, Am. Soc. Heating, Refrig., and Air- Cond. Eng. Inc., 50(6), 28-40.

Hsu, C., Sandford, B.A. (2007). The Delphi Technique: Making Sense of Consensus, Practical Assessement Research and Evaluation, 12(1), 10. https://doi.org/10.7275/pdz9-th90

Jalaei, F., Jrade, A. (2014). “Integrating Building Information Modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings”, J. Inf. Technol. Constr., 19, 494–519. https://www.itcon.org/2014/29

Jie He, B. J., Ye, M., Yang, L., Fu, X. P., Mou, B., & Griffy-Brown, C. (2014). The combination of digital technology and architectural design to develop a process for enhancing energy-saving: The case of Maanshan China. Technology in Society, 39, 77-87.

Kim, J.I., Kim, J., Fischer, M., Orr, R. (2015). BIM-based decision-support method for master planning of sustainable large-scale developments, Autom. Constr., 58, 95–108. https://doi.org/10.1016/j.autcon.2015.07.003

Liao, Y., Lezoche, M., Panetto, H., Boudjlida, N. (2016). Semantic annotations for semantic interoperability in a product lifecycle management context, Int. J. Prod. Res., 54, 5534–5553. https://doi.org/10.1080/00207543.2016.1165875

Ma, J., Cheng, J.C.P. (2017). Identification of the numerical patterns behind the leading counties in the U.S. local green building markets using data mining, J. Clean. Prod., 151, 406–418. https://doi.org/10.1016/j.jclepro.2017.03.083

Mehta, B.Y.P.K. (2001). Reducing the Environmental Impact of Concrete, Concrete Internacional, 61–66.

Muller, M.F., Esmanioto, F., Huber, N. and Loures, E.R. (2019). A systematic literature review of interoperability in the green Building Information Modeling lifecycle, Journal of Cleaner Production, 223, 397–412. https://doi.org/10.1016/j.jclepro.2019.03.114

Muller, M.F., Garbers, A., Esmanioto, F., Huber, N., Loures, E.R., Canciglieri, O. (2017). Data interoperability assessment though IFC for BIM in structural design – a five-year gap analysis, J. Civ. Eng. Manag., 23, 943–954. https://doi.org/10.3846/13923730.2017.1341850

Muller, M.F., Loures, E.R., Junior, O.C. (2015). Interoperability Assessment for Building Information Modelling. Proc. 3rd Int. Conf. Mechatronics, Robot. Autom., 224 – 231. https://doi.org/10.2991/icmra-15.2015.45

Mzyece, D., Ndekugri, I.E. and Ankrah, N.A. (2019). Building information modelling (BIM) and the CDM regulations interoperability framework, Engineering, Construction and Architectural Management, 26(11), 2682–2704. https://doi.org/10.1108/ECAM-10-2018-0429

OMG, Object Management Group (2019) Case Management Model and Notation. Version 1.0. http://www.omg.org/spec/CMMN/1.0/PDF/.

Oti, A.H., Tizani, W. (2015). BIM extension for the sustainability appraisal of conceptual steel design, Adv. Eng. Informatics, 29, 28–46. https://doi.org/10.1016/j.aei.2014.09.001

Ren, R. and Zhang, J. (2021). A New Framework to Address BIM Interoperability in the AEC Domain from Technical and Process Dimensions, Advances in Civil Engineering, 2021, 8824613. https://doi.org/10.1155/2021/8824613

Saka, A. B. and Chan, D. W. M. (2019). A global taxonomic review and analysis of the development of BIM research between 2006 and 2017, Construction Innovation, 19(3), 465–490. https://doi.org/10.1108/CI-12-2018-0097

Schlueter, A., Thesseling, F. (2009). Building information model based energy/exergy performance assessment in early design stages, Autom. Constr., 18, 153–163. https://doi.org/10.1016/j.autcon.2008.07.003

Sheth, A. P. (1999). Changing Focus on Interoperability in Information Systems: From System, Syntax, Structure to Semantics, Interoperating Geographic Information Systems, The Springer International Series in Engineering and Computer Science, 495, 5–29, Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-5189-8_2

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders, Autom. Constr., 18, 357–375. https://doi.org/10.1016/j.autcon.2008.10.003

Tibaut, A., Kaučič, B., Perhavec, D., Panetto, H., Tiano, P. (2017). Knowledge engineering approaches for building materials domain. In: International Conference on Construction Materials for Sustainable future, 1, 864- 870.

U.S. Green Building Council. (2017). Green Building Facts. Available at: www.usgbc.org, Accessed time: May 2018.

Venugopal, M.; Eastman, C. M.; Teizer, J. (2015). An ontology-based analysis of the industry foundation class schema for building information model exchanges, Advanced Engineering Informatics, 29 (4), 940–957. https://doi.org/10.1016/j.aei.2015.09.006

Wang, H., Zhai, Z. (John) (2016). Advances in building simulation and computational techniques: A review between 1987 and 2014, Energy Build., 128, 319–335. https://doi.org/10.1016/j.enbuild.2016.06.080

Wang, X. and Chong, H. Y. (2015). Setting new trends of integrated Building Information Modelling (BIM) for construction industry, Construction Innovation, 15(1), 2–6. http://doi.org/10.1108/CI-10-2014-0049

Wong, J.K.W., Zhou, J. (2015). Enhancing environmental sustainability over building lifecycles through green BIM: A review, Autom. Constr., 57, 156–165. https://doi.org/10.1016/j.autcon.2015.06.003