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INTEROPERABILITY FOR SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY – A BIM BASED FRAMEWORK

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Tese apresentada ao Programa de Pós-Graduação em Engenharia de Produção e Sistemas da Escola Politécnica da Pontifícia Universidade Católica do Paraná, como requisito parcial à obtenção do título de doutora em Engenharia de Produção e Sistemas.

Orientador: Prof. Dr. Eduardo Rocha Loures
Coorientador: Prof. Dr. Osiris Canciglieri Junior

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2020

Pontifícia Universidade Católica do Paraná
Escola Politécnica
Programa de Pós-Graduação em Engenharia de Produção e Sistemas

TERMO DE APROVAÇÃO

Marina Figueiredo Muller

INTEROPERABILITY FOR SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY – A BIM BASED FRAMEWORK

Tese aprovada como requisito parcial para obtenção do grau de Doutor no Curso de Doutorado em Engenharia de Produção e Sistemas, Programa de Pós-Graduação em Engenharia de Produção e Sistemas, da Escola Politécnica da Pontifícia Universidade Católica do Paraná, pela seguinte banca examinadora:

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Curitiba, 30 de abril de 2020.

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RESUMO

A indústria da construção tem um grande impacto sobre o meio ambiente, portanto, a construção sustentável apresenta-se como uma exigência crescente da sociedade. No entanto, a preocupação com construções verdes não deve apenas ser considerada durante a fase de construção, mas também durante todo o ciclo de vida da edificação, integrando todas as fases, desde o projeto até a demolição. Para garantir essa integração em todo o ciclo de vida, a interoperabilidade se torna uma questão importante. BIM (*Building Information Modelling*) surge como um meio para resolver questões de interoperabilidade na indústria de Arquitetura, Engenharia e Construção, compartilhando modelos através de formatos abertos e permitindo a comunicação entre agentes. Esta pesquisa apresenta um levantamento do cenário atual através de análises e avaliação de interoperabilidade, juntamente com uma revisão sistemática da literatura com base em um modelo de decisão multicritério e análise de dados qualitativa. Com base nos requisitos de sustentabilidade, interoperabilidade e de ciclo de vida obtidos a partir da literatura e das avaliações de interoperabilidade, é proposto um framework. Este framework irá apresentar maneiras de organizar as informações, processos e irá permitir que os usuários tomem decisões embasadas, levando em conta o impacto na sustentabilidade. Finalmente, uma aplicação do framework será proposta para estruturas de concreto armado moldado *in loco*, considerado elemento com relevância em diversas fases do ciclo e com grande impacto na sustentabilidade. Desta forma, os usuários serão capazes de acompanhar requisitos de sustentabilidade ao longo de todo o ciclo BIM e melhorar os processos na indústria da construção em direção a processos mais interoperáveis, minimizando a perda de dados, melhorando a comunicação e eficiência.

Palavras-chave: *Building Information Modeling*. Sustentabilidade. Ciclo de Vida. Interoperabilidade. Ontologia. Processos.

ABSTRACT

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 lifecycle of the building, integrating all stages from the design up until the demolition/deconstruction. To ensure this integration throughout the lifecycle, interoperability becomes an important issue. BIM (Building Information Modelling) arises as a mean to unravel interoperability matters in the Architectural, Engineering and Construction industry, by sharing models through open formats and enabling communication amongst agents. This research presents an analysis of the scenario through data experiments, along with a systematic literature review based on a multicriteria decision model and qualitative data analysis. Based on the sustainability, interoperability and lifecycle requirements obtained from the experiments and the literature, a framework is presented. This frame will present ways to organize information, shape processes and allow users to take relevant decisions considering sustainability and to weight options. Finally, an application of the framework is proposed for cast-in-place concrete structures, considered a relevant element in different phases of the lifecycle and with great impact on sustainability. This way, users will be able 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, improving communication and efficiency.

Key-words: Building Information Modelling. Sustainability. Lifecycle. Interoperability. Ontology. Processes.

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LIST OF ABBREVIATIONS

ABNT	Associação Brasileira de Normas Tecnicas
AEC	Architecture, Engineering and Construction Industry
AHP/ANP	Analytic Hierarchy Process/ Analytic Network Process
BIM	Building Information Modelling
BIM2BEM	Building Information Modeling to Building Energy Modeling
BOB	Building Object Behaviours
BPMN	Business Process Modelling Notation
BPOpt	BIM-based performance optimization
BREEAM	Building Research Establishment Environmental Assessment Method
bSDD	BuildingSMART Data Dictionary
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
DMN	Decision Model Notation
DSRM	Design Science Research methodology
EIF	European Interoperability Framework
GBS	Green Building Studio
gbXML	Green Building XML
GIS	Geographic Information System
GRD	Green Retrofit Design
GUID	Globally Unique Identifier
HTML	Hypertext Markup Language
IAI -1	Information Acquisition Instrument
IDEF	Icam DEFinition for Function Modeling
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
ifcXML	Industry Foundation Classes Extensible Markup Language

IFD	International Framework for Dictionaries
ISSO	International Organization for Standardization
LabMCDA	Multi Criteria Decision Supporting Methodologies Laboratory
LEED	Leadership in Energy and Environmental Design
LOD	Level of detail
MCDM	Multicriteria Decision-Making Method
MVDs	Model View Definitions
NBR	Norma Brasileira
OWL	Web Ontology Language
PAR	Photosynthetically Active Radiation
PPGEPS	Industrial and Systems Engineering Graduate Program
ProKnow-C	Knowledge Development Process - Constructivist
Promethee	Preference Ranking Organization Method for Enrichment of Evaluations
Protégé	Free and Open Source Ontology Framework Editor For Building Intelligent Systems
PUCPR	Pontifical Catholic University of Parana
QDA	Qualitative Data Analysis
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
SLR	Sistematic Literature Review
SWRL	Semantic Web Rules
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TTL	Terse Triple Language
URI	Uniform Resource Identifier
USGBC	U.S. Green Building Council
UTF-8	8-bit Unicode Transformation Forma
XML	Extensible Markup Language

SUMMARY

1 INTRODUCTION

Sustainable construction presents itself as a growing force in the in the construction industry, and its influence must be considered not only the design stage, but also in the entire lifecycle of the AEC industry. BIM (Building Information Modelling) can allow the management of the lifecycle improving interoperability and allowing for more efficient and sustainable buildings (WONG; ZHOU, 2015).

The AEC industry has some unique characteristics, which can lead to some special needs in communication among stakeholders. This communication must happen properly in all the stages of the building lifecycle (conception, design, construction management etc.). One of these characteristics is that the AEC industry produces unique products. Every building is a singular product; none is the same as any other. This means that every building needs its own specific design and management that need to be conducted in a practical and fast manner. Another characteristic is that the AEC industry is heterogeneous. In one project there will be architects, structural designers, contractors and engineers from many different specialties (civil, mechanical, hydraulic, electric, etc.). These two specific characteristics lead to a great need for efficient interoperability among the agents and entities in AEC environment (GRILO; JARDIM-GONCALVES, 2010). The lack of interoperability can cause a series of problems in the industry. According to the EIF (European Interoperability Framework, 2004) interoperability means the ability to exchange data and allow information and knowledge share in business processes, through information and communication technology (ICT). To address this issue, Building information Modeling – BIM has emerged as an important technology to aid the AEC industry to improve interoperability.

The lifecycle of a building is constituted of five stages: design, construction, operation, maintenance and demolition/deconstruction. Each stage presents different challenges for sustainable construction and influences it in different ways. For example: the impact of the use concrete structures is not relevant during the operation stages, however, it impacts the demolition stage largely, since concrete residues have a great environmental impact. This is why the information must permeate the lifecycle without data losses, so sustainability data can feed the process, allowing users to create more sustainable buildings. Concrete structures, specifically, still need improvement in interoperability (MULLER, 2017) and permeate the entire lifecycle presenting relevant environmental impact (MEHTA, 2011), therefore providing an interesting case for the application of the framework.

Important categorizations of sustainability are green certifications, such as LEED (Leadership in Energy and Environmental Design), developed in 1998 by the U.S. Green Building Council (USGBC) to provide the construction industry 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 well established in the AEC industry as LEED. The certification provides a guideline for sustainable building, as well as certifications for constructions that achieve a certain number of points, considering the fields: Location and transportation, sustainable sites, water efficiency energy and atmosphere, materials and resources, indoor environmental quality, innovation and regional priority. Points in each field may vary according to construction type. BIM can aid users to keep track of points and perform simulations, choosing the most sustainable solutions for each project.

BIM arises as a mean to solve interoperability issues in the AEC industry, by modelling objects, sharing them through open formats and facilitating communication amongst agents (EASTMAN et al., 2008). However, along with the emerging of BIM, many other interoperability issues emerge and measures must be taken to reach higher interoperability stages or maturity levels (SUCCAR, 2009). 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´s (2008) enterprise interoperability framework. That divides interoperability issues by barriers (conceptual, technological and organizational) and concerns (business, process, service and data) through three approaches: integrated, unified and federated.

Regarding Interoperability concerns, business approaches interoperability in the strategic and organizational levels. Process is related to requirements necessary to align processes for the lifecycle. Service interoperability is the concern of an enterprise to register, aggregate and consume services of external sources. Service focuses on the need to make services from different companies to work together. Finally, data refers to the need for different software, platforms and systems to work together. Specifically, for BIM, scholars (GRILO; JARDIN-GONÇALVEZ, 2010) present BIM maturity levels as Communication, coordination cooperation, collaboration and channel. A framework can aid this process by organizing knowledge, as a data structure representing a situation through attached information (MINSKY, 1975).

In the first part of this study preliminary assessment of interoperability both for concrete structures and sustainability are presented. This analysis show the gaps and room for improvement in both fields. Afterwards, a literature review will be presented, linking the lifecycle of a building, interoperability and sustainability concepts. From this literature review, an interoperability framework for BIM is proposed. This framework will consider the construction lifecycle as well as interoperability concerns, integrating these areas with sustainability markers. The model can be applied to different systems in a building, such as concrete structures, led lighting, plumbing, etc. The application chosen to present this frame are concrete structures, since structures represent a big part of the building´s cost and embodied energy, and cast-in-place concrete structures specifically tend to influence a building´s sustainability through all stages, even until the demolition/deconstruction with great environmental impact (MEHTA, 2011). This framework will be based on ontology to structure the data, BPMN (Business Process Modelling Notation) to structure the processes and services and a DMN (Decision Model notation) to connect LEED points to the processes in the business level. These elements are presented and applied in the following chapters.

1.1 JUSTIFICATION

BIM alters the way that professionals work in the AEC industry. The public sector can potentially take the chief role to boost and enable the adoption of BIM in the industry. Recently, BIM implementation sustained growth intensively as more and more governmental bodies and non-profit organizations in several countries worldwide have adopted BIM (CHEN; LU, 2015). This considerable growth requires efficient interoperability and frameworks for effective BIM adoption.

Also, efficient BIM interoperability supports sustainability in buildings, through the with the use of state-of-the-art IT tools (ARASZKIEWICZ, 2016) and with the use of innovative strategies in green buildings (WU; ISSA, 2014).

The lack of interoperability in BIM open formats is a known problem, (MULLER et al., 2017) however, this may mean that underlaying factors in interoperability issues occur also in more structural levels. This thesis aims to provide a framework to structure BIM interoperability processes services and business guidelines. Interoperability and consequently the lack of suitable communication can be an important barrier to implementation of BIM from the project stance (EADIE et al., 2014).

1.2 ORIGINALITY

The originality of this research will be seen mainly in its concern for the entire lifecycle of the construction. Most researches do not comprehend the entire lifecycle of a construction, and some stages such as design and maintenance are rarely studied (MULLER et al., 2019). The use of BIM allowed this study to cover the entirety of the lifecycle.

Also, this thesis will present the use of some methodological and managerial artefacts that are not common solutions in the AEC industry, such as the semantic notation of processes and its use to guide decision processes. Also, this thesis will be concerned with interoperability as a whole, not only with the aspects related to data, but will also consider business, service and process aspects (CHEN, 2018). This holistic approach to interoperability is not so common in the construction industry as well. The justification and originality

The justification and originality of this thesis lies in the simultaneous and coherent consideration of the lifecycle, interoperability and sustainability dimensions. Consistency is supported by meeting the need for knowledge modelling to share information throughout the lifecycle, supporting sustainability decision in the light of interoperability requirements.

1.3 RESEARCH PROBLEM

BIM arises as to support interoperability in the AEC industry, by modelling objects, sharing them through open formats and facilitating communication amongst agents. However, open BIM data formats are not effective enough, and processes need structuring to support interoperability throughout the lifecycle of a construction, especially if sustainability requirements are considered. Therefore, a BIM framework is needed to ensure interoperability in sustainable constructions.

1.4 RESEARCH QUESTION

How can Building Information Modelling in an interoperable environment support the processes and decision making toward more sustainable buildings?

1.5 RESEARCH OBJECTIVES

Develop a conceptual framework for the decision-making processes for BIM interoperability in a sustainable lifecycle based on an ontological data structure and propose an application for cast-in-place concrete structures.

1.5.1 Specific Objectives

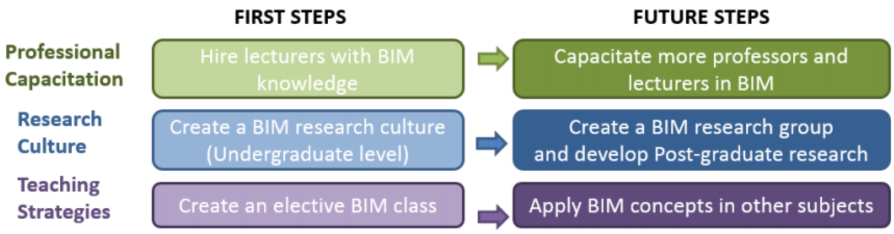
i. Identify weaknesses in the current BIM interoperability for sustainability and cast-in-place concrete structures;
ii. Gather information in the literature to support a framework for the sustainable BIM lifecycle;
iii. Structure and describe the methodology for the development of a framework model for BIM interoperability in a sustainable lifecycle;
iv. Structure a BIM-based ontology for cast-in-place concrete structures;
v. Develop processes for cast-in-place concrete structures;
vi. Propose a decision model for sustainable constructions by semantically annotating the processes with the ontology.

1.6 BIM RESEARCH AT PUCPR – RESEARCH CONTEXT IN THE PROGRAM

This thesis was developed in the Industrial and Systems Engineering Graduate Program (PPGEPS), Pontifical Catholic University of Parana (PUCPR), in the research line of “Modelling, Control and System Automation”, focusing in System Interoperability applied for BIM, beginning a series of research in the field.

BIM adoption barriers by companies can be divided in two main categories: project management barriers and training barriers (IBRAHIM, 2006). Training barriers can be overcome by BIM adoption in the university, however, few universities taught BIM, especially considering the Brazilian reality, so young professionals used to reach the market without BIM vision (BARISON; SANTOS, 2011; COELI et al., 2013). In this scenario, PUCPR started the initiative of BIM adoption in three main fields: Staff capacitation, research culture and teaching strategies, as seen in Figure 1.

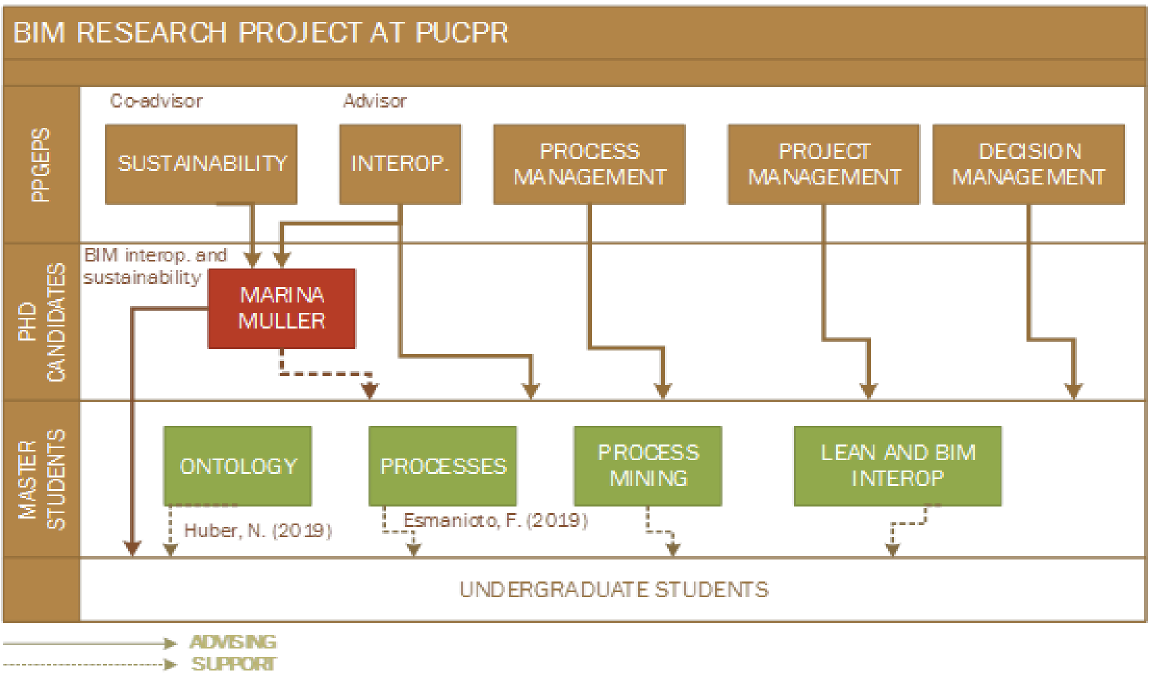
Figure 1 - BIM adoption steps in the university



Source: Muller, 2016.

This thesis is part of the BIM group initiatives at PUCPR, especially in the development of research culture field shown in the previous figure. Figure 2 presents diagram of the structure of the BIM research project. In the first line there are the research lines in the program that are involved in the BIM initiative: Sustainability, interoperability, project, process and decision management. The professors of this lines are involved mainly as advisors and co-advisors of the master and PhD students. And PhD and master students are involved in advising and giving support to undergraduate research. This structure can be seen in detail in Figure 2. Some results and papers published by the group are not strictly part of this thesis, however, they represent some interesting contributions and are presented in the appendixes.

Figure 2 - BIM group organogram



Source: Author.

1.7 DOCUMENT STRUCTURE

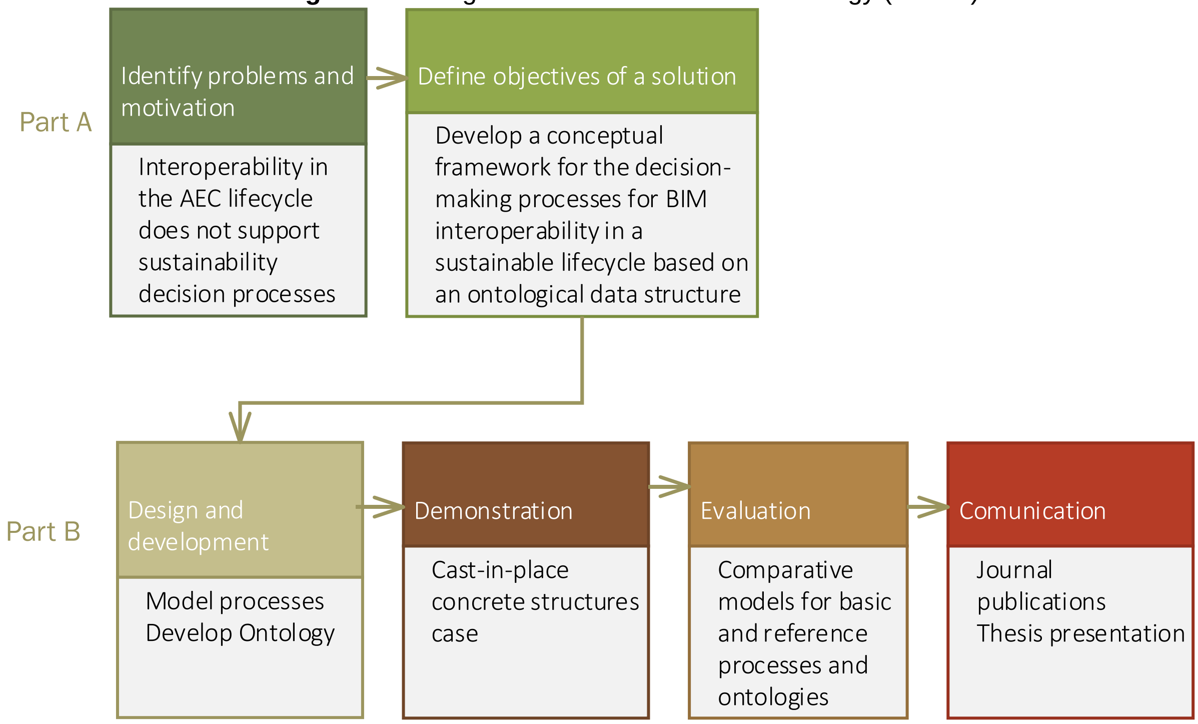
This thesis methodology was developed based on the six steps of the Design Science Research methodology (DSRM) (PEFFERS et al., 2007). Peffers steps are: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication. This methodology was developed for information systems research.

In the case of this research the problem identified is that the Interoperability in the AEC lifecycle does not support sustainability decision processes, therefore an objective to solve this was determined: Develop a conceptual framework for the decision-making processes for BIM interoperability in a sustainable lifecycle based on an ontological data structure. In the design and development step, processes models, ontologies and decision models were created, and demonstrated in the next step in a cast-in-place concrete structures case. Then, this model can be evaluated in the next step through comparative models for the basic and reference ontologies and processes. Finally, in the last step, the results are communicated through academic publications. This schema can be seen in Figure 3.

Also this thesis will be structured in two parts. The first part will be named part A, and in it the preliminary analysis, systematic literature review and framework proposal will be presented. Part a correlates to the first two steps of the DSRM methodology.

In part B the development of the processes, ontologies and decision models will be presented. This part also correlates to the final four steps of the DSRM methodology.

Figure 3 - Design Science Research Methodology (DSRM).



Source: Adapted from (Peffers et al., 2007)

This document is structured in 9 chapters. In the first chapter the topic is introduced and the research objectives are presented, along with the basic structure of the thesis and its context in the PPGEPS program. In the second chapter the methodology is presented and structured based on the objective and specific objectives, presenting the structural sequence for all the stages of the research, however, each section has its own methodology, which will be detailed in more depth each chapter.

Then, the thesis is structured in two parts: Part A and B. In the first part of the research (Part A), preliminary studies are presented, that direct the SLR. From these preliminary studies and literature review, a framework is proposed. The development of the framework and its application is presented in part B.

On the third chapter the preliminary analysis that motivated the development of the framework are described. This chapter presents two different data interoperability analysis. The first is related to concrete structures IFC (Industry Foundation Classes) transfers, and the results showed that even though data interoperability has increased in the last five years, it is still not developed enough to support and interoperable process. The second analysis is related to the interoperability of analysis related to sustainability issues. The tests showed that interoperability in this type of analysis is no efficient enough as well. This led to the question of whether this lack of interoperability is only local or this means that there are more structural interoperability issues, in business, processes or services. Also to the concern whether this interoperability issues occur throughout the lifecycle or are restricted to certain stages.

To answer this a systematic literature review was developed which is presented on chapter four. This review was structured to identify the convergence of studies in interoperability, sustainability and BIM lifecycle. From this research it was possible to notice that the Green BIM lifecycle has been studied thoroughly in the past couple of years, representing an exponential growth on the topic. Even with this growth, it can be noticed that papers tend to focus on one stage of the lifecycle alone. Also, it was noticed that more than half of the papers are concerned with the design, a few consider the construction stage, but very few consider the final stages of the lifecycle. When considering sustainability, issues related to energy and atmosphere also make-up more than half of the studies. Topics related to materials and resources also received some attention, but the other aspects such as Indoor environmental quality, innovation and regional priority, sustainable sites and water efficiency are very under-covered.

Also, the broader aspects of interoperability, services and business, are often not studied, while more technical aspects of data interoperability receive more attention. So, along with this lack of a holistic view of the system, an analysis of these topics in the light of interoperability is needed. Confirming the need for a framework to structure BIM interoperability in a sustainable environment for cast-in-place concrete structures, presented on the objectives.

In chapter five the framework is proposed. Since the SLR showed a lack of studies encompassing all stages of a buildings lifecycle, this model considers all stages of a building, from design to demolition. Also, the framework presented is BIM-based, since BIM can aid in the management of this lifecycle. To solve the data transference issues observed in the preliminary studies, an ontology is used to structure this data. To organize the processes, BPMN is used. Finally DMN is used for the decision support model to guide the processes to more sustainable directions.

In part B the development and application of the framework is presented. Part B starts with chapter six, in which the development of the ontology for cast-in-place concrete structures is presented. In this chapter a comparative of the ontology from IFC models to an ideal ontology extracted from cast-in-place concrete standards, providing support to solve the data interoperability issues described in the preliminary studies.

In chapter seven the development of the process models is presented. A comparative of processes using no or low BIM to full BIM is described, and the results provide validation for BIM based framework, since BIM processes provided the most interoperable solution. In chapter eight a decision model is structured, this decision model uses semantically enriched processes. The processes developed in chapter seven are annotated with the ontology presented on chapter six, and the ontologies provide the inputs for decisions in the processes concerning sustainability.

Finally, in chapter nine the thesis is conclusion is presented, the findings are discussed, and their alignment with the objectives proposed in chapter one is verified. Also, contributions are presented, and the possible applications and future works are proposed. The structure of the thesis, and each chapter's correlation to the specific objectives can be seen Table 1.

Table 1 - Thesis structured by publications

Part	Chapter		Specific Objectives
	1	Introduction	
	2	Methodology	
A	3	Preliminary Setting – Concrete structures and sustainability	1
A	4	Literature Review	2
A	5	Framework model	3
B	6	Ontology	4
B	7	Process model	5
B	8	Decision model - DMN	6
	9	Conclusion	

Source: The Autor

1.8 SCIENTIFIC PUBLICATION

This thesis was conceived and structured based on scientific papers to be published in journals. Some of which are already published and some that are under the process of being prepared for submission or are already submitted. The list of articles and their current state of publication, as well as the chapter in which they appear in this thesis is:

- Data interoperability assessment though IFC for BIM in structural design - a five-year gap analysis: published in the Journal of Civil Engineering and Management, 2017.- Qualis A1 Section 3.1 of chapter 3;
- A Systematic Literature Review of Interoperability in the Green Building Information Modeling Lifecycle. Published in the Journal of Cleaner Production – chapter 4 – Qualis A1;
- Interoperability Framework for Building Information Modeling based on Sustainability. Published as an expanded abstract in the proceedings of the 8th International Workshop on Advances in Cleaner Production, 2019, currently being adapted for publication in the Journal of Cleaner production as full paper. – Can be seen in chapter 5 and 8;
- Multicriteria Decision Making Model for the Choice of Interoperable BIM Software and Environmental Analysis. – Under preparation for submission – Section 3.2 of chapter 3;
- Ontology-based IFC Requirements for a Lifecycle Characterization for Cast-In-Place Concrete Structures– Under preparation for submission - Chapter 6;
- Interoperability assessment of a BIM-based construction life cycle from a process perspective – Under preparation for submission - Chapter 7;

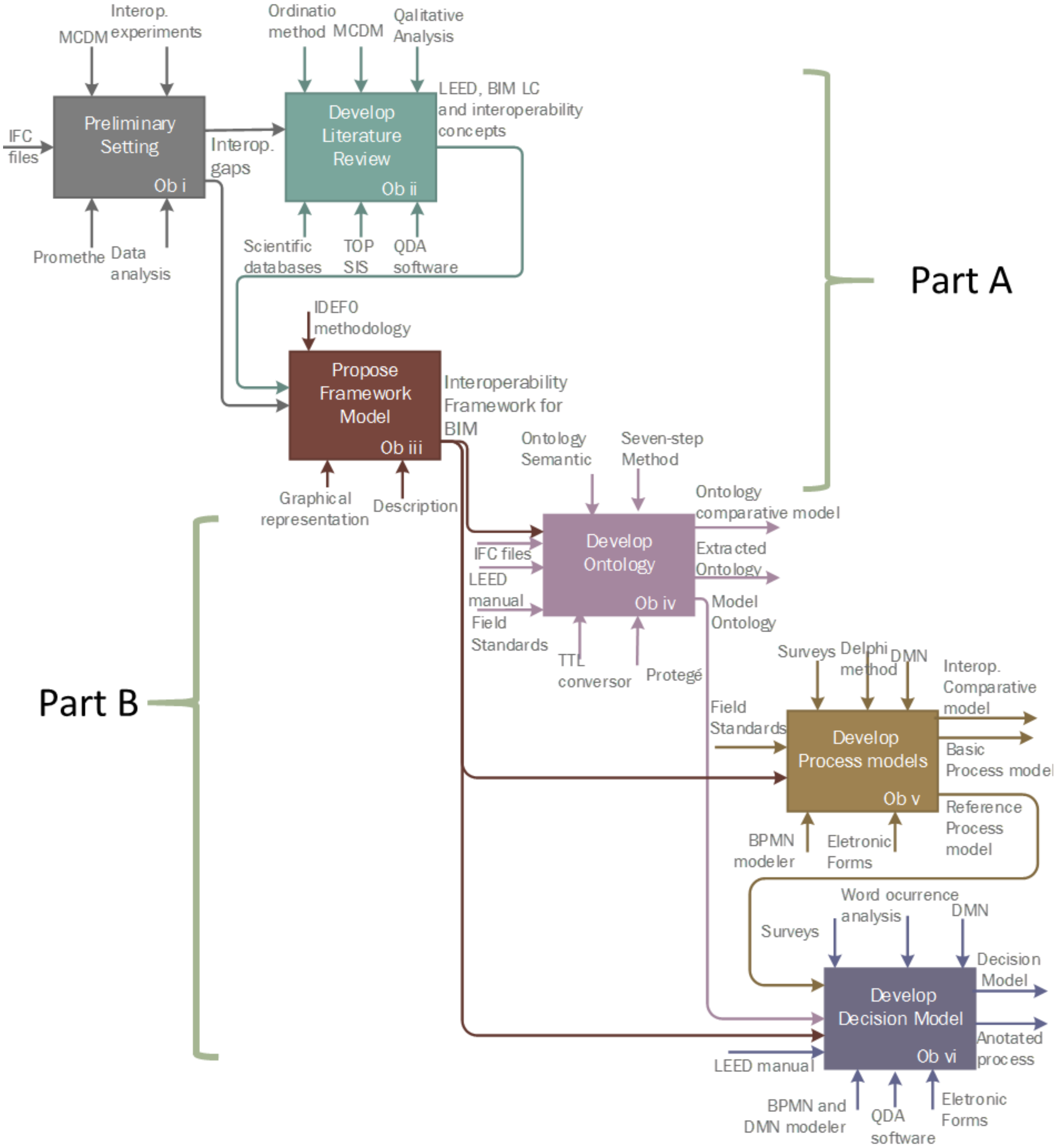
Other articles related to this thesis but not a part of its main structure were published and are available in the appendixes. They are:

- Interação das Estratégias do BIM e Lean Construction sob a perspectiva de Processo, Política e Tecnologia. Published in: XXVI SIMPEP Desafios da engenharia de produção no contexto da indústria 4.0, 2019. (Proceedings);
- Developing BIM Culture in a University - Past and Future Steps. In: ISPE International Conference on Transdisciplinary Engineering, 2016, Curitiba. (Proceedings) and TRANSDISCIPLINARY ENGINEERING: CROSSING BOUNDARIES. 1ed (Book);
- Interoperability Assessment for Building Information Modelling. In: 5th International Conference on Structures and Building Materials (ICSBM 2015), 2015, Shenzhen. (Proceedings).

2 RESEARCH STRATEGY

The research methodology is developed in six parts. These parts are structured in an IDEF0 diagram, considering the inputs, control mechanisms and outputs from each part, as well as its influence on each other, and the specific objectives that they cover, and can be seen in Figure 4.

Figure 4 - IDEF0 diagram for the methodological structure



Source: The Author

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.

2.1 PRELIMINARY SETTING AND JUSTIFICATION FOR THE STUDY

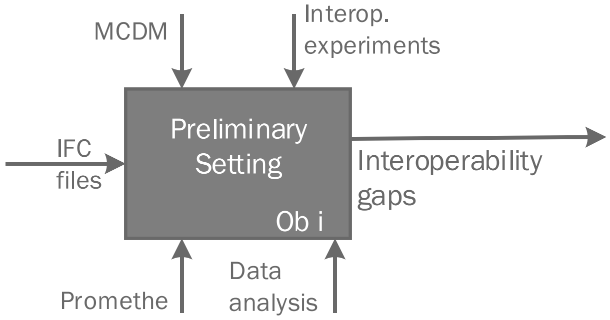
This stage is comprised of two assessment studies that present data experiments based on IFC . IFC is an open format for BIM developed by Building Smart (2016). This part is developed to achieve the first specific objective “Identify weaknesses in the current BIM interoperability for sustainability and cast-in-place concrete structures.”

The first data experiment analyses the transferences of cast-in-place concrete structure models through IFC over five years. Files transferred were analyzed for non-conformities in a preliminary study, and then the same experiment was developed five years later. Even though some improvement was perceived, data interoperability still needs improvement in the field. The article that described this experiment is named “Data Interoperability Assessment Through IFC for BIM in Structural Design – A Five-Year Gap Analysis”.

The second data experiment analyzed software for sustainable design. Models were transferred between systems through IFC and also checked for non-conformities. The results were analyzed by Promethee (Preference Ranking Organization METHod for Enrichment of Evaluations) (ref), a multicriteria decision-making method (MCDM). Results showed that often, systems can generate IFC models effectively, but can´t always read them as well. The article that described this experiment is named “Multicriteria Decision Making Model for the Choice of Interoperable BIM Software and Environmental Analysis”. The articles are presented in chapter 3.

These interoperability gaps perceived from the experiments will later provide the foundation for the systematic literature review and the justification for the need of the framework proposed.

Figure 5 - IDEF0 diagram for the preliminary settings



Source: Author.

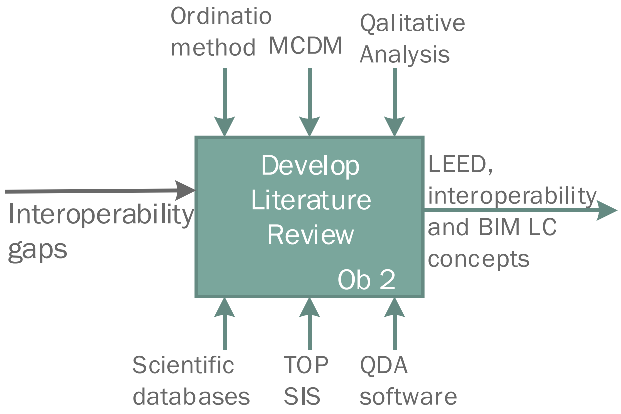
2.2 SYSTEMATIC LITERATURE REVIEW

This stage presents the development of a systematic literature review. This part was developed to present the state of the art of the field, as well as to provide LEED, interoperability and lifecycle concepts. The selection of the papers was developed based on the Ordinatio (PAGANI et al., 2015) method complemented with a MCDM- TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), which can be used to aid group decision-making (HUANG; LI, 2012). From the gaps noticed in the preliminary studies, a search was developed for papers with the keywords from the topics interoperability, sustainability and lifecycle.

After the selection, a qualitative analysis was performed on a QDA (qualitative data analysis) software, identifying papers focused on each of the subcategories of the fields. Also, from the results, a relational factor was identified, showing which lifecycle stage had the most influence on each LEED field.

These results are described in chapter four and published in the paper entitled: “Interoperability in the green BIM lifecycle - a systematic literature review based on a multicriteria decision making/analysis method”.

Figure 6 - IDEF0 diagram for the SLR



Source: Author

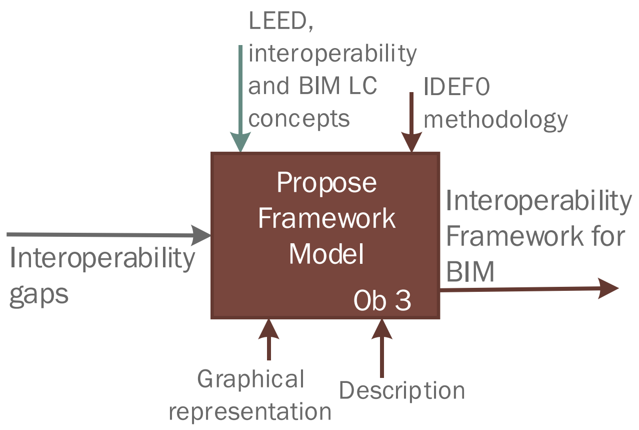
2.3 FRAMEWORK

In this part a framework for BIM interoperability in sustainable buildings is proposed. The methodology of the framework is structured from the gaps perceived in the preliminary analysis and concepts extracted from the systematic literature review. The design of the framework is illustrated in graphics and the structure for development and application are modelled in IDEF0 diagrams. This part is connected to the main objective and is detailed in Figure 7 also as an IDEF0 diagram.

Also, an application of the frame is presented in the following sections, and present a proof of concept for the frame, applied to cast in place concrete structures. Three main objects are developed within this framework. An ontology set to structure the data, processes to structure the sequencing of activities and a decision model to apply the sustainability concepts to the processes.

This frame is also structured in two stages: one basic model that considers pre-BIM, or early BIM and a reference model, proposing BIM as a foundation for the framework.

Figure 7 - IDEF0 diagram for the framework



Source: Author.

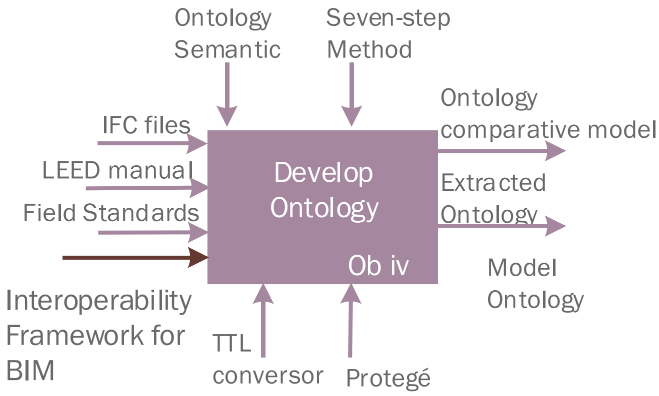
2.4 ONTOLOGY

This stage is constituted of de development of an ontology to structure the data used in the processes and a proposal and its schema can be seen in Figure 8. The ontology can be developed in a preliminary stage by extracting an RDF (Resource Description Framework) file from an IFC model into the Protegé platform (DI MASCIO et al., 2013). In the case of this project, a model for concrete structures was used. In this model, several structural elements were present (such as different types of beams, slabs and columns).

Through a Systematic Literature Review it was possible to identify all reinforced concrete standards and where they are inserted in the lifecycle phase of a edification (design, construction, operation/maintenance, demolition/deconstruction). From this standards, an ontology can be constructed by the Seven-Step method, which is considered to be a well-established approach and suitable for the purpose of this research (GAO et al., 2017). Like Protégé, this seven-step method was developed by Stanford University School of Medicine. Also, an ontology for LEED can be structured to aid in the future stages of the decision model.

Finally, a comparison of the ontology extracted from the BIM model and the ontology generated based on the literature and standards can be presented, mapping where there is room for improvement in the IFC ontology. The diagram for this part shown in Figure 8.

Figure 8 – IDEF0 diagram for the ontology



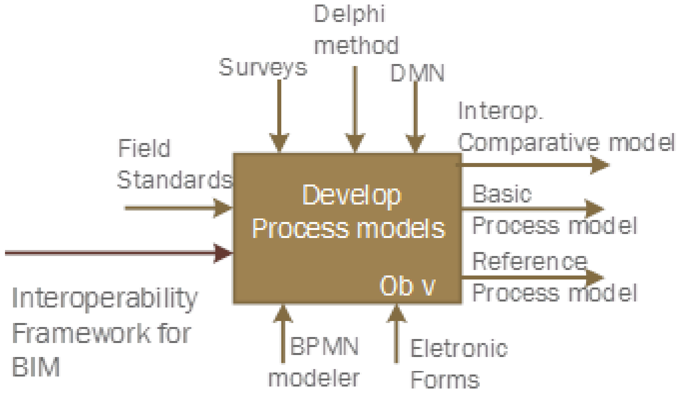
Source: Author.

2.5 PROCESS MODELS

This stage of the research is constituted process models for the Reference and Basic stages. Its schema can be seen in Figure 9. The processes for cast-in-place concrete structures are developed for all the stages of the lifecycle using BPMN (Business Process Model Notation). A preliminary version is developed based on the literature. This version goes through surveys for the as-is model (ABDELHADY et al., 2013) and Delphi rounds the to-be model (OKOLI; PAWLOWSKI, 2004) and a refined version is proposed.

A comparison of both processes can be developed, considering interoperability concerns. This comparison can be useful to understand where interoperability is gained by the use of BIM. The diagram for this part shown in Figure 9.

Figure 9 - IDEF0 diagram for the process models



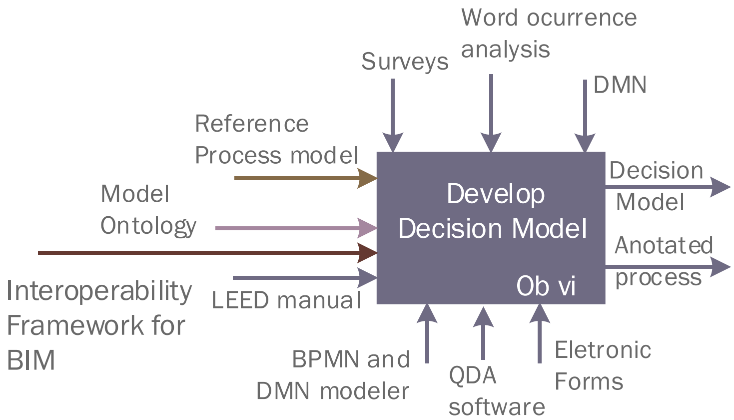
Source: Author.

2.6 DECISION MODEL AND PROCESS ANOTATION

To connect the process to the ontology, semantic annotation can be used (LIAO et al., 2016). The ontology is annotated to the process by a survey, and the information can be stored in the BPMN reference model itself. Users are asked about which type of data and information is used for each task of the processes.

Also in this stage, a relational matrix is developed. This relational matrix crosses these ontological concepts of concrete structures with the LEED manual categories and scores. This data is then structured in a DMN model, and connected to the processes via the annotated ontology, providing users with a tool to aid decision making toward more sustainable buildings.

Figure 10 - IDEF0 diagram for the decsion model



Source: Author.

2.7 THESIS STRUCTURE

The thesis is structured as presented in Table 2. The structure correlates each section of the methodology to the specific objectives and to a specific product for each. Also, it shows the type of methodology used. After each chapter, a section will be presented positioning it into the general context of the thesis.

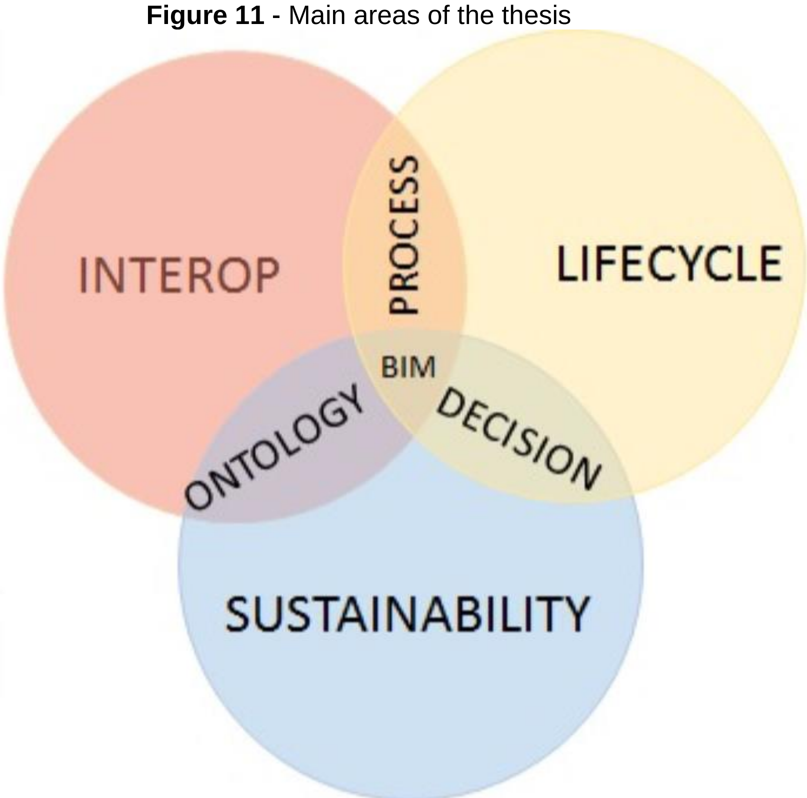
This thesis also can be seen as the intersection of three main areas: Interoperability, sustainability and lifecycle. Processes, ontology and decision serve to unify these areas supported by BIM, as can be seen in figure 11.

Table 2 - Thesis structured by publications and research method

Part	Chapter	Products	Research method	Specific Objectives
	1	Introduction		
	2	Methodology		
A	3	Preliminary Setting – Concrete structures and sustainability	**Data Experiments**	1
A	4	Literature Review	**SLR based on a MCDM**	2
A	5	Framework model	**Propositional**	3
B	6	Ontology Influence matrix	**Data extraction and survey**	4
B	7	Process model	**Survey and Delphi method**	5
B	8	Decision model - DMN	**Semantic Anotation**	6
	9	Conclusion		

Source: Author

Figure 11 - Main areas of the thesis



Source: Author

PART A

PRELIMINARY AND PROPOSITIONAL OUTLINE

3 PRELIMINARY ANALYSIS

This chapter presents two different data interoperability analysis. The first, section 3.1, is related to concrete structures IFC transfers, and the results showed that even though data interoperability has increased in the last five years, it is still not developed enough to support and interoperable process. The second analysis, section 3.2, is related to the interoperability of analysis related to sustainability issues. The tests showed that interoperability in this type of analysis is no efficient enough as well. This led to the question of whether this lack of interoperability is only local or this means that there are more structural interoperability issues, in business, processes or services. Also to the concern whether this interoperability issues occur throughout the lifecycle or are restricted to certain stages.

3.1 DATA INTEROPERABILITY ASSESSMENT THROUGH IFC FOR BIM IN STRUCTURAL DESIGN – A FIVE-YEAR GAP ANALYSIS

The AEC industry commonly presents some individualities, which may lead to distinct needs in communication between stakeholders and companies. This communication needs to happen correctly in all the phases of the lifecycle of a building – (i) planning and design, (ii) construction, (iii) operation, (iv) repair and maintenance and (v) demolition. Each of these phases requires different semantics and workflows. One of these unique characteristics is the fact that the AEC industry creates unique products. Every building and its construction is a singular product, different from any other. Because building models require different semantics for different workflows over a project's lifecycle, the communication in all the phases of the lifecycle of a building needs to happen correctly (VENUGOPAL et al., 2015; WONG; ZHOU 2015).

This particular scenario amongst other industries means that all buildings need their own specific management and design to be conducted with efficiency and effectiveness. One more characteristic is that the AEC industry is not homogeneous in terms of the involved actors. In one single project there will be architects, engineers from several specialties (civil, structural, hydraulic, mechanical and electric, etc.) and contractors. In addition, the elaboration of a construction project is highly collaborative, and besides the fact that they usually comprise several areas, these professionals are spread in offices that use different software and platforms. These specific characteristics lead to a pronounced necessity for efficient interoperability between the entities and agents in the AEC environment (GU; LONDON, 2010).

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". Many efforts have been made to address interoperability barriers, and the exchange of information between the various disciplines of the AEC industry is still one major problem (YANG; ZHANG, 2006). The inefficient or even lack of interoperability may cause several compatibility and clash problems that occasionally may only become evident during the execution stage. The electrical system intersecting doors and windows or the plumbing overlapping with beams or columns are a few examples that exemplify this scenario (GRILO; JARDIM-GONCALVES, 2010).

To aid this process in the AEC industry, Building information Modelling – BIM was created and has been developed as an important technology to support interoperability in this area. BIM is a process in which building models are created through software; data from all the sectors involved in the lifecycle of the building should be included in the models. However, the main barriers to the adoption of BIM by the market are the difficulties in interoperability among platforms (GRILO; JARDIM-GONCALVES, 2010; MULLER et al., 2015). This fact leads to a vicious cycle: interoperability between BIM systems doesn't seem to be in a stage where it is satisfactory enough for the adoption of BIM, and in turn BIM must be more widely adopted to in order for interoperability to be improved.

Studies show expenses of 15 million dollars with losses derived from problems concerning the lack of interoperability in the BIM scenario (VENUGOPAL et al., 2015). The study of Liu et al. (2016) points to the same problem, since many structural engineers often adopt computational and structural modelling software with different formats from BIM and IFC standard. In this regard, Hu et al. (2016) advocate that inadequate integration and interoperability continue to cause an economic burden and are often considered key factors for the initial resistance to new technology in project design.

To better address interoperability issues in AEC/BIM, literature points to a need for specific studies on interoperability influence factors and assessment methods (JEONG et al., 2009; GRILO; JARDIM-GONCALVES, 2010; MULLER et al., 2015).

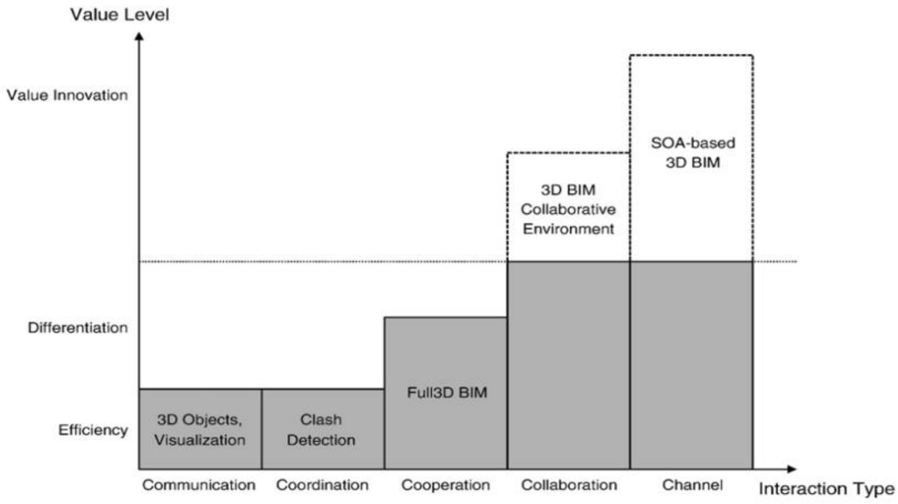
With this scenario in mind, the research described in this study is structured as follows. In Section 1, the background for the research is established, and based on the literature, a process map for cast-in-place concrete structure design companies was developed in a scenario without BIM. This processes map showed that many stages in the design process were focused on clash detection and similar activities. In order to improve this scenario, BIM is proposed as a tool in a new process map. However, for this to become possible, the need for interoperability among platforms is necessary. So experiments focusing on IFC file sharing were developed, to verify whether using BIM as a repository for building design and file sharing was possible or not in the casting-place concrete structure domain. The methodology for these experiments is described in and the results are presented in the further sections. Finally, conclusions for the experiments and research perspectives are presented.

3.1.1 BIM Interoperability

According to the European Interoperability Framework (EIF, 2004): “Interoperability means the ability of information and communication technology (ICT) systems and of the business processes they support to exchange data and to enable the sharing of information and knowledge”. This EIF’s definition can be used in the AEC industry as well, especially through BIM.

In order to characterize an evolution of BIM interoperability, levelling models are proposed, as shown in Figure 12. These values levels express how interoperability through BIM can contribute to companies’ competitiveness. Communication is the first and more basic level. In this structure, the main concern is with the use of 3D modelling. This is because 3D visualization allows better understanding, henceforth, better communication of the design. Coordination is the second level. In this stage, users are able to perform clash detection, overlap prevention, etc. The third level is known as cooperation. In this case, full 3D BIM is expected, as well as cost predictions, supply chain visibility, construction and energy simulations, etc. This level is focused on obtaining advantages by sharing work among agents. The fourth level, collaboration, assumes BIM use in collaborative environments. And the fifth level, channel, expects automatized environments permeated through the whole process, including the production stages (GRILO; JARDIM-GONCALVES, 2010).

Figure 12 - Interoperability value levels



Source: Grilo; Jardim-Gonçalves, 2010.

Chen et al. (2008) interpret interoperability through three axes: concerns, barriers and approaches. Approaches could be understood as interoperability levels. This means that interoperability can be in a level where it is considered integrated, unified or federated. Interoperability barriers can be conceptual, technical or organizational. This means that there is more to interoperability then the concerns related to software and technical issues. In order for interoperability to occur properly, not only technological issues should be solved, but also processes must be aligned and organizations must commit to interoperability.

Finally, authors divide interoperability concerns in four groups (concerns) and four levels. These levels can be linked to Building smart's guidelines and specific documents for better interoperability in the AEC industry (Building Smart is an international agency concerned with innovation and interoperability in the AEC industry, and will be discussed further on). Figure shows four interoperability concerns described in literature (CHEN et al., 2008), that can be related to BIM dimensions, as described:

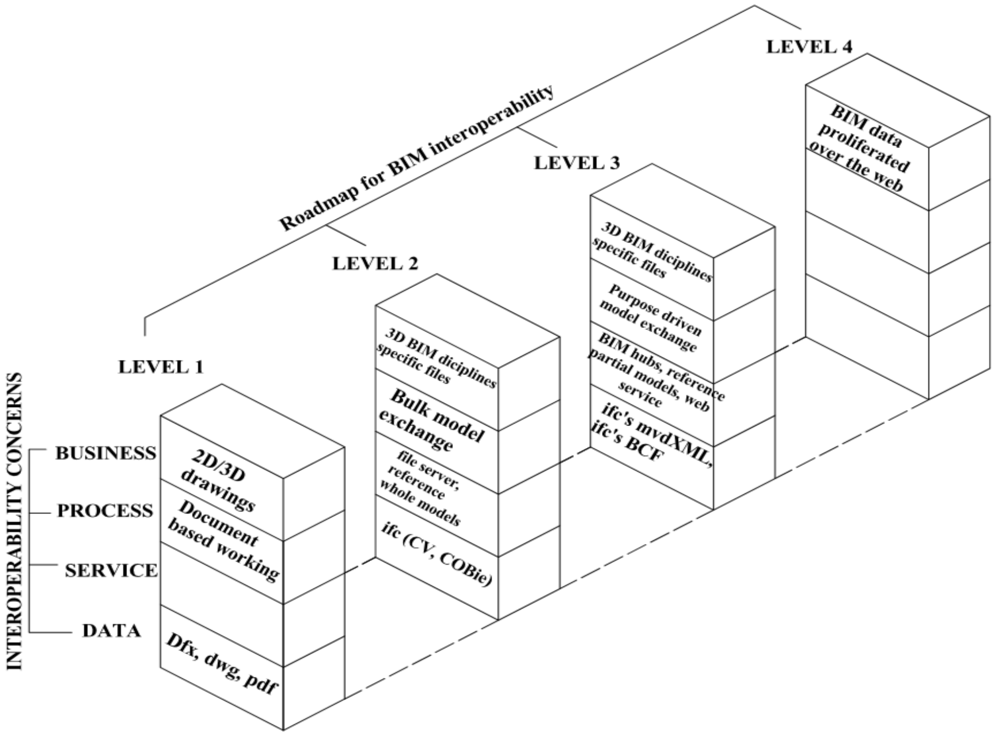
- Business: is concerned with interoperability in the strategic and organizational levels. This correlates to BIM because the use of BIM is usually a strategic action in the company. Stakeholders need to be involved in the adoption process;
- Process: is related with the requirements necessary to align the processes for construction, design, and operation. By using BIM instead

of traditional 2D CAD, companies change not only their way of designing, but it alters the whole process of building and operation. This is strongly related to Building Smarts' IDM – Information Delivery Manual, which formalizes the processes throughout the construction industry (EASTMAN et al., 2008).

- Service: service interoperability is the concern of an enterprise to aggregate, register and consume services of external sources. It focuses on the need to make all services from different companies work together. In BIM this is represented by the role of suppliers that need to provide detailed information about their products. This is also strongly connected to a Building smart document. In this case, it is the IFD (International Framework for Dictionaries) or BuildingSMART Data Dictionary (bSDD). Since suppliers need well-established definitions and ontologies for a better interoperability in the AEC industry. Also Rezgui et al. (2013) point that a big barrier to BIM adoption is the fact that agents in the service field (clients, designers and contractors) are still using 2D or paper-based files.
- Data: this concern refers to the need for different software, platforms and systems to work together. Multimedia content, digital resources and documents need to be usable, available and comprehensive by all stakeholders (EASTMAN et al., 2008). This concern is addressed by Building Smart through their open format, the Industry foundation Classes (IFC).

The levels in Figure 13 are based on the interoperability value levels (GRILO; JARDIM-GONCALVES, 2010) and Buildings Smart's roadmap to interoperability (2014). The concerns described by Chen et al. (2008), form the vertical axis. This connection between both proposals can be described as a path for improved interoperability in the AEC industry (MULLER et al., 2015). Considering the figure described, it can be observed that the research developed in this study is currently located in the highlighted box – IFC concerns for data interoperability – currently on the second level.

Figure 13 - Roadmap for BIM interoperability



Source: Author.

Also, further literature considers three interlocking fields of activities pertaining BIM, instead of the four enterprise interoperability concerns described in Figure 13. The first field is the technology field, which is related to the development of software, hardware and systems. Next, the process field is related to procurement, design, construction, manufacture, use, management and maintain of the structures. Finally, the policy field gathers tasks focused on delivering research, preparing practitioners and minimizing conflicts in the AEC industry. This study is located in the intersection of the policy field, since it aims to develop interoperability aiming to minimize data conflicts, and the technological field, considering its relationship to software development through IFC data files (VENUGOPAL et al., 2012).

Building Smart's Interoperability Standard for BIM

BIM systems are one sort of object oriented CAD. This means that, for example, a wall is perceived by the system as an object with the properties of a wall, such as thickness, height, length, as well as non-geometric characteristics, such as cost, material, suppliers, etc. These characteristics are Building Object Behaviours

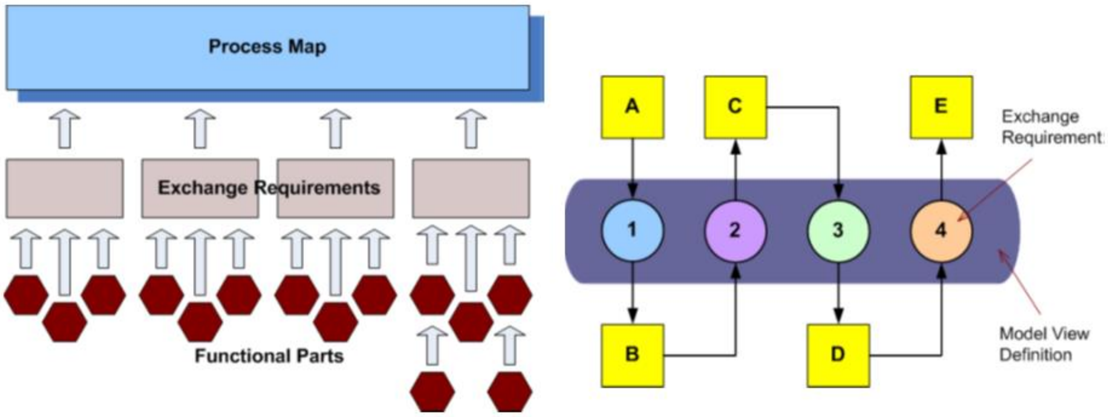
(BOB). This requires special cares and concerns with interoperability, since the information of the objects must be transferred correctly to agents involved in the design and construction processes. BIM is also a kind of parametric modelling and can be distinguished from CAD modelling by these characteristics (LEE et al., 2006):

- Users can manipulate and generate shapes, add constrains and new parametric relations. Also, these shapes may be altered by editing the values in the pre-defined parameters.
- A parametric system should use 3D modelling, since 2D is not sufficient to represent a complex model.
- Such systems should be object-based and feature based. These objects can be constrained to each other if necessary.

These inefficiencies in interoperability can lead to rework, mismatched information, uncertainty and insecurity about the reliability of the data. Faced with this scenario, professionals in the AEC industry created the International Alliance for Interoperability (IAI) – current Building Smart, which aims to promote innovation and interoperability between architecture, engineering and construction software. To ensure this interoperability Building Smart developed Industry Foundation Classes (IFC) (SKIBNIEWSKI; ZAVADSKAS, 2013). The IFC is a neutral standard, and its main goal is to standardize the classes of object-oriented systems in an open format so that multiple applications can use it to share data (BUILDINGSMART, 2014). IFC is also registered in the International Organization for Standardization. Due to this fact, IFC is widely used in architecture, engineering, construction and facility management (LEE et al., 2016a, 2016b).

In order to aid the improvement of interoperability in BIM platforms, BuildingSMART develops four main document types. The first document is the IDM – Information Delivery Manual, a BuildingSMART’s standard for processes. It defines details of how, when and what kind of information should be supplied by which agent and at which stage of the project (WIX; KARLSHOEJ, 2006). The IDM is comprised of functional parts, exchange requirements and Process Maps. The requirements appear in detail in the Information Delivery Manual (IDM), which contains implementable specifications for software vendors (LEE et al., 2016a). A functional part describes information as a small set of IFC information needed to perform a certain task. Exchange requirements are the sets of model information applied to each case, and the process maps organize these sets of information, as shown in Figure 14 (WIX; KARLSHOEJ, 2006).

Figure 14 - Right: Process Maps, Exchange Requirements and Functional Parts. Left: Schema for model view definitions



Source: Wix; Karlshoej, 2006.

As a second artefact, Model View Definitions (MVDs) are related to software requirements for IFC implementation. It formalizes the information exchange processes for systems, as shown in Figure 15 (WIX; KARLSHOEJ, 2006; BUILDINGSMART, 2014). The MVDs map the system import/export features and IFC. This binding correctness must me checked by developers and users. Some studies have developed automatic checking; however, this automatic checking does not apply to all cases, especially considering heterogeneous industry as the AEC field, so users may have to resort to manual checking of MVDs and IFCs (LEE et al., 2016b). The third document is the IFD (International Framework for Dictionaries) or BuildingSMART Data Dictionary (bSDD). It is a dictionary of terms for libraries and ontologies (WIX; KARLSHOEJ, 2006). Finally, as the forth artefact, Industry Foundation Classes (IFC) represents a neutral and open standard for BIM. It may be used to exchange information between different systems and platforms (BUILDINGSMART, 2014).

The development, implementation and deployment of BIM standards should follow three basic stages. In the first stage, developers elicit knowledge from the industry model the business process and prepare an IDM. The second stage is called the “construct” stage. In this moment MVDs and specifications are developed and implemented. In the final stage, guidelines are prepared for deployment and early adopters’ experiences are used to refine the BIM standard (SACKS et al., 2010).

Interoperability for Concrete Structures

The exchange of information between architectural projects and structural projects still lacks adequate support, as well as the automation of structural analysis and exchange between diverse software applications in an open environment (QIN et al., 2011). One special requirement for interoperability for concrete structures, are the reinforcement bars. A lack of development in this area is commonly described. IFC is not perfectly prepared to receive this kind of information, and some software does not export this information as well (KIM et al., 2013).

To provide efficient interoperability of reinforcement bars, some authors suggest that these elements should be shared as individual elements within assembly, considering their relationships to the parts in which the bars are inserted. It is also important that systems consider the differences in the reinforcement bars of cast-in-place and precast concrete structures, since both have different needs (ARAM et al., 2013). Also, semantic web can be used to promote interoperability between BIM models and product catalogues, such as precast concrete structures (COSTA; MADRAZO, 2015). However, cast-in-place concrete structures don't follow pre-determined shapes or catalogued elements, and have other special requirements for interoperability.

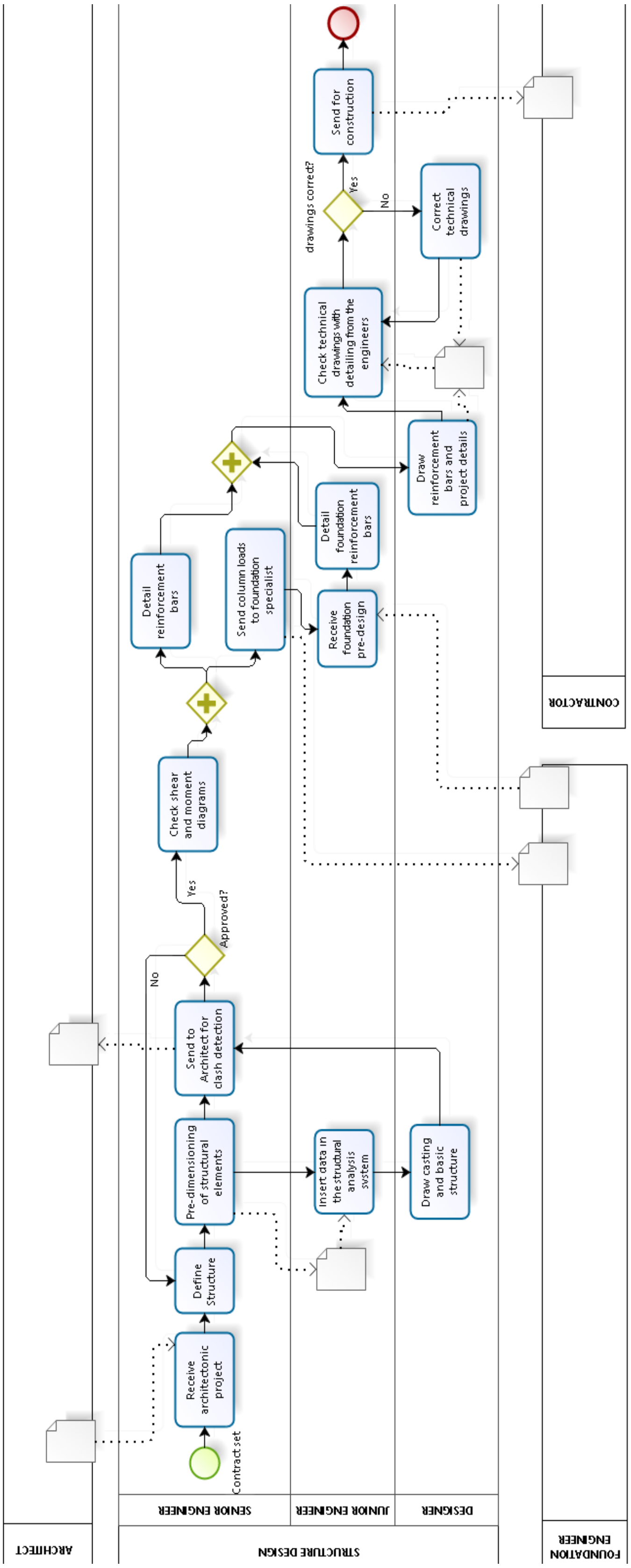
When considering shapes for modelled objects, literature presents three possibilities: (i) objects can be disjoint (meaning that they never occupy the same space), (ii) nested (meaning that one shape is completely inside the other) and (iii) overlapping (when one shape is only partially occupying the same space as the other). These concepts are extremely important for cast-in-place concrete structures, because structure elements often are overlapping (such as the place where beams meet columns) or nested (such as reinforcement bars inside any given structural element). It is important for software to subtract the intersecting areas, in order not to generate errors in the concrete quantity take-offs (VENUGOPAL et al., 2012).

Process Maps

Based on literature and in industrial best practices (GRILO, JARDIM-GONCALVES, 2010; KIM et al., 2013; MULLER et al., 2015), a process map using BPMN to detail the information flow and tasks in a structural engineering design company was carried out. Firstly, a company that doesn't use BIM was considered. As show in Figure 15, the process without BIM, requires many stages of clash checking, verification and file transferring. These files transferring’s are often not in the same format, so users need to export files to different formats and sometimes even re-enter data in different systems.

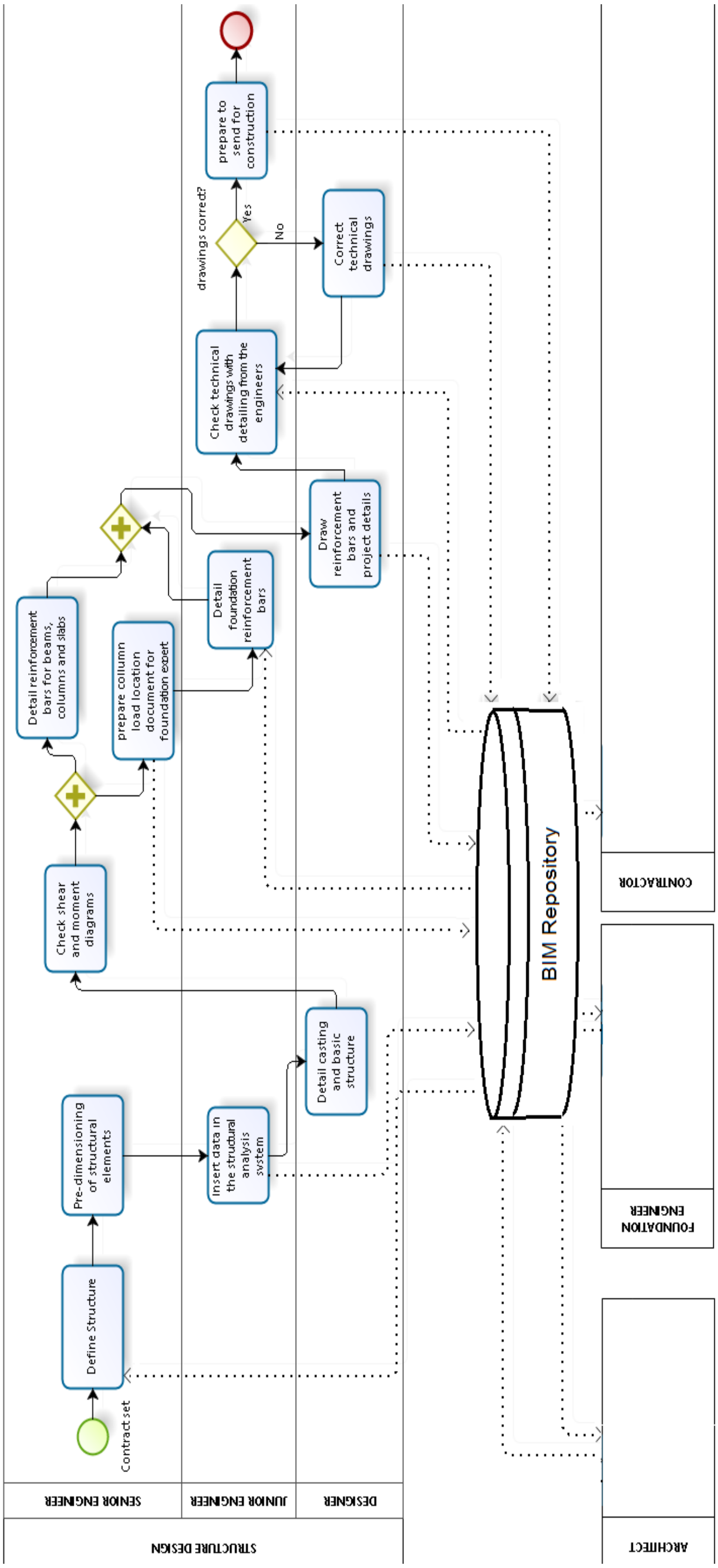
Based on further literature (ARAM et al., 2013; SACKS et al., 2010; VENUGOPAL et al., 2012), it was possible to suggest a process map with the use of BIM, shown in Figure 15. This represents an improvement on the process, since many tasks and file transfers could be simplified or even excluded, minimizing errors and saving time. In this map, BIM is shown as a repository to aggregate all the information needed.

Figure 15 - Process map of a structural design company



Source: Author.

Figure 16 - Process map of a structural design company using BIM



Source: Author.

With the use of a BIM model as a repository, these processes become much more automatized, and designers may insert their data directly in the model repository, minimizing or automating clash and error detection. For this process to work, all users involved must either work on the same platform or use an interoperable open file such as IFC. From the process maps, it can be noticed in the importance of data interoperability, since for the use of a BIM repository, users should agree on an interoperable format. Hence, the experiments with data interoperability were developed. The present research presents interoperability tests of IFC for cast-in-place concrete structures, and some suggestions for improvement of this standard, in an attempt to facilitate this process, allowing users to communicate and interoperate properly.

Interoperability Experiments for IFC

Generally two non-visual methods can be used when analysing IFC models: direct text or direct objects. As the text may vary, the best method is the comparison of objects. The procedure for certification of Building Smart uses a combination of visual and syntactic tests. At first, models originated in an application are exported and imported within the same system and then exported to other software. The certification process is based on real life needs of IFC interoperability. It can be done by exporting simple objects, such as a wall, a wall with an opening, or by testing complete and more complex models, such as a commercial building. Tests with complex models allow evaluators to assess the interoperability in situations that are closer to the reality (JEONG et al., 2009).

Three main kinds of interoperability export/import tests are described: one-to-many, one-to-self and many-to-many. In one-to-many tests, one model generated in one system is exported to many other systems. In many-to- many tests, models from lots of different software are exported to other systems and in one-to-self experiments, one model is exported and imported in the same application (LIPMAN et al., 2011).

When discussing interoperability assessment, it should be taken into consideration what kind of BIM objects are being analysed. Such objects can be divided into three main categories (EASTMAN et al., 2008):

- Made to be stored, such as plumbing and electrical parts, are modelled only once according to the catalogue.

- Custom made, such as windows and doors, are also catalogued, but need to have parameters that the user may change.
- Designed-engineered components, more complex, need to be designed, detailed and manufactured according to customers' requests, so the BIM components need to be developed for each situation and specific software for these purposes can be used.

Since literature, along with the development of the process maps, showed some fragility in BIM data transferences, this research focused primarily in the data aspects of BIM interoperability, mainly IFC. This is because the lacks of correct standards lead to breaks in the information and process flows. Based on these import/export experiments described in this section, and especially considering cast-in-place concrete structures singularities as a Designed-Engineered component, experiments to evaluate IFC interoperability were developed. These experiments are better described in the next section, as well as its results and suggestions for improvement based on them.

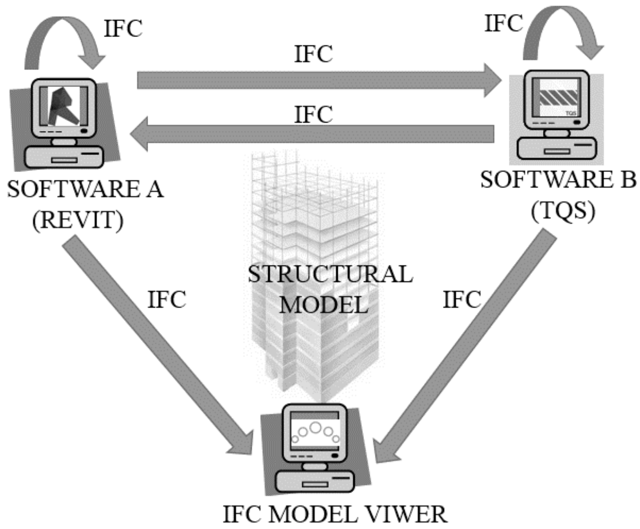
3.1.2 Data Analysis Experiment Methodology

The method used in this study is founded in a data analysis experiment, through file import/export from proprietary formats to IFC. The experiments were conducted twice, with a gap of five years to better analyse the development and drawbacks of data interoperability. This study focuses on cast-in-place concrete structures, which are designed components and present the biggest challenge for BIM modelling.

The experiment was based on experiments presented in Jeong et al. (2009) with precast concrete structures. Even though experiments are similar, the object of analysis presents some great differences, mainly due to the fact that precast concrete structures are subdivided in individual pieces, while cast-in-place concrete structures are monolithic, creating some special needs and barriers for interoperability as stated before.

Then, a similar procedure was developed in the experiments. Files containing structural elements were exported and imported among platforms, as shown in Figure 17. Not only the BIM applications were used, but also the IFC model viewer was employed. This allowed researchers to verify if the software were having difficulties reading the model or exporting it. This kind of test is called many-to-many (including one-to-self roundtrips) (LIPMAN et al., 2011).

Figure 17 - Model transfers



Source: Author.

Data collecting was performed visually, by checking the model and marking on a spreadsheet which structural elements and their characteristics had been transferred correctly. The structural elements analysed in these experiments were: beams, slabs, columns, stairs and ramps (stairs and ramps were included in the category slabs). The characteristics checked in the models were based on the literature as well. Considering the special needs for cast-in-place concrete structures, the items selected to be analysed in this experiment were:

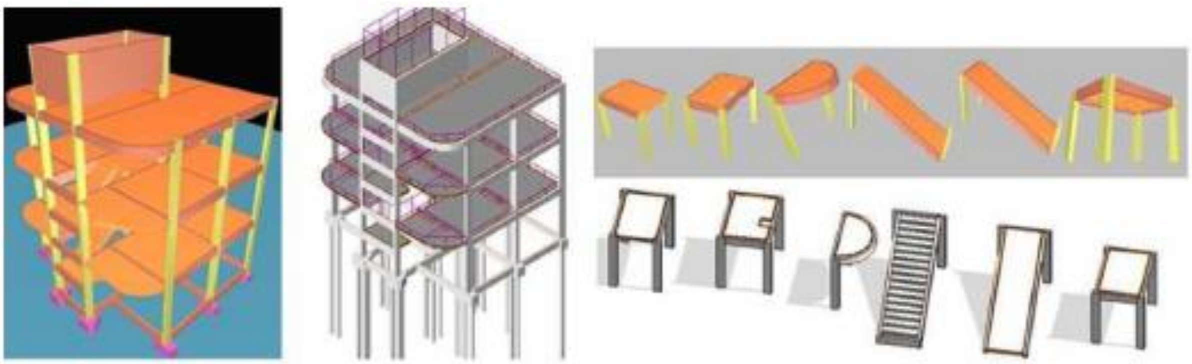
- Material/type, considering whether the material for the concrete characteristics were transferred correctly, and if the element was seen as the object as which it was proposed (pillar, beam etc.);
- Placement of the objects;
- GUID (Globally Unique Identifier) which is the code that identifies the objects;
- Geometry.

The transfers were marked as complete, incomplete and partial. Scores in a system similar to the Likert scale were attributed: 1 to complete, 0.5 to partial and 0 for incomplete. Then an average was calculated involving all the characteristics of each element. Authors in other studies (JEONG et al., 2009) had used only binary association in tests, and often needed to justify why an item was considered correctly transferred or not, so the need for a partial option during checking was perceived. Many objects were modelled, this included a complete building and sets of different kinds of elements:

- Beams: single span, multiple span, containing an opening, curved, with height variation and sloped.
- Slabs: simple monolithic, with an opening, ribbed, curved, sloped (ramp) and stairs.
- Columns: rectangular (one and two story-height), round, with section variation and L-shaped.
- Building: two apartments by floor, three story height with parking spaces below the building.

Some of the examples of the models produced in software A and B can be seen in Figure 18**.** After five years from the first tests, the experiments were conducted again using more recent versions of the software. The tests had the same structure as the first ones, using the same structure types and the same software.

Figure 18 - Examples of models generated in Software A and Software B

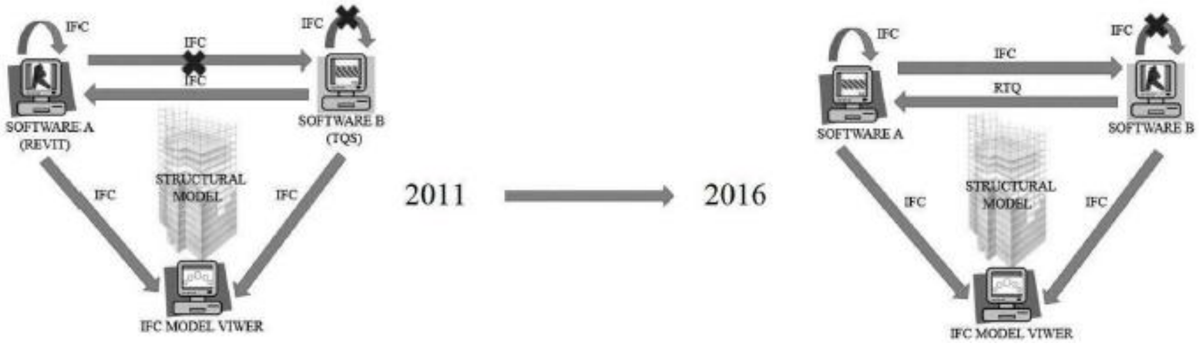


Source: Author.

3.1.3 Results From Data Interoperability Experiment

When transferring IFC models, some systems work as a sort of black box. They can generate IFC files, but are unable to receive IFC files. This was a great problem perceived in the first experiment. Software B could not receive IFC files, so a big part of the transactions was incomplete, as seen in Figure 19. This causes users to need to import reference files through 2D systems. Challenges presented by cast-in-place concrete structural models go beyond the fact that the structure is monolithic (for example, there is no physical separation between slab and beam), there is also the need for intricate reinforcing bars detailing, the use of specific concrete type, etc.

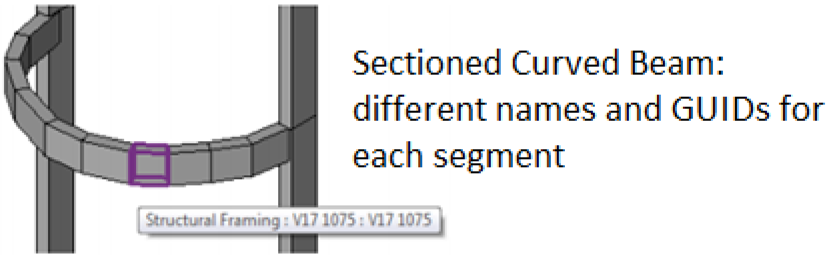
Figure 19 - Model transfers in the experiments



Source: Author.

In the geometry analysis, the most difficulties met were related to sectioning the objects. Even though casting-place concrete structures are monolithic, BIM systems present difficulties treating it as such. A slab does not end when it meets a beam, and neither does the beam end when it meets the slab, so the volume in this intersection belongs to the slab as well as to the beam. This creates another problem, because when elements get sectioned, they are assigned with different GUIDs as well. The errors perceived the transferences of the GUIDs were mainly due to geometry errors. Systems have presented some difficulties with more complex geometries such as curves as well. Often curved elements were broken in smaller pieces, as shown in Figure 20.

Figure 20 - Curved beam split into smaller parts



Source: Author.

Another big concern was the reinforcing bars and detailing. Detailing is an important part of concrete structures, and hardly any information was transferred in the

IFC files properly. Only in one case the reinforcing bars were transferred, and still as a characteristic of the object, not as a bar itself. No loads were transferred in any cases either. The need for better transferring of concrete structures models was also confirmed by literature (ARAM et al., 2013).

Table 3 shows the averages described in the methodology section. The results show us that the biggest problem lies with the material characteristics, as it has the lowest of the average scores. This probably happens because including material information in the objects is a somewhat new concept in the AEC industry. Before BIM, models had extensive geometry, but all material information was presented in writing.

Table 3 - Results from the first experiments

OBJECT	GUID	PLACEMENT	GEOMETRY	MATERIAL	TOTAL
COLUMNS	0.583	0.667	0.500	0.383	0.537
BEAMS	0.618	0.667	0.513	0.538	0.583
SLABS	0.583	0.633	0.578	0.525	0.580
TOTALS	0.595	0.656	0.530	0.482	0.567

Source: The Autor

In the second stage of the experiment conducted 5 years later, few changes and improvements were noticed, and in some cases, even some drawbacks could be perceived.

This highlights the need for improvement in data interoperability for BIM. Even though software B is still not able to import IFC files, developers presented a plugin for Software A. This way, system A exports its files directly to proprietary files used by software B (called RTQ). A total of five transfers were analysed as shown in Figure 20. The same scoring methodology was used as in the original experiment. As in the first experiment, four characteristics were analysed through visual inspection: GUID, placement, geometry and material.

The averages from the second analysis can be seen in Table 4, and it could be perceived that materials are still the area that needs the most development in casting-place concrete structures, since they still have the lowest score. The new version of the software also had particularly a great difficulty in processing objects with openings and curved geometry. This time, some loads were transferred to the slabs; however in some cases the files joined permanent and variable loads. This can become a problem, because different types of loads use different coefficients and go through different combinations to determine the final moments, sheer forces and compression on the columns.

Table 4 - Results from the second experiments

OBJECT	GUID	PLACEMENT	GEOMETRY	MATERIAL	TOTAL
COLUMNS	0.780	0.800	0.740	0.800	0.780
BEAMS	0.767	0.967	0.767	0.733	0.809
SLABS	0.800	0.933	0.733	0.583	0.762
TOTALS	0.782	0.900	0.747	0.705	0.784

Source: The Author

Considering the average total score of the evaluations, it can be perceived that in the five year gap, there was an improvement of approximately 38% (considering an average of 0.567 for the first analysis and of 0.784 for the second).

A common problem found during transfers was related to the geometry of some structural elements as curves, sloped beams and beams with multiple spans. These structural objects were sectioned in multiple elements, losing their original structure and therefore creating new GUID codes. The model should consider the elements overlapping, since not only this is more geometrically accurate to reality, but also probably would prevent the program from creating a new GUID for each section of the structural element.

A suggestion to overcome the problems with loads and reinforcement bars is for both to be considered objects in IFC schema. These objects should be hosted in the structural elements, so this would make it easier for the systems to generate elements and to transfer them correctly. Another possibility to improve interoperability is for systems to give users the option to use the regulations of their own regions. This would allow a much greater integration with systems from different countries.

In addition, material wise, the tests didn’t present satisfactory results as well. It is very important for material information to be transferred correctly, since the kind of concrete used relates directly to structural resistance.

Loads should also be an object of attention, since loads presented great problems in the transfers. These two areas are especially relevant, since errors in these characteristics can lead to structural accidents, even endangering human lives. This aligns to views on the use of BIM for structural design by Jeong et al. (2009).

According to the authors, the correct transference of material and loads are essential to efficient modelling.

3.1.4 Conclusion of the section

Building information modelling is forecasted to be an important agent on interoperability in the AEC industry according to literature (SKIBNIEWSKI; ZAVADSKAS, 2013). However, in order to develop and improve IFC data interoperability, the special needs of the AEC industry should not be disregarded in the development of the software and their ability to export proprietary files to IFC files. Special attention needs to be given to geometrical characteristics of the models, materials and detailing in order to develop interoperability through IFC in cast-in-place concrete structures.

However, in a gap of 5 years, some evolution in extensibility and adaptability were observed in all four elements analysed. The rise in 38% interoperability score shows some improvement in the field. This advance in the data concern in essential for improvement in business, process and services concerns, since professionals are not likely to advance with BIM to higher value levels without technical developments in the more basic levels, especially concerning data. This is due to the fact that when data is not transferred correctly, not much can be developed in the structural analysis and modelling field. So, cast-in-place concrete's unique characteristics should be considered in future versions of IFC, especially the overlapping of structural parts, the use of reinforcement bars and the need for precision in loads and materials.

It could also be noticed that the use of BIM would represent an improvement on the structural design process. The process can become much shorter, and files exchanges are minimized, especially considering BIM as a repository. Also the communication with other companies can be greatly improved, since a BIM repository may connect structural engineers, architects, foundation engineers and contractors. Since literature and the development of the process maps showed some fragility in BIM data interoperability, this research focused primarily in the data aspects of BIM interoperability. The other three concerns (service, process and business) should be addressed with more depth in further sections.

3.2 PRELIMINARY ANALYSIS – MULTICRITERIA DECISION MAKING MODEL FOR THE CHOICE OF INTEROPERABLE BIM SOFTWARE AND ENVIRONMENTAL ANALYSIS

The building information modeling concept (BIM) has distinguished itself in the whole civil building lifecycle, since its design, optimization, construction, and operation (DONG et al., 2014). With such increase, a number of BIM software was created, e.g. Autodesk Revit, ArchiCAD, Vico, Bentley Micro station, etc. Each software provides different solutions for the several AEC fields (architecture, engineering and construction) industry. Besides the most known BIM platforms already mentioned, in which it is actually possible to model almost the whole project, there is complementary software also called tools or plugins that make use of the model's parametric information to analyze or complement what was not present in the base program.

The existence of such software, tools, and plugins diversity derives from the multidisciplinary nature of civil engineering, in which several professionals work in parallel, making use of different technologies. In addition, the temporary nature of a construction makes it a challenging environment for the fulfillment of interoperability requisites (STEEL et al., 2012; HU et al., 2016). Interoperability is defined as the ability of systems and organizations to work together and interoperate (VENUGOPAL et al., 2015). So that such interoperability is efficient, standards are required to guide the translation and loading of information contained in a BIM software. In this way, the transmission between different software and tools is possible, even if not from the same company.

One of the efforts that made several software and applications work together was the creation of the IFC and gbXML standards. IFC represents an open, international standard that promotes information exchange between different BIM software (AKBARNEZHAD et al., 2014). GbXML, additionally, extends its function to the extraction of relevant information of the physical and thermal aspects of environmental and energy analysis in other software or applications. IFC and gbXML have helped the interoperability evolution, once objects no longer comprise 3-dimension formats, but on the other hand, relevant information such as price and thermal data (NEGENDAHL, 2015).

Despite the initiatives to promote information interoperability among BIM software, information exchange through open standards are not entirely developed nor supported in the various software in the market. Besides that, geometry and data loss issues are commonly observed after this data transfer process (GARCIA; ZHU, 2015). These problems reduce the efficiency of BIM software usage, and thus interoperability needs be constantly tested and assessed (KIM et al., 2015). This test is required whenever a program is successfully updated, as well as when new information is inserted into the project.

In this research, interoperability between two BIM software is assessed: Archicad and Revit, as well as their respective energy analysis tools, the EcoDesignSTAR and the GreenBuilding studio. To do so, the same construction with the same material information is modeled in both software and, based on this premise, information is exchanged through the IFC and gbXML standards. Another application also helps assess this exchange: through the DDS-CAD Viewer the IFC and gbXML properties can be displayed.

After the data exchange process, effectively transmitted data are analyzed and tabled, e.g. the number of doors, and quality of the information, e.g. if the transmitted areas have different values. Based on such qualitative and quantitative information, the PROMETHEE, a multicriteria decision making/analysis (MCDM/A) method, was applied in order to evaluate which software combinations and tools have higher interoperability, and if the fact that the software belonging to the same company contributes to interoperability.

3.2.1 Interoperability for BIM and sustainability

The concept of Building Information Modeling was initially proposed in 1975, aiming to visualize and quantify building project analyses and improve building efficiency (WANG; ZHAI, 2016). On the one hand, BIM is regarded as a mere software application, while on the other hand, it consists of a process to project and manage building information (LIU et al., 2016). Additionally, BIM can be defined as a group of interactive policies, processes, and technologies employed in order to provide a digital-based management methodology for the design and project information (CHO et al., 2014).

One of the issues that BIM can solve is the problems of interoperability that exist between the different disciplines of the ACS, since they can all be represented in a single model. Also, the same model can be covered in parallel, facilitating the identification of conflicts, and thus resulting in the project productivity increase (DONG et al., 2014). The model can be either 3D (tri-dimensional) or 2D (bi-dimensional), in which information is parametric, i.e., a change in part of the model implies in the update of all other perspectives. Besides the model parametric geometry, other aspects such as costs, quantitative aspects, and analyses are instantaneously modified, with no need to revise the entire project in order to manually update it (NGUYEN et al., 2010).

As per the IEEE definition, interoperability is the ability of two or more systems or components to exchange information and make use of the imported information. Interoperability is possible thanks to implementation of patterns. Chen divided interoperability into three categories according to barriers: conceptual, technological, and conceptual (CHEN et al., 2008). This study focuses on the technological category, in which barriers are associated with patterns to present, store, exchange, process, and communicate data and information through software.

Some technological interoperability approaches can be pointed out from a literature review. In the BIM and software field there are efforts concerning structural projects such as in (HU et al., 2016), in which one can find a contribution to interoperability improvement between architectonic design and structural models. Muller et al. (2015) provide a study on the technological progress in the field of data interoperability between IFC and BIM during five years, focusing on structure software.

In the field of BIM and Sustainability interoperability, the authors Guzman; Garcia; Lee (2015) bring up the data exchange between building project and energy models, showing an automated solution through the (XSLT) to mitigate interoperability issues. Such solution includes a set of instructions to facilitate the information interchange among the construction design and the energy modeling fields. Other studies also present models and validations in order to ensure data exchange interoperability of a building information model (STEEL et al., 2012; LEE et al., 2015).

In face of the mentioned elements, a paradigm change arises in the information updates and relations among the various AEC areas, resulting in price and time reduction as well as a quality increase in the whole building lifecycle (CHO et al., 2014; LU et al., 2014). The BIM also comprises sustainability and energy issues via applications that can be either internal or external to the software. Tools are programs that make use of information from specific software to analyze or to perform a specific function. In this way, besides the possibility to model the entire project at once, analyses can be done so as to determine how efficient a certain building is. By using an already finished model, the time required to create a new energy model is reduced, once it is possible to export information that is relevant to such analyses with specific extensions in gbXML base (HAM; GOLPARVAR-FARD, 2015).

Therefore, the BIM can be regarded as a great advancement, as CAD was at the time, given its diverse and integrated applications. There is, however, a long way ahead (LIU et al., 2016), once even among professionals who already employ the BIM as their main tool, limitations are still observed, e.g. lack of interoperability and integrity in the data transmission among the existing software in the market (LEE et al., 2015).

IFC

IFC is the BIM's main data extension, considered as standard, and supporting data transfer among different software from different suppliers (MA; ZHAO, 2008). IFC stands for Industry Foundation Classes and, technically speaking, is an open data format programmed so that every professional is able to transfer and work on the same BIM project (CHARDON et al., 2016). It is considered an open standard extension because its copyrights do not belong to a single company. Therefore, it is widely employed by BIM software.

Concerning the data transfer of a project, Rahmani et al. (2015) state that the IFC architecture divides a BIM file into five subsets: (1) *Geometry* regards the data used for geometry definitions, e.g. central lines of the walls, areas, and perimeters; (2) *Geometric Relations* regards horizontal and vertical references of the elements; (3) *Name Attributes* regards data required to map objects and semantic definitions of the entities as well as analyses of the object classes; (4) *Domain Specific Attributes* regards data required for the functional definition of each analysis entity such as load types in a thermal zone for energy analysis; (5) *Instance-Specific Attributes* regards the variables pointed towards external data sources (SANGUINETTI et al., 2012).

Recent studies show, however, that IFC export format incurs on data loss of parametric and dynamic models of the project stages, mainly in the project initial stage. Several researches reveal poor data transfer or with relevant data loss between a software and another BIM via IFC (NEGENDAHL, 2015).

With regard to sustainability, common approaches refer to import and export tests with file extensions between BIM programs and analysis tools, with or without IFC support. A reoccurring extension in this type of research is the gbXML (RAHMANI et al., 2015).

gbXML

Extensible Markup Language (XML) is an extension in which a set of text-format rules creates a framework to transmit information. It was applied to the BIM through the gbXML (Green Building XML) and the ifcXML (HAM; GOLPARVAR-FARD, 2015).

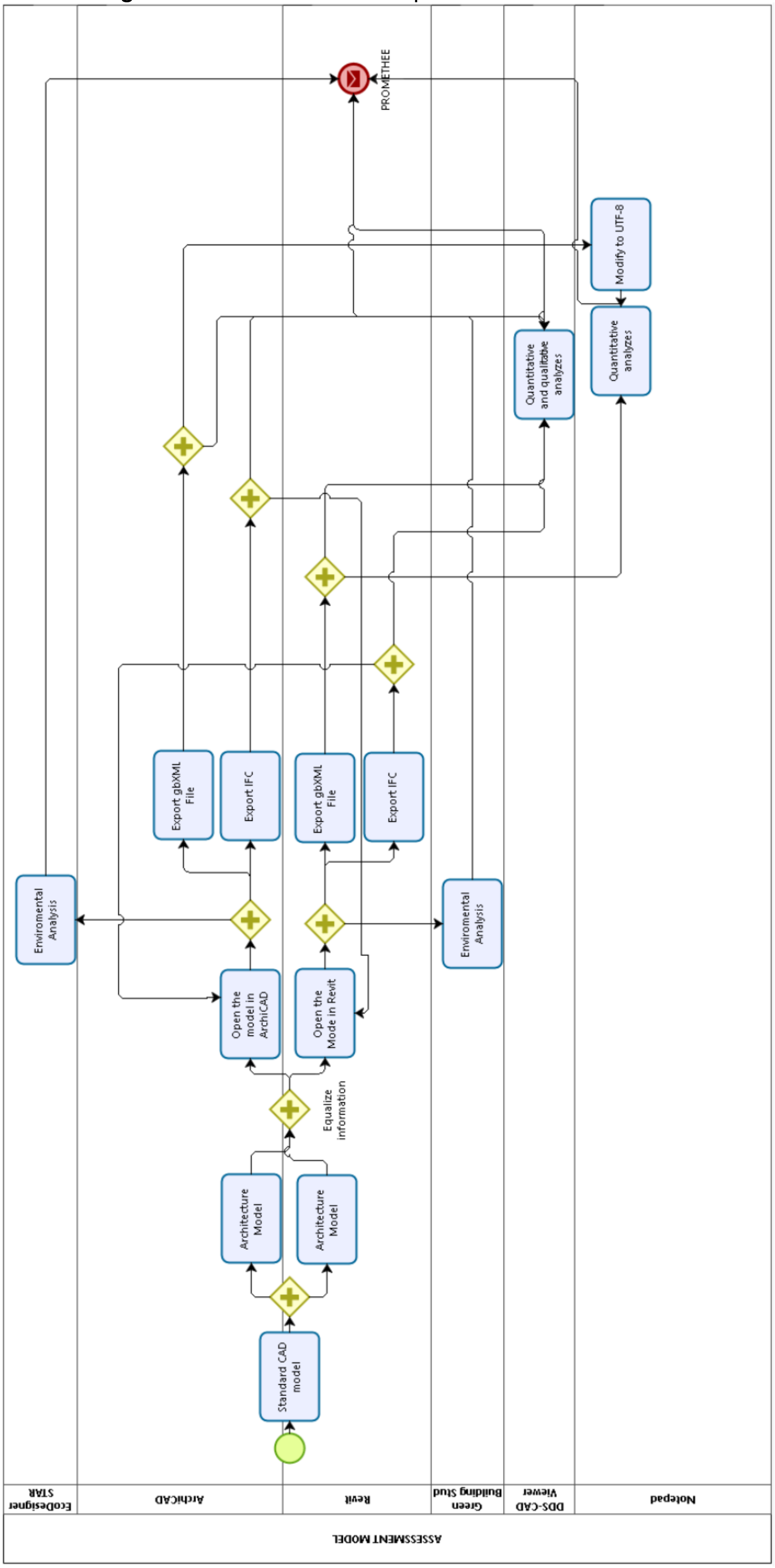
For most engineering analysis tools, not all semantic information contained in the BIM are essential. Furthermore, attempts to export all building information from the BIM often fail, once the building model is either quite complex or not appropriately developed for the simulation. Energy simulation tools that require just a thermal view of a building can be mentioned as an example – therefore implying a simplistic building representation containing all information about each bedroom such as volume, geography, and adjacency (WANG et al., 2015).

As a result, gbXML became a standard framework that filters sustainability information within the BIM, in addition to being supported by several market-leading developers such as Autodesk, Graphisoft, and Bentley (GARCIA; ZHU, 2015). One of the gbXML advantages lies in its capacity to transfer relevant, detailed descriptions of a single building or group of buildings, which can be imported or employed both by software and energy analysis and simulation tools (JALAEI; JRADE, 2014). According to the official website (2018), gbXML is currently at version 6.01 and its type of extension is supported by more than 40 software and tools.

3.2.2 Assessment Model

The multicriteria decision making/analysis (MCDM/A) are used to improve the decision-making processes, reducing uncertainties and inconsistencies, thus reaching the adequate choices as much as possible (RE et al., 2014). One of these methods is the PROMETHEE, which was developed in the 80ies by Jean-Pierre Brans aiming to rank alternatives, given a set of criteria (CHEN; PAN, 2015).

Figure 21 - BIM assessment process model in BPMN

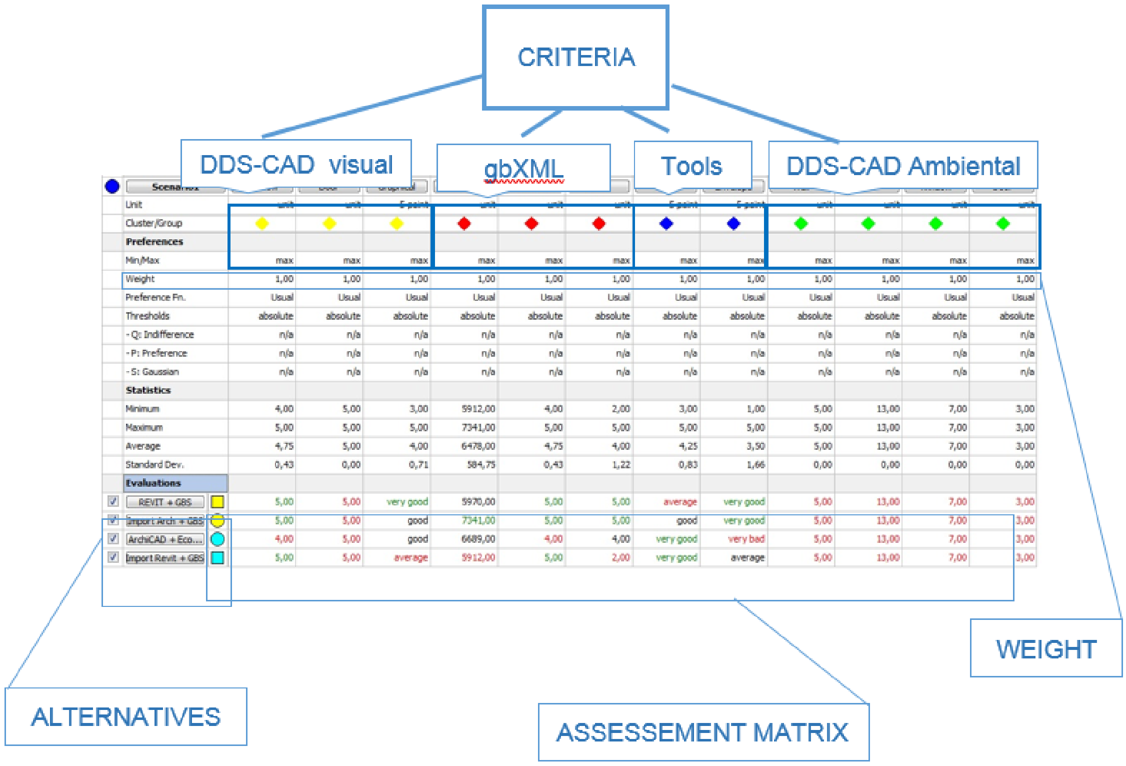


Source: The Author.

Through the Visual Promethee platform and based on data obtained from the previous analyses, 04 alternatives and 12 analysis criteria were created. Each alternative is associated with a category, in which the color yellow represents Revit and blue represents ArchiCAD. Additionally, the geometric forms represent the tools: the square stands for GBS and the circle corresponds to EcoDesign. As a result, each combination of program and tool corresponds to a different color and geometric format.

The criteria were also subdivided into 04 different colors. In yellow, the criteria regarding analyses visually performed by the DDS-Viewer. In red, the criteria regarding the analyses extracted from the notepad of the gbXML files. The criteria referring to the values extracted from the native tools of the programs are in blue, while criteria regarding data from the environmental analyses in the DDS-Viewer feature the green color. Figure 22 illustrates the PROMETHEE assessment structure, its criteria (and weights), alternatives, and the assessment matrix with the value of each assessment (criterion vs. alternative) under the perspective of the measured unit in question.

Figure 22 - Assessment model in the Visual Promethee platform



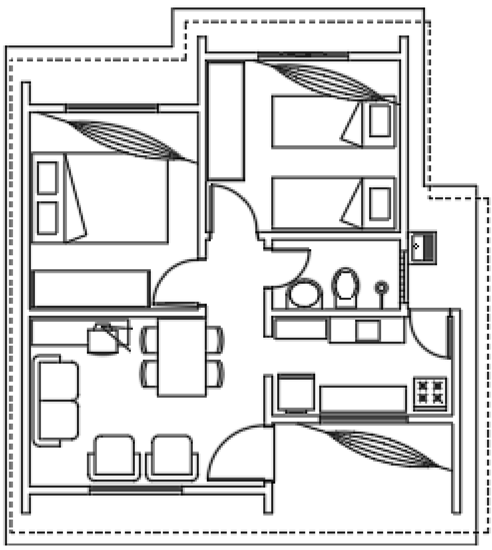
Source: Author.

3.2.3 BIM Model Implementation

The original file of the Caixa Econômica Federal project comprised a floor plan in the .DWG format, commonly used in CAD software. The project regarded standard public housing with two bedrooms, one WC, one living room, and one no-door kitchen in front of the living room. The construction consisted of walls made of 12-centimeter ceramic bricks, wooden doors, aluminum windows, and wooden roof beam with ceramic tiles, as per Figure 23.

In the model analyzed in the present research, the ceramic-tiled roof was replaced by a waterproof concrete slab, since the environmental analysis software GBS is unable to perform its analyses with the roofing model presented in the original files. The software chosen to model the project in BIM were the most commonly employed in the Brazilian market (CLASSES, 2009) – Autodesk Revit and Graphsoft ArchiCad. All measures were accurately preserved and copied to the new BIM models.

Figure 23 - Humanized Architectonic Project



Source: Author.

The environmental analysis takes into account internal volumes, materials, openings, and environmental data inserted into the model. Spare walls were removed to facilitate the analysis tools processing. Environmental values were aligned between the two softwares, e.g. the heat transfer coefficient, which was adjusted in order to be the same in both software and in all windows, doors, slabs, and walls. The accuracy of modeling heat properties such as thermal resistance (R-value) or thermal transmittance (U-value) for building elements is one of the most influential factors in the calculation of the thermal loads and associated energy consumption (LAGÜELA et al., 2014).

After concluding the models, environmental reports were generated by embedded tools. In Revit, the standard environmental analysis tool is the Green Build Studio, which can be accessed either by the program environmental analysis resource or by sending a gbXML file over the supplier website. Either case, results are the same. ArchiCad, in its turn, makes use of the EcoDesign Star as a standard analysis tool.

In order to provide the analyses, energy models were created in Revit and zones in ArchiCad. Such tools generate reports described in Table 5. A basic analysis datum, usual among environmental tools, referred to the area of both the generated volumes and the envelope. These are basic data for the creation of the other items mentioned above, and thus were tabled.

Table 5 - Tools and Data

Green Build Studio	**Eco Design Star**
Energy lifecycle cost	Sample Thermal Block Energy Balance
Renewable energy potential	Daily Temperature Profile
Yearly carbon emissions	HVAC Design Data
Yearly energy usage/cost	Energy Consumption by Targets
Energy usage: Fuel	Energy Consumption by Sources
Energy usage: Electricity	Environmental Impact
Monthly heat load	Renewable Building System Summary
Monthly cooling load	Baseline Performance
Monthly fuel consumption	Baseline Energy Costs
Monthly electricity consumption	Performance Rating Table
Monthly peak demand	Energy Consumptions and Savings
Yearly Windrose (Speed Distribution)	
Yearly Windrose (Frequency Distribution)	
Monthly Wind Rose	
Green Build Studio	**Eco Design Star**
Monthly project data	
Yearly temperature range	
Climate daily average	
Humidity	

Source: The Author

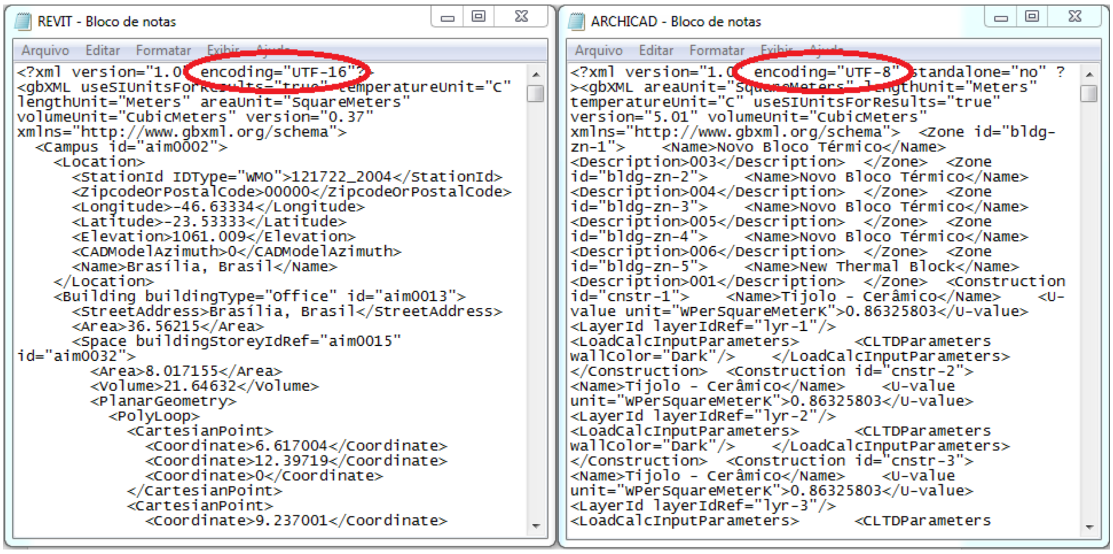
After performing the BIM internal tests, two import files were generated: one in gbXML and another in IFC. In the IFC files, some export parameters, e.g. the version of the IFC 2x3 Coordination View 2.0, were adjusted. As a result, definition properties increased in order to cover as much data volume as possible as well as increase the geometric detailing level to High. In the gbXML files, there are two export options in Revit – one through energy models and other through the use of environment/space volume. As in ArchiCAD models derive from volumes and zones, in Revit the corresponding option was employed.

The gbXML file is opened on Notepad and the pure data are analyzed. In the file, the quantity of windows, doors, and words are analyzed. In Revit, the searching process is easier, since word-based search (e.g. the word "DOOR") resulted in door data, given that the "openingType" attribute was "NonSlidingDoor". This attribute is based on the family category with which the object matches in the original file – for instance, there are 07 attributes for "openingType", which basically depend on the surface opening degree; if it is adjustable or fixed, if hinged or sliding. This type of attribute is used for doors and windows.

In the Revit file, "fixedwindows" were used for the windows and "NonSlidingDoor" for the doors. In the ArchiCAD file, however, opening information was mixed up, requiring adjustments in the number of windows and doors based on the span size created by each element, i.e., elements with height above 2 meters were considered doors, while openings with height below 2 meters were considered windows. But this could be a problem nevertheless, in case windows and doors had similar or non-standard sizes. In this specific analysis, however, differentiation can be identified. Another important information extracted from files without gbXML changes was the number of words, taking it that a larger quantity of words represents a larger volume of data exported by the program.

Through this syntactic analysis and direct comparison between the native files presented by different software, it could be attested that files generated in ArchiCAD employed the text codification type "UTF-8", while text files generated by Revit held the UNICODE text codification, according to Figure 24. This was the reason why gbXML files deriving from Revit were not open in the DDS-Viewer program, thus featuring an interoperability issue that can be manually reverted through the text modification in the file. After perceiving such difference in the file texts, the issue was solved by saving a new copy of the XML file using "UTF-8" codification via Notepad.

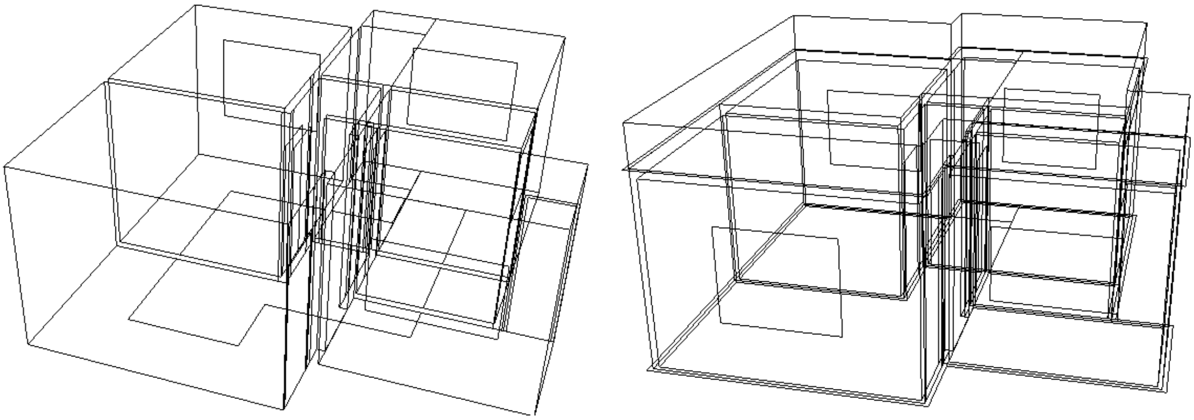
Figure 24 - UNICODE Notepad text



Source: The Author.

Once both files had the same technical features, a visual assessment of the model objects was performed in the DDS-Viewer, which consisted in counting windows and doors, in addition to analyzing quality and detailing of the exported models. For the model quality assessment, a 05-point scale was created, where 05 means the perfect detailing and 01 the worst possible scenario. In a perfect detailing, volumes are well defined, without loose lines, and with the appropriate number of elements such as doors, windows, and parapet. In Figure 25, the visual assessment evinces the frontal window is not present in the left figure of ArchiCAD.

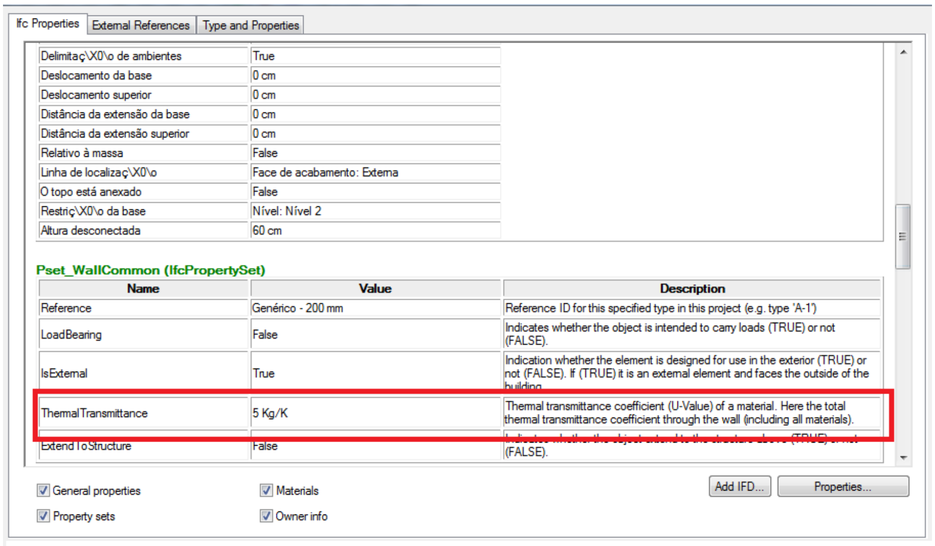
Figure 25 - Wireframe Project



Source: The Author.

Another DDS-Viewer analysis is done through the IFC file. This file was directly opened by both programs, without requiring any change in the file root. The integrity of the environmental data inserted into the windows, doors, slabs, and walls was checked as well as the consistency of the migrated data. In Figure 26 in red, the heat properties were analyzed.

Figure 26 - Table of properties



Source: The Author.

After performing the analyses of the gbXML and IFC files, the IFC files were exchanged between the Revit-ArchiCAD and ArchiCAD-Revit programs. In this way, each program opened the model designed and edited by its competitor, generating new IFC and gbXML files as well as carrying out environmental analyses in its native tools. The generated files went through the same analyses as the original files, and thus data loss in IFC migration could be verified.

3.2.4 Analysis of results

This Section presents the results for interoperability data exchange formats and systems, providing details of the analysis on each case.

Green building Design and EcoDesign STAR

The analyses generated in the Green Building Design and the EcoDesign Star brought out divergences since the preliminary analyses in the pure files of each software. While GBS presented an area of 63.00m^2 in the external wall, EcoStar provided an area of 93.78m^2. Even the floor area had discrepancies – GBS showed

37m² and EcoStar 33.45m², which is the correct value in the project. The analyses of the files imported from the other program via IFC also presented divergences, mainly with respect to the external wall area, in which the file generated in REVIT (and analyzed in EcoStar) provided a result of 69.34m². Such value is much closer to the expected 63.00m² than the 93.78m² from the native file. The results can be observed in Table 6.

Table 6 - Results from Green Building Design and EcoDesign STAR

RESULT	EXPECTED	Revit + GBS	ARCH + GBS	ARCH + ECOdesign STAR	Revit + EcoDesigner STAR
GBS-ECOstar					
Floor Area	33.45	37	33	33.45	33.44
Ext.Wall Area	63	63	63	93.78	69.34

Source: The Author.

DDS-CAD Viewer with gbXML file

In this analysis, a great difference in detailing quality and model detailing is observed as files are first opened. And in this scenario, the Revit native is better, given to its well-defined lines, all doors and windows at the correct positions, perfect volumes, and the roof parapet profile. The worst case was the ArchiCAD native file, which presented a model with a missing window, unclear lines, and incoherent data. Even the Revit file exported to ArchiCAD has a richer and safer detailing degree than the pure one. In all models, doors were appropriately placed. Only in the pure ArchiCAD there was a door missing in the model. Results are shown in Table 7.

Table 7 - Results from DDS-CAD Viewer with gbXML file

RESULT	EXPECTED	Revit + GBS	ARCH + GBS	ARCH + ECOdesign STAR	Revit + EcoDesigner STAR
Vizualizador Viewer					
Window	5	5	5	4	5
Door	5	5	5	5	5
Detailing	great	great	good	good	intermediate

Source: The author

DDS-CAD Viewer with IFC file

The analyses performed in the DDS-CAD Viewer with the IFC file regard the environmental data transfer such as “ThermalTransmittance” to the model. Values were assigned to slabs, windows, doors, and wall. Such data were replicated in all cases, except from the ArchiCAD file exported to Revit, in which the IFC was generated because the slab heat information could not be provided. Results are shown in Table 8.

Table 8 - Results from DDS-CAD Viewer with IFC file

RESULT	EXPECTED	Revit + GBS	ARCH + GBS	ARCH + ECOdesign STAR	Revit + EcoDesigner STAR
IFC					
Door	3,7021	3,7021	2,5572	2,56	3,702
Window	6,7018	6,7018	6,7018	6,7	6,7018
Wall	5	5	5	5	5
Slab	13,33333	13,3333	Not Transferred	13,3333	13,3333

Source: The Author.

gbXML Text File

The gbXML files were open in Notepad and analyzed one by one. A relevant information regards the number of words in each file – the file generated in ArchiCAD, imported by Revit, and then generating the gbXML, was the largest with 7341 words. On the other hand, the worst case referred to the Revit file imported by ARchiCAD, which had a total of 5912 words. Furthermore, although the DDS-Viewer was able to decipher the gbXML files (in the Revit file exported to ArchiCAD), it was not possible to find all 05 doors in the model (the text file accounted for 02 doors only). As well as in the IFC analysis, the living room window in the file deriving from the native ArchiCAD was not present. Results can be seen in Table 9.

Table 9 - Results from gbXML text file

RESULT	EXPECTED	Revit + GBS	ARCH + GBS	ARCH + ECOdesign STAR	Revit + EcoDesigner STAR
GBXml					
Words	Highest	5970	7341	6689	5912
Windows	5	5	5	4	5
Doors	5	5	5	5	2

Source: The Author

Promethee Assessment Model

As per the model in Figure 27, and based on the data obtained according to 12 analysis criteria in Table 10 the table was divided into four groups according to the aspect and software analyzed, namely the DDS-CAD visual, gbXML, Tools, and DDS-CAD environmental. Under this criteria assessment perspective, a scenario formed by two main software (Revit and ArchiCAD) and two tools (Green Build Studio and ECOdesign STAR) was ranked.

Table 10 - Assessment Criteria

DDS-CAD Visual	Window	Quantity of doors - visually
	Door	Quantity of windows - visually
	Graphical	Graphical quality
gbXML	Words	Quantity of words
	Window	Quantity of words with the door function
	Door	Quantity of words with the window function
Tools	Area	Building internal area
	Envelope	Envelope area
DDS-CAD Environmental	Wall	Wall heat transfer coefficient
	Slab	Slab heat transfer coefficient
	Window	Window heat transfer coefficient
	Door	Door heat transfer coefficient

Source: The Author.

The Visual PROMETHEE platform assimilates information so that maximum and minimum values are considered as ideal. So that it understands which exact core values would be the best, however, a 05-point scale was created, in which the actual value is the maximum score in the scale. Then, the lower score the larger the deviation from the actual value, as in Table 11.

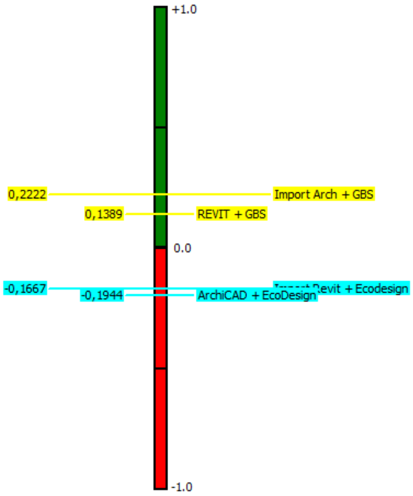
Table 11 - 05-Points Scale

Floor	Scale	Wall
41,45	Verybad	83
39,45	Bad	78
37,45	Average	73
35,45	Good	68
33,45	Very Good	63
31,45	Good	58
29,45	Average	53
27,45	Bad	48
25,45	Very Bad	43

Source: The Author

As a result from the assessments, as shown in Figure 27, a ranking was created, in which the Green Build Studio tool stood out and reached the first and the second place in this research. The best match between program and tool was for the pair ArchiCAD and Green Build Studio, which proved to be a fairly stable combination, with a scale never lower than “GOOD”, and always above average at all aspects. The worst match was ArchiCAD and EcoDesign STAR, which showed that programs face many interoperability issues, e.g. a window disappeared from the file exchanged between them.

Figure 27 - Result from the Promethee ranking

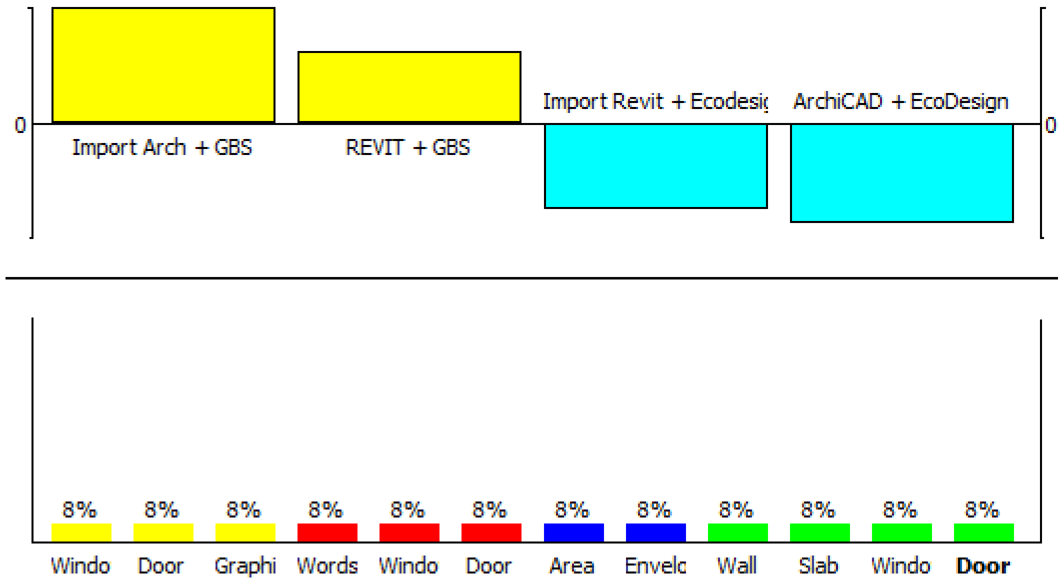


Source: The Author.

Through the Visual PROMETHEE platform, the sensibility of the obtained ranking was analyzed, as shown in Figure 28, acting upon the criteria weighting. For the sensibility analysis, all weights were initially isometric, so as to indicate that all assessed criteria had the same interoperability and sustainability importance. In case the weights were changed due to professional needs, e.g. increasing the Graphi requisite sensibility from 8% to 12%, the Revit + GBS pair would take over at the first place, proving that weight-sensible changes may affect the final result. In a scenario where the main analysis criterion is the architectonic project area, the positive highlight in EcoDesign STAR, increasing the criterion weight to 37% would be necessary, so that the pair Revit + EcoDesign STAR moves up to the first position, followed by ArchiCaD + EcoDesign STAR.

In so doing, taking assertive decisions about which program to use, developing strategies, and implementing relevant changes rely on the competitive advantages that each program provide. And also, weights need to be sensitized and pondered for each user according to the project requirements.

Figure 28 - Sensibility Analysis



Source: Author.

3.2.5 Conclusion of the section

Through the proper analyses in different formats and internally in the programs, the data exchange inefficiency among programs was attested, with relevant data loss both in IFC and gbXML export. Also, the fact that a tool and the main program are from the same developer was not sufficient to ensure the integrity of the data transferred and analyzed. In our analyses with isometric pondering of weights, programs and tools from mixed suppliers performed better, featuring the match between the main program from Graphisoft (ArchiCAD) and the supporting tool from Autodesk (Green Build Studio) the leading position in the ranking.

Standards with gbXML are good at loading environmental information, but the lack of a single language among programs conflicts with the viewers, which are able to interpret the same information in different ways. There are syntactic issues to be solved in gbXML standards. The fact that the generated post-export files have more words than the original file attests such issues.

Although the IFC interoperability is not based on the environmental perspective, it was a good file for sustainable data transfer, loading the information analyzed in this study.

At last, what can be inferred from the analyses is that when IFC files and translators are used to export or import the building data, one must consider that they are not sufficiently robust to transfer data with the same quality of the original model. The engineering, architecture, and civil construction scenario is evolving to BIM software, and interoperability issues must be solved so that such technology establishes its presence in the marketplace.

With the interoperability assessment model via the Promethee method, it was possible to sustain the compatibility analyses, thus enabling the replication in other BIM interoperability researches, both structural and environmental. The assessment method proved to be quite promising in the BIM interoperability assessment and in different analyses and decision perspectives.

In this way, the continuation of this research is intended, with the employment of complementary MCDM/A methods such as AHP/ANP and Electre TRI family. Such methods allow the characterization of a diagnostic analysis of more relevant criteria in the BIM interoperability analysis as well as the ranking of BIM structures in relevance categories at a specific stage of the BIM Lifecycle.

3.3 CHAPTER ALIGNMENT IN THE THESIS

On this chapter the preliminary analysis that motivated the development of the framework were described. This chapter presented two different data interoperability assessment experiments, where BIM files were transferred, and the quality and quantity of information lost was analysed.

The first analysis was related to concrete structures IFC transfers. IFC files were exported from software to software and information gaps in the processes were verified. This experiment was developed twice, five years apart, and the results showed that even though data interoperability has increased in the last five years, it is still not developed enough to effectively support and interoperable processes.

The second experiment was related to the interoperability of sustainability analysis systems. The tests showed that interoperability in this type of analysis is not efficient enough as well, however the use of multicriteria decision methods provided interesting results in the characterization and diagnostic of BIM interoperability.

The advance in the data concern in essential for improvement in business, process and services concerns, since professionals are not likely to advance with BIM without technical developments in the more basic levels, especially concerning data.

Another question raised was whether interoperability could be sustained throughout the lifecycle in the AEC industry. So, from these insights, the three axis for the systematic literature review were structured: Lifecycle, Sustainability and interoperability. Also, decision models and methods proved to be an interesting tool in BIM interoperability assessments, therefore being thoroughly used in this study. Finally, due to its special characteristics described in the first study, cast-in-place concrete structures was selected as an application case in the further development of the thesis.

4 LITERATURE REVIEW - A SYSTEMATIC LITERATURE REVIEW OF INTEROPERABILITY IN THE GREEN BUILDING INFORMATION MODELING LIFECYCLE

Sustainability has a growing role in the construction industry, and its importance must be considered not only in the design stage but also the entire lifecycle of a building. BIM allows the management of the lifecycle (from design to demolition), however, the biggest part of research papers focuses on the design stage. This way, maintenance and demolition/deconstruction stages tend to receive less attention (WONG; ZHOU, 2015), and all stages of the lifecycle should be considered to improve the process. In order to provide the construction industry with paths to improve sustainability, green certifications can be implemented. One of the main certifications is LEED, developed by the USGBC in 1998, which was chosen to structure this research. Other certifications, such as BREEAM, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) and Green Star are also relevant in the AEC industry (Architecture, Engineering and Construction Industry) (COSTA et al., 2018; MA ; CHENG, 2017). LEED was chosen as a structuring element in this review due to its global penetration, criteria homogeneity and lifecycle consideration (SUZER, 2015; DOAN et al., 2017). Also, when considering interoperability aspects, LEED also shows prevalence due to its clarity, openness and versatility (NGUYENA; ALTAN, 2011). Table 1 provides a comparison between green certifications in the AEC industry.

BIM allows users to add properties related to sustainability to objects, and then it creates the possibility to develop an analysis of many aspects connected to sustainability, such as carbon emissions, water efficiency, lighting, etc. However, for these analyses to work properly, a certain level of interoperability maturity is required. Pingaud (2009) defines interoperability as the ability of systems, natively unknown among each other, to interact in order to establish harmonious and collective behaviors, without modifying in depth their individual structures or behaviors. An improved interoperability in the BIM cycle can enhance the maturity of sustainability in the construction industry. The connection between interoperability and sustainability is described as inseparable and inherently linked by Dassiti et al. (2013): "In a global networked environment deeply affected by financial crises, climate change and pandemics, the necessary economic, environmental and social/ethical sustainability cannot be achieved without sustainable interoperability". Interoperability can also be understood in many organizational levels, such as data, service, process and business, as described by Chen (2008) and is used to structure interoperability issues in this review.

There has been limited academic literature so far discussing the definition of green BIM, however, it can be understood as the use of BIM tools to improve sustainability and building performance (WONG; ZHOW, 2015; WU; ISSA, 2014). A systematic literature review for the Green BIM cycle arises from the perception that it can be beneficial to study this topic in this tri-axial manner. First, to use BIM throughout the lifecycle, interoperability needs to be further developed. Also, considering that sustainability can be improved by the use of BIM, and that interoperability and sustainability are inherently linked, a literature review connecting all three fields is presented to better understand the relevance of the connections between these fields, hereby demonstrated by three axis. The first axis represents sustainability and contemplates the six subcategories of LEED version three: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and innovation in operation and regional priority. This study considered papers from 2006 until mid-2018, presenting a twelve-year panorama on sustainability and BIM.

Table 12 - Comparison between green certifications in the AEC industry.

CRITERIA	BREEAM	LEED	CASBEE	Green Star NZ
Clarity (Well-defined, easily communicated, and clearly understood among multiple parties.) - Nguyena and Altan, 2011	Meet criterion	Meet criterion	Meet criterion with exception	Meet criterion with exception
Credit weights - Suzer, 2015	May differ according to region	Constant for every location	May differ according to region	May differ according to region
Development approach (system was developed using a consensus-based, lifecycle analysis or expert opinion) - Nguyena & Altan, 2011	Does not meet the criterion	Meet criterion	Meet criterion	Does not meet the criterion

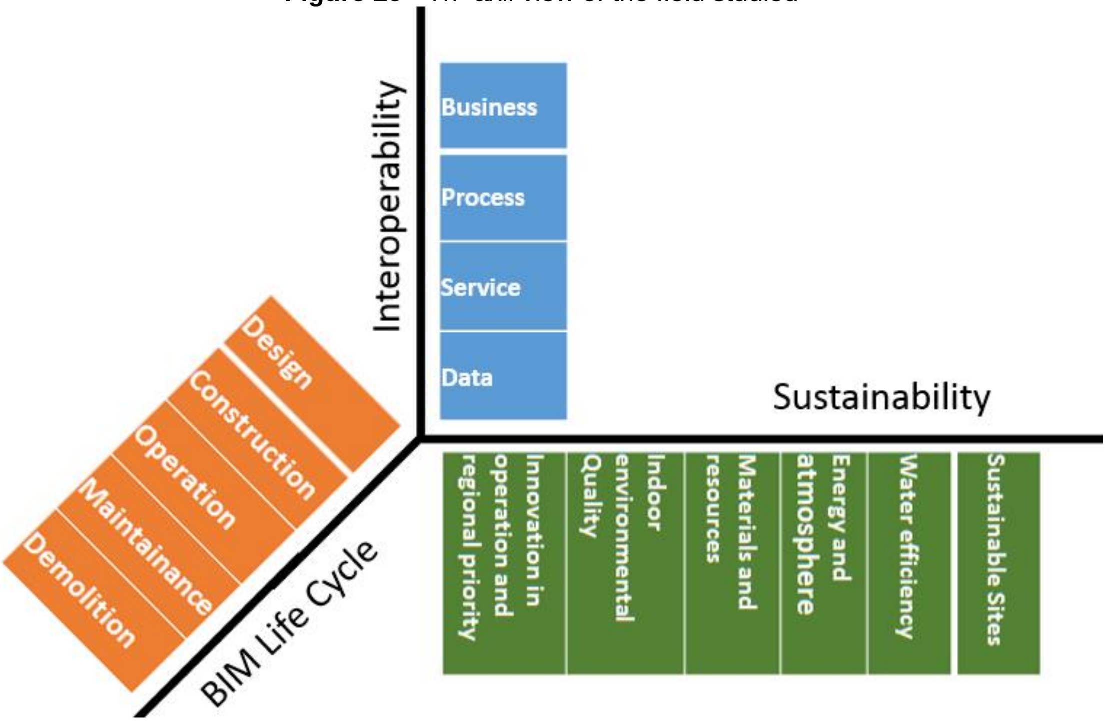
Lifecycle assessment - Doan et al. 2017	Design, Built, Operation and Refurbishment	Design, Built, Operation and Refurbishment	Design, Built, Operation and Refurbishment	Design, Built and Refurbishment
Market Penetration - Doan et al. 2017	Popular use in the European Union	Global adoption	Mainly in Japan	Mainly in NZ
System openness - Nguyena & Altan, 2011	Meet criterion with exception	Meet criterion with exception	Does not meet the criterion	Does not meet the criterion
Versatility (Number of systems that use it as its basis for development or comparison) - Nguyena & Altan, 2011	12	10	1	0

Source: The Author

The second axis shows the lifecycle stages of a building: planning and design, construction, repair and maintenance, operation and demolition (WONG; ZHOU, 2015). Finally, the third axis relates to interoperability concerns and maturity, and are data, service, business and process. These perspectives can be seen in Figure 29 This multidisciplinarity of the study requires a systematic literature review, to present results in a comprehensive and structured manner.

In the first part of this study, an introduction was presented. Next, a description of the methodology adopted for a systematic literature review, detailing the search and selection of the final pool of papers is presented. Considering the difficulty to select relevant papers to a research enveloping three fields, a multicriteria methodology was adopted. Next, a quantitative and qualitative analysis of the selected papers, classifying them according to described fields is presented. Then, a review containing the most relevant issues in each subtopic is presented in section detailed. Finally, conclusions from the research and suggestions for future works and possibilities of use of this review, such as base for knowledge structuring and process detailing are described.

Figure 29 - Tri -axil view of the field studied



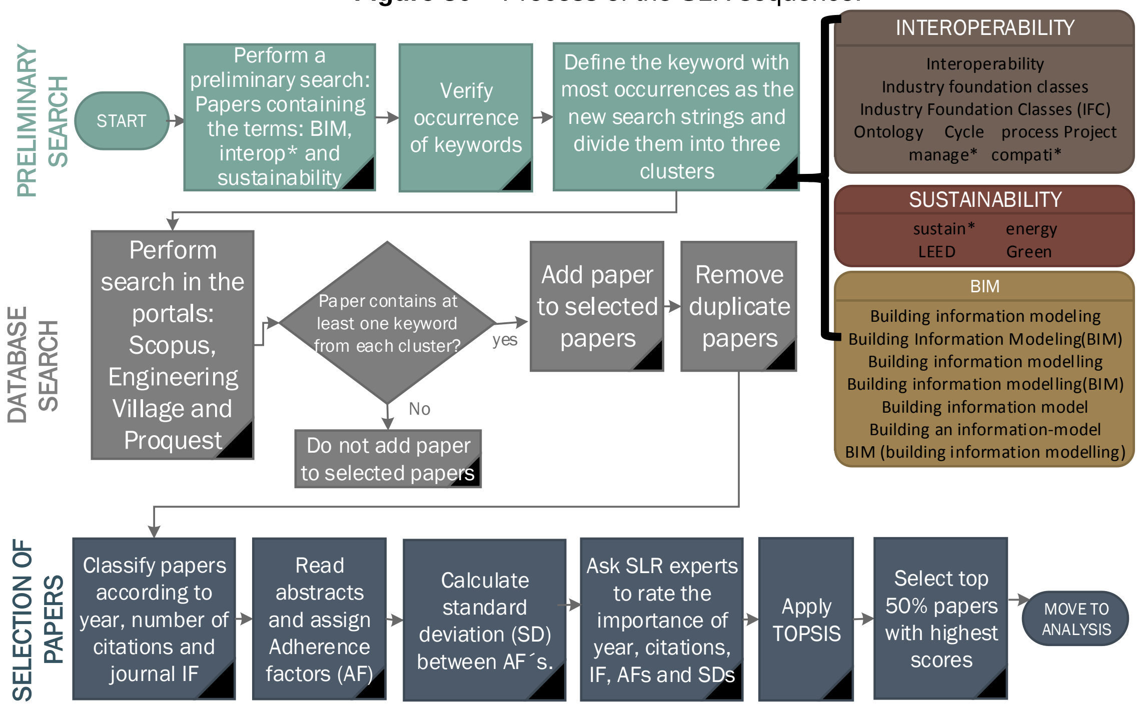
Source:

4.1 METHODOLOGY

A systematic literature review is a methodology used to identify, evaluate and interpret research relevant to a determined topic area, research question or phenomenon of interest. There are three main reasons for performing a literature review: To summarize the existing evidence in a topic, to identify gaps in the state of the art to propose areas for further investigation and to provide a framework to appropriately position new research activities. (KITCHENHAM; CHARTERS, 2007). These three reasons apply to the study of BIM interoperability and sustainability, however, mainly the last one correlates to this study. This study can provide information for the development of models, directions and frames for BIM interoperable sustainability. The combination of the Ordinatio method (PAGANI et al., 2015) and TOPSIS multicriteria decision method (HWANG; YOON, 1981). Ordinatio was chosen to provide the comprehensive search and robustness of papers (with high numbers of citations and from journals with high impact factors) allied with a multicriteria decision method, in the case TOPSIS (HWANG; YOON, 1981), to provide a robust and effective selection of papers, ensuring that papers were aligned with the topic at hand. This combination of methods allowed for the selection of papers not only relevant to the research, but most importantly, papers with relevant academic influence.

The method is shown in Figure 30 and was developed in three steps: (i) preliminary search, (ii) database searches, (iii) selection of papers. In the preliminary search, papers containing the terms BIM, intero* (including interoperability, interoperable, etc.) and sustainability were searched and their keywords were analyzed and structured into three clusters (interoperability, sustainability and BIM). In the second stage (database search), three portals were searched for papers containing at least one word in each cluster, therefore the selected papers would relate to the three areas studied. In the third stage (selection of papers), papers were classified according to year, journal impact factor (IF), number of citations, adherence factor (AF) and standard deviation of AF. Finally, the TOPSIS method was applied and the papers with the highest scores were selected. Sections following describe this process in detail.

Figure 30 – Process of the SLR sequence.



Source: The Author

4.1.1 Preliminary search - strings and keywords selection

First, a preliminary search in the Science direct portal was executed. In this search, journals containing the words "BIM and Sustainability" and "BIM and Interoperability" in the title, abstract and keywords were selected. The keywords of these journals were ranked from most frequent to least frequent and then separated into three clusters (BIM, Interoperability and Sustainability), as shown in Table 13.

Table 13 - Selected keywords

Sustainability		Interoperability		BIM	
Word	Nº of occurrences	Word	Nº of occurrences	Word	Nº of occurrences
Sustain*	12	Interoperability	22	BIM	21
Energy	15	Industry foundation classes	6	Building information modeling	13
LEED	2	Industry Foundation Classes (IFC)	4	Building Information Modeling (BIM)	9
Green	5	Ontology	3	Building information modeling	8
		Cycle	2	Building information modeling (BIM)	2
		Process	4	Building information model	2
		Project	4	Building an information-model	2
		manage*	9	BIM (building information modelling)	2

Source: The Author

4.1.2 Database Searches and Selection of papers

Based on the selected keywords from the first step, searches were executed on three databases: Scopus, Engineering Village and Proquest. The first search criteria used was that at least one word of every cluster should be present in the abstract, title or keywords of the journal. Also, only papers in English and from journals were searched. Finally, a ten-year gap was established (papers ranging from 2006 to 2018 were selected).

The search returned the following results:

- Scopus - 262 document results – 97 available;
- Engineering Village - 214 document results – 155 available;
- Proquest – 35 document results – 20 available.

From the total of 511 papers, 272 had the full version available. After duplicated papers were excluded from the total of papers with the full version available, a pool resulting in 230 papers were selected.

To exclude from the pool papers either irrelevant to the subject or papers without scientific recognition, a multicriteria method was applied. However, before this decision, the first method considered for the selection was the Ordinatio method, described by Pagani et al*.* (2015), that considers the relevance of the Impact factor of the Journal the paper was published, the number of citations and the importance of recent papers that haven´t received many citations yet. This method consists of adding the impact factor of a journal, the number of citations it has received, to a factor that considers the relevance of how recent a paper is, as described in Equation 1.

$$InOrdinatio = (IF/1000) + alpha * [10 - (ResearchYear - PublishYear)] + Citations \quad (1)$$

However, the Ordinatio method was not enough, since many papers that seemed relevant to the research were left out in a preliminary analysis. Also, papers with many citations or a high impact factor, but disconnected from the topic, were included. To aid in this scenario, an adherence factor was created. Three researchers involved in the BIM interoperability studies were asked to attribute a score to the journals based on their title and abstract.

The scores were as follow:

- 0 – Not related to the topic;
- 2 – A little related to the topic;
- 4 – Somewhat or partially related to the topic;
- 6 - Related to the topic
- 8- Very Related to the topic
- 10 – Extremely related to the topic.

After the scores were applied, the standard deviation from the scores applied by the researchers was calculated, since high standard deviation shows uncertainty about the results. Also, the Impact Factor (IF) considered for this research was the 5-

year IF. If the 5-year IF was not available, journals were classified using the IF for the most recent year.

So, to unify the five criteria in the selection process, a multicriteria methodology named TOPSIS was applied. TOPSIS was developed (Hwang; Yoon, 1981) as a multicriteria decision method based on the concept that the best alternative is the closest to the ideal alternative and further away from the negative ideal. The main seven steps for the application of TOPSIS (SRIKRISHNA, 2014) are:

i. Define the goal, in this case, the selection of the most relevant articles from the literature;

ii. Define the important criteria for the selection of the alternatives and calculate a decision matrix. The five criteria used (year, number of citations, Impact factor, adherence factor and standard deviation) were submitted to three experts in systematic literature review, and they were asked to rate the importance of the five factors, and the averages of the weights given by them are presented as follows in Table 14.

Table 14 - Weights provided by specialists.

Year	Impact factor	Number of Citations	Adherence Factor	Standard Deviation
0.157	0.241	0.229	0.265	0.265

Source: The Author

iii. Normalize the matrix according to Equation 2.

$$R_{ij} = \frac{x_{ij}}{\sqrt{\Sigma_{i=1}^{n} x_{ij}^2}} \quad (2)$$

Where x_{ij} corresponds to each element in the decision matrix and n corresponds to each column in the matrix;

iv. Multiply each element in the normalized decision matrix by the weight corresponding to that column;

v. Select from each column the best ($v_j +$) and worst ($v_j -$) values according to each criterion (ideal positive and ideal negative solutions). After that, calculate the distance between each element in the matrix e its corresponding ideal positive and negative solution according to Equation 3.

$$S_i^{+=\sqrt{\Sigma_{j=1}^{m}}} \quad (3)$$

Where S_i + and S_i – correspond to the distances of the alternatives to the ideal positive e negative, i corresponds to each criteria, m corresponds to each line in of the matrix, v_{ij} corresponds to each element of the matrix referring to an alternative e v_j + e v_j – correspond to the values of ideal positive and negative;

vi. Calculate the relative proximity C_i of each alternative to the ideal solution through Equation 4:

$$C_i = \frac{S_i^-}{(S_i^{-+} + S_i^-),} \quad (4)$$

$$0 \leq C_i \leq 1.$$

Rank the alternatives by their relative proximity C_i. The papers were ranked according to the highest score, and the ones with the top 50% score were selected for analysis, making up a pool of 115 selected papers. The whole process can be seen in Figure 30, and the scores are presented in Table 15.

4.1.3 Analysis

In order to better analyze the selected papers, three main areas, comprised of subcategories, were identified. This way, papers could be categorized according to which topics they discussed in depth. Firstly, the sustainability areas were identified in each of the papers. Even though other certifications such BREEAM (UK) and Green Star (Australia) have great importance, the LEED credit categories were chosen due to its relevance in the environmental certification and its worldwide use in the Architecture Engineering and Construction – AEC field. Also, LEED was chosen as a guideline for the categories because it was the only certification that appeared in the keywords from the preliminary search. The sub-categories are sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and innovation in operation and regional priority. After that, papers were classified according to which parts of the Building lifecycle they enveloped. These categories include building planning and design, construction, repair and maintenance, operation and demolition (WONG; ZHOU, 2015).

For the interoperability section, Chen´s et al. (2008) framework for enterprise interoperability was selected, since it´s parameters suit BIM research adequately to analyze BIM´s barriers and parameters. Also, it has already been used effectively in past BIM research that present interoperability researches and schemas based on this framework (MULLER et al., 2017). The framework presents three dimensions: The first are the interoperability barriers, divided into conceptual, technological and organizational. The second are the Interoperability approaches (Integrated, unified and federated). Finally, the author establishes four main interoperability concerns:

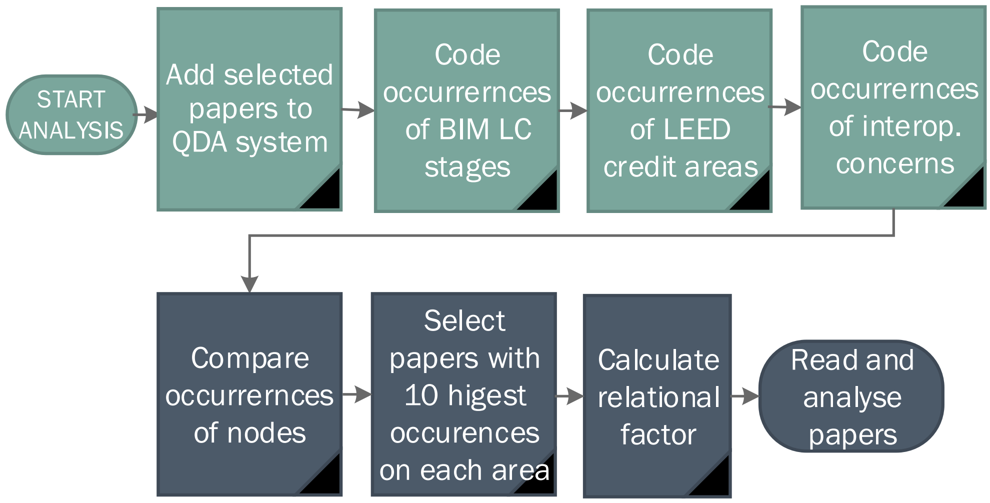
- Business: interoperability in the strategic and organizational levels.
- Process: describes requirements necessary to align the processes for construction, design, and operation.
- Service: service interoperability is the concern of a company to register, aggregate and consume services of external sources.
- Data: this concern refers to the need for different, platforms, software and systems to work together and use common languages.

The interoperability concerns were chosen as the third axis of the research, so concerns could be collected and categorized. This way, interoperability issues in sustainability can be identified.

So, considering these three categories and fifteen subcategories, the selected journals were analyzed with the aid of a QDA software. Nodes were added when one of the subcategories appeared. A node is a mark created by the system, in order to aid the analysis and quantification. The analysis process is described in Figure 31.

In each of the sub-categories, the top 10% papers with the most nodes were selected to describe that area and results can be seen in Table 15. A paper with the number 1 in one topic indicates that it had the most nodes on that topic, number 2 is the second and so on. Also, the field “score” indicates the score the paper received in the multicriteria decision method, therefore being selected to the main pool. A detailed review of each sub-category is presented in the next section.

Figure 31 – Process of the analysis of papers.



Source: Author.

Table 15 - Journals by sub-areas

Papers	Score	Sustainability						Interoperability				BIM lifecycle				
		Sustainable Sites	Water efficiency	Energy and atmosphere	Materials and resources	Indoor Environmental	Innovation in operation	Business	Process	Service	Data	Design	Construction	Operation	Maintenance	Demolition/deconstructi
Akbarnezhad A. *et al.* (2014)	0.466									1			10			1
Al-Ghamdi, S. G.; Bilec, M.M. (2015)	0.466	9	2				9									
Al-Ghamdi, S.G., and Bilec, M.M., (2017)	0.484															
Alwan, Z. *et al.* (2015)	0.470		6			10	2									
Alwan, Z., et al. (2017).	0.478															
Andriamamonjy, A., et al. (2018).	0.479							10								
Araszkiewicz, K. (2016)	0.465															
Arayici, Y. *et al.* (2011)	0.468							7								
Arayici, Y., et al. (2018).	0.465							8								
Azhar, S. *et al.* (2011)	0.470		5			11	6									
Azzi, M. *et al.* (2015)	0.470															
Behzadi A.(2016)	0.469															
Bu, S. *et al.* (2015)	0.47			1					4	7		10			9	

Papers	Score	**Sustainability**						**Interoperability**				**BIM lifecycle**				
		Sustainable Sites	Water efficiency	Energy and atmosphere	Materials and resources	Indoor Environmental	Innovation in operation	Business	Process	Service	Data	Design	Construction	Operation	Maintenance	Demolition/deconstructio
Chardon, S. *et al.* (2016)	0.467											12				
Chi, H.L. *et al.* (2015)	0.468	7											2	1		
Cho, Y.K.; Gai, M. (2013)	0.461															
Chong, H.-Y.,and Wang, X., (2016)	0.464														6	5
Costa A. *et al.* (2013)	0.468													2		
Costin, A., et al. (2018).	0.465										4		6	5	2	
Crosbie, T. *et al.* (2010)	0.471			3												
Curry, E. *et al.* (2013)	0.467							4		3	1			11	11	
Dıaz-Vilarino, L. *et al.* (2013)	0.468						3									
Ding, L. *et al.* (2014)	0.865	11											1			
Dong, B. *et al.* (2014)	0.470		10								5			10		
El-Diraby, T., et al. (2017).	0.484							3		10						
Eleftheriadis, S., et al. (2017).	0.456															9
Farghaly, K., et al. (2018).	0.465														5	
Gan, V.J.L., et al. (2018).	0.465															
GhaffarianHoseini, A.,et al. (2017).	0.464															
Gimenez, L. *et al.* (2016)	0.465					2										
Goçer, O. *et al.* (2015)	0.468					9		12	3	6				12		

Paper	Score	Sustainability						Interoperability				BIM lifecycle				
		Sustainable Sites	Water efficiency	Energy and atmosphere	Materials and resources	Indoor Environmental	Innovation in operation	Business	Process	Service	Data	Design	Construction	Operation	Maintenance	Demolition/deconstructio
Gökçe, H. U. , Gökçe, K.U., (2014) a	0.466		9							4	3			7	8	
Gökçe, H.U.; Gökçe, K.U. (2014) b	0.466															
Gordon, V.R.; Holness P.E.	0.46															
Gourlis, G., and Kovacic, I., (2017).	0.475															
Gulliver, S. *et al.* (2013)	0.468							9								
Guzman Garcia, E.; Zhu, Z. (2015)	0.468				11											
Habibi, S., (2017)	0.464					5										
Ham, Y. *et al.* (2015)	0.468															
Han, R. *et al.* (2016)	0.469						4									
Harmathy, N. *et al.* (2016)	0.469			2		7										
He Jie, B. *et al.*	0.469			11		12	5					7				
Hiyama, K. *et al.*	0.469											2				
Hjelseth, E. (2010)	0.470															
Hong, J., et al. (2017).	0.464								5							
Iddon, C.R.; Firth S.K. (2013)	0.464		8		7								11			
Ilhan, B.; Yaman, H. (2016)	0.469				4											
Jalaei,F.; Jrade A. (2014)	0.467			5	3		11					6				
Jang, S., and Lee, G., (2018).	0.484	12							6							
Janssens H., (2013)	0.467		11													

Papers	Score	Sustainability						Interoperability				BIM lifecycle				
		Sustainable Sites	Water efficiency	Energy and	Materials and	Indoor	Innovation in	Business	Process	Service	Data	Design	Construction	Operation	Maintenance	Demolition/deconst
Jeong, S.K.; Ban Y.U. (2011)	0.469															
Jeong, W.*et al.* (2014)	0.469				1				7		6					
Jiao, Y. *et al.* (2013)	0.468							2		5	2		12	8		
Jrade, A.; Jalaei, F. (2013)	0.466				6		7					11				
Jung, N., et al. (2018).	0.465					3					9	8				
Kim, J. *et al.* (2015)	0.469		12													
Kim, J.I. *et al.* (2015)	0.471		3						11					4		
Kim, J.I., et al. (2016).	0.464															
Kim, M. *et al.* (2014)	0.468									2						
Kim, Y.-C.,et al. (2017).	0.464															3
Klein, L. *et al.* (2012)	0.471	8														
Kuo, H.J.,et al. (2016).	0.478															
Ladenhauf, D., et al. (2016).	0.483															
Larsen, K. E. *et al.* (2011)	0.463	10														
Liu, S. *et al.* (2015)	0.466											4		9		11
Lu, W., et al. (2017).	0.464												9			7
Ma Z. and Zhao Y. (2008)	0.461									8	12					
Ma, Z.; Cheng, Y. (2017)	0.468															
Mah, D. *et al.* (2011)	0.473	6			8				12				3			
Marzouk, M., et al. (2018).	0.465															
Marzouk, M.; Abdelaty, A. (2014)	0.461					4										
McGlinn, K., et al. (2017).	0.478															
Merschbrock, C., et al. (2016).	0.442	4														
Merschbrock, C., et al. (2018).	0.443															
Migilinskas, D., et al. (2016).	0.478															
Najjar, M., et al. (2017).	0.478															12
Negendahl, K. (2015)	0.463								10			1		6		
Nguyen, T.H. *et al.* (2010)	0.464		7													

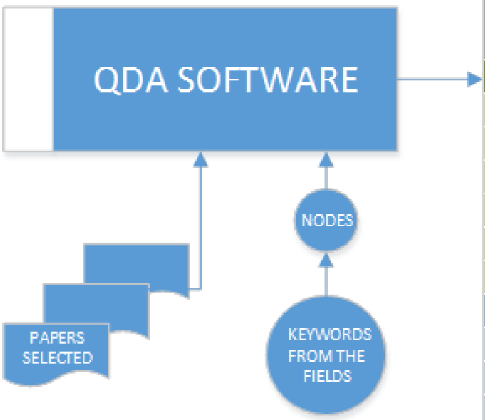
Papers	Score	Sustainability						Interoperability				BIM Lifecycle				
		Sustainable Sites	Water efficiency	Energy and	Materials and	Indoor	Innovation in	Business	Process	Service	Data	Design	Construction	Operation	Maintenance	Demolition/deconstr
Ning, G., et al. (2017).	0.464															
Nour , M. *et al.* (2015)	0.468			8						11					7	
Parand, R., et al. (2016).	0.414		1													
Park, J.W., et al. (2017).	0.443					8										
Peng, C., (2016).	0.464				9		12									4
Rahmani Asl, M. *et al.* (2015)	0.470			12					8	12		9				
Rebolj, D. *et al.* (2011)	0.225				2											
Sanguinetti, P. *et al.* (2012)	0.465										7	5				
Sanhudo, L., et al. (2018).	0.484			9							11					
Santos, R., et al. (2016).	0.464												8		12	
Schlueter, A.; Thesseling, F. (2009)	0.469			10												
Shadram F. *et al.* (2016)	0.473	3		6	5											
Soust-Verdaguer, B., et al. (2017).	0.464															8
Soust-Verdaguer, B., et al. (2018).	0.465															
Stadel, A. *et al.* (2011)	0.471															
Sun, S. *et al.* (2016)	0.470			4												
Szonyi, L. (2010)	0.465														10	
Tan, P. Y. *et al.* (2015)	0.467	2														
Tian, Y.; Yue H. (2016)	0.469															
Tixier, A.J.P. *et al.* (2016)	0.198										10					
Valero, E., et al. (2016).	0.464															
Wang, C. *et al.* (2015)	0.470										8					
Wang, H.; Zhai Z. (2016)	0.471			7		1										
Wang, Y. *et al.* (2013)	0.468														1	
Watson, A. (2011)	0.472						10	6								
Wong, J. Zhou (2015)	0.462												7	3	3	2
Wu, I.-C. ; Chang, S. (2013)	0.466															
Wu, P. *et al.* (2014)	0.471				10			11							4	6
Wu, P. *et al.* (2016)	0.468					6	1			9						10

Wu, W.; Issa, R.R.A. (2014)	0.469						8	1	1							
Yeoh, J.K.W., et al. (2018).	0.483															
Zanni, M. *et al.* (2014)	0.473							5	2			3				
Zhang, H., et al. (2018).	0.415		4						9							
Zhang, S. *et al.* (2015) a	0.469															
Zhang, S. *et al.* (2015) b	0.467	5			12								4			
Zhong, B., et al. (2018).	0.484															
Zhou, Y. *et al.* (2015)	0.466	1											5			

Source: The author

From the analysis in the QDA software, shown in Figure 32, it could be noticed that Interoperability is the topic least discussed, while sustainability and lifecycle have approximately the same amount of nodes. Within the topic of interoperability, data and process are discussed more often. Business interoperability, however, is not so frequently discussed. It can be inferred, that while most authors are concerned with base levels of interoperability, it is not seen as a priority at the strategic level. Authors that discuss lifecycle tend to focus on the earliest stages, as design and construction. Topics at the end of the lifecycle, such as maintenance and demolition/deconstruction receive much less attention (demolition being the least discussed topic of all). Within sustainability, energy was the topic most discussed, presenting more nodes than any other subtopic. Indoor environmental quality and water efficiency had fewer mentions.

Figure 32 - Number of nodes on the Journals analyzed.

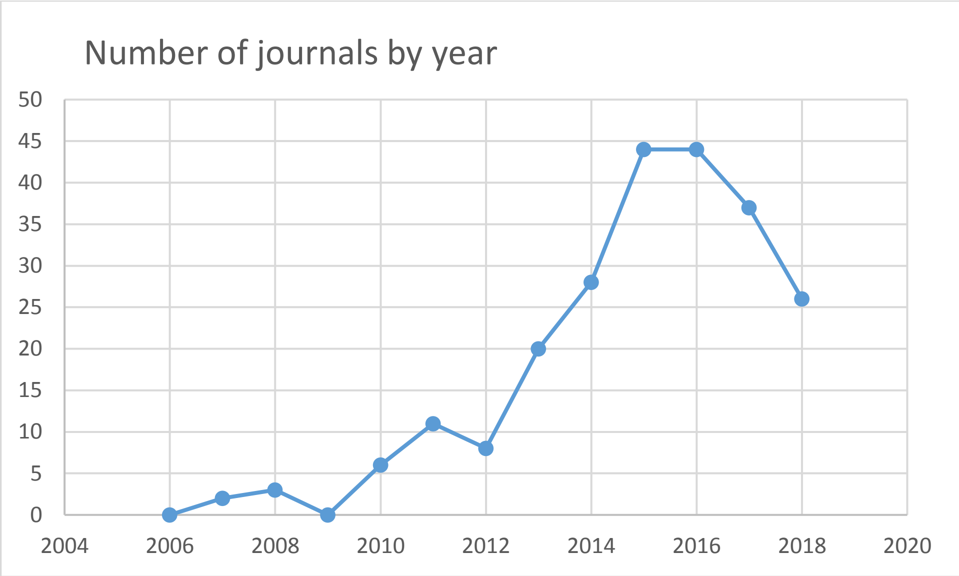


Name	Number of papers	Number of nodes
SUSTAINABILITY	113	16788
1 SUSTAINABLE SITES	87	1359
2 WATER EFFICIENCY	61	793
3 ENERGY	109	11243
4 MATERIALS	102	2008
5 INDOOR ENVIRONMENTAL QUALITY	57	891
6 INNOVATION AND REGIONAL PRIORITY	78	494
LIFE CYCLE	113	18940
1 DESIGN	113	9056
2 CONSTRUCTION	110	7824
3 OPERATION	91	958
4 MAINTAINACE	66	632
5 DEMOLITION	40	470
INTEROPERABILITY	113	12174
1 BUSINESS	51	384
3 SERVICE	73	606
2 PROCESS	113	4418
4 DATA	110	6766

Source: The Author

Also, most papers searched were published from 2015- 2016. A growth in publications from 2009-2015 seems like an important factor in BIM research for interoperability in sustainability. After that, researches seem to have stabilized, noticing that the search was performed before the end of 2018, and these values will likely increase before the end of the year. This is shown in a graph in Figure 33 .

Figure 33 – Number of papers published by year.



Source: Author.

In 2006, not a single paper on the topic appeared in the searches. This corroborates the decision of searching within twelve years, since if the search extended for more years probably very few or even no papers would be available, as it can be seen from the curve in the graph from Figure 33.

4.1.4 Review and Discussion of Selected Papers

This section presents the contents of the searched papers structured in three main areas: Sustainability, lifecycle and interoperability. Sub-categories discuss the main concern and some of its relations to the other fields. Further discussion on the topics relationships is presented in chapter 5: Integrated analysis and future research.

4.2 SUSTAINABILITY AND LEED

LEED is a standard developed by the USGBC for building sustainable constructions that have better performances in the areas of sustainable sites, water savings, energy efficiency, materials use, indoor air environmental quality and innovation. These credits may vary according to the type of construction. In this case, LEED for new constructions version three is being considered to structure this section of the review. Each subsection presents a discussion on sustainability especially related to BIM and interoperability.

Innovation in operation and regional priority

Credits in LEED related to region and innovation can be improved when Green BIM technologies are applied, especially when using state-of-the-art IT tools (ARASZKIEWICZ, 2016). BIM also can influence and improve creative thinking and innovative strategies in green buildings (WU; ISSA, 2014).

Considerations to regional characteristics can be very relevant to achieving sustainable performances. Cold regions, industrial or rural areas, for example, all have special characteristics and needs (HAN et al., 2016). Regional impacts are also relevant when considering vegetation. BIM can be used to conduct simulations for sun-shading design or retrofitting for the outdoor space. This can be done according to the regional function, spatial properties, space requirements, and the characteristics of group activities (HE et al., 2014).

Another important factor for considering in the regional aspects in LEED is the fact that energy costs in the different locations may vary significantly based on many local and regional variables. Also, diverse types of energy supply and plant efficiencies should be considered (AL-GHAMDI; BILEC, 2015). These factors, along with maturity levels, regulatory and environmental requirements must be taken into consideration for more sustainable power distributions (AZZI et al., 2015).

Sustainable Sites

Points awarded in LEED for sustainable sites may vary from building function, for example, higher education facilities tend to score higher on site selection (Wu *et al.* 2016).

It is also important to consider that sites where most of the energy comes from sources other than fossil fuels show good results in terms of low environmental impact on climate change. The authors even suggest that buildings with higher environmental impacts due to fossil fuel-based energy sources should be required to achieve higher levels of energy generation and efficiency than others (AL-GHAMDI; BILEC, 2015).

An efficient selection of the construction site also influences the building´s embodied energy, since sites further away from manufacturers tend to spend more energy on material transportation. These characteristics may be acquired through BIM automated processes, considering locations and material take-offs (SHADRAM et al., 2016). Not only the location of the site and it´s distance from suppliers, but even climate condition may interfere, since cold regions demand more energy for curing concrete, for example (MAH et al., 2011). Also, it is important to consider on-site BIM for interoperability improvement, resulting in improvement in Information quality, the centralization of information repositories and greater speed of information flow. (MERSCHBROCK; NORDAHL-ROLFSEN, 2016)

Building modeling can be used to analyze, simulate and optimize site planning, especially if paired with sensors and other automation systems, minimizing loss and delays (ZHOU et al., 2015), (CHI et al., 2015). Also, information about consumed materials can be retrieved from the construction site as it is used (DING et al., 2014). Authors even consider that the use of BIM can aid construction sites in workforce safety (ZHANG et al., 2015).

BIM can combine many different software and sensors to in simulations to determine PAR (photosynthetically active radiation) in urban areas. These analyses can also help to improve urban green space design and selection of plants for better performance (TAN; ISMAIL, 2015).

Indoor environmental quality

LEED points connected to indoor environmental quality are usually very relevant in projects well qualified, since it corresponds to 15 of the points awarded (Wu *et al.* 2016), especially when considering analysis for LEED credits, BIM can aid indoor environment quality. Ventilation, indoor thermal characteristics, acoustics and daylighting can be predicted by various methods or even combinations of computational methods (WANG et al., 2016). Also, monitoring through BIM can aid to better control the Heating, ventilation, and air conditioning system - HVAC, which can ensure the efficient consumption of energy (MARZOUK; ABDELATY, 2014).

Computer analysis also may aid in the analysis of building thermal properties and of adequate windows. Thermal comfort can be improved significantly with adequate glazing type. The economic aspect is also important when improving the thermal properties of the building envelope, since construction expenses and materials are taken into consideration according to their performance and investment aspect (HARMATHY et al., 2016).

Natural ventilation can provide fresh air and improve indoor comfort having zero energy consumption. To achieve this, specific building orientation should be determined by modeling. For example: In the northern hemisphere, houses favor the south, which not only maximizes the sunlight in winter but also provides a good heating condition in the summer. Nevertheless, cold winds that may cause heat loss should be considered. These simulations can be aided or performed by BIM systems (HE et al*.,* 2014).

Authors (GÖÇER et al., 2015) also emphasize the importance of post-occupancy evaluation to consider indoor air quality, daylight quality, thermal comfort, visual comfort and sound control. This is important so the occupants' comfort may also be analyzed qualitatively. Enhancement of indoor environmental quality should also be considered in green retrofit design (BU et al., 2015). Some suggested measures for reducing the building's CO2 emissions are reducing (within the limits of comfort) the fresh air volume, extending the range of indoor temperature, improving insulation performance of walls, windows and roofs and using natural ventilation (PENG, 2016).

Water Efficiency

It is possible to estimate the amount of water that can be recovered by a building at each location, through weather data. This recoverable amount includes greywater reclamation for outdoor usage and rainwater harvesting on the building (Al-Ghamdi and Bilec, 2015). Also, at the operation stage sensors can be developed to detect and measure parameters such as water/gas/electricity meter readings (GÖKÇE; GÖKÇE 2014; DONG et al*.,* 2014).

Water analysis can be quickly executed by using BIM during design and even pre-design stages. This creates the possibility to make early changes and improve results in this area (AZHAR et al*.,* 2011).

Authors also state that building functions may interfere with water usage, for example, manufacturing buildings tend to use more water than commercial buildings (KIM et al*.,* 2015). Another relevant issue with water usage is the fact that heating water influences greatly in energy consumption, so by limiting the water, energy consumption can be limited as well (IDDON; FIRTH, 2013). This can even be reduced by solar thermal water heating systems on building roofs and facades (GÖKÇE; GÖKÇE, 2014). Another way to reduce water usage is passive cooling, which reduces makeup water to the cooling tower (JANSSENS, 2013).

Energy and atmosphere

The construction industry uses a major part of the primary energy, which leads to global warming and a generation of greenhouse gases (BU et al., 2015). These emissions are directly linked to the energy that the building consumes to maintain its use, such as the lights and energy of the appliances, and for thermal comfort such as heating or air conditioning systems (SCHLUETER; THESSELING, 2009). This is why efficient energy consumption in the lifecycle of buildings is at the heart of urban sustainability development (CROSBIE et al., 2010).

Important decisions about sustainable design of buildings are made at the conceptual stage of the construction lifecycle (JALAEI; JRADE, 2014), for example, the choice of an appropriate natural ventilation that can help to reduce the use of energy for thermal comfort, the heat insulation and sunshade should be observed in the early design stages. (JIE HE et al., 2014.). It is possible to carry out these energy consumption analysis using software that uses BIM. Currently, BIM tools have the option of providing the user with the opportunity to model and explore construction alternatives that can save energy, avoiding having to redo all the geometry (CROSBIE et al., 2010).

Concerning interoperability for energy simulation through BIM, a real-time connection between authoring tools and energy analysis systems must be established. This suggests that modifications on the model could affect the simulation without exporting/importing files between systems. To accomplish this, a steady flow of information would have to happen between programs using a data scheme or suitable energy analysis plugins must be developed within authoring tools (SANHUDO et al., 2018).

Materials and Resources

In order to obtain the success in a project, an understanding of the functional criteria of the building materials is fundamental. Throughout the lifecycle, building materials consume energy. In this scenario, the use of BIM tools can help in the decision-making stages, which have a high impact in cost in all energy-related steps from the project (JALAEI; JRADE, 2014). Using Building Information Modeling to Building Energy Modeling - BIM2BEM, it is possible to take advantage of data such as materials, parametric objects, and building geometry to generate energy simulations from the building (JEONG et al., 2014).

It is also possible to incorporate sustainability components into the conceptual stage of the project through sustainable design, identifying associated materials and components based on the green building certification systems (JRADE; JALAEI, 2013). In addition, the use of BIM and the integration with a database allows the calculation of CO2 emissions in different types of construction methodology (MAH et al., 2010).

There is a research gap regarding the greenhouse gas systematic approach to the lifecycle of building materials (WU et al., 2014). Construction materials can be improved with respect to embodied carbon. It is observed that the use of special concrete mixtures, the exchange of PVC frames for wood in windows and the change in the external coating of the brick reduced by 24% the embodied carbon in a building, which represents a 5% reduction in a 60-year lifecycle (IDDON; FIRTH, 2013). The reuse of materials significantly reduces carbon emissions as well as cost and energy from demolition and transportation to landfills and recycling sites. With the use of BIM software, it is possible to add recycling taxes to the materials, determining if such materials are suitable for recycling. Suitability of materials can be determined through pre-defined data libraries (AKBARNEZHAD et al., 2014). Another alternative is the use of nanotechnology, since materials that consist of carbon not only emit less pollution in the production and transport as other types of materials, but they present better performance and resistance with less weight (REBOLJ et al., 2010).

4.3 LIFECYCLE

A building´s lifecycle tends to be more complex than any other product, since it takes many years to reach the point where it is demolished and subsequently recycled. This extended lifecycle presents then special needs and documentation, and all stages can be accompanied through BIM to ensure more sustainability in the process (WONG; ZHOU, 2015). This section presents the construction industry main issues according to each phase of the lifecycle, especially considering BIM interoperability and sustainability.

Design

In the early design stages, most tools are insufficient to provide performance simulations while being flexible for a rapid design process. To improve this process, integrated dynamic models combine a design tool, a performance simulation tool and a visual programming language to provide better support for the designer during the early stages of design. There are three methods to integrate design tools and Building performance simulation in the early design stages: combined models (limited to the functionalities of the modeling environment), central model (exchange information by defining a common exchange format) and distributed model (disengaged from a top-down control and one directional model operation by using a middleware system to modify, filter and extend operator definitions) (NEGENDAH, 2015). Early design phases may also be aided from datasets based on users past experiences, objectives, constraints project and design philosophies of users, to generate default configuration settings to be used in new projects (HIYAMA et al., 2014).

Process mapping is essential to adjust the design process, especially when trying to achieve sustainable design, not only describing the tasks and actors, but also determining the Level of detail – LOD in the stages. A good process management, and communication of involved actors, and consistent reviews are also essential factors (ZANNI et al., 2014).

Many variables such as operation cost, construction cost, carbon emission, and comfort are relevant in a green construction. This set of variables can be used to determine an optimal solution, based on Pareto or other multi-criteria decision methods (LIU et al., 2015).

For optimal system interoperability for BIM analysis in the design stage, some specifications should be met. Firstly, systems should allow data mapping and reading from internal formats to external formats, (such as IFC, Extensible Markup Language – XML, spreadsheets…). Next, platforms must include capabilities to apply object attributes and to allow mapping functions to be linked to numerical and textual data. Also, It must support geometry modification. The platform must also allow these capabilities to access and include data from different sources (material property libraries, longitude- latitude tables, etc.). Finally, a platform should be capable to read back results from analysis from the applications and display design information and suggestions. Another important fact is that depending on the level of model development, information required in the analysis can be defaulted to normative values. If the information exists, it can substitute the defaults (SANGUINETTI et al., 2012).

It is possible to evaluate a BIM model sustainability by calculating the LEED points that can potentially be gained during the conceptual design stage. This process is implemented in four steps (JALAEI; JRADE, 2013):

i. Developing the 3D sustainable design by using green families and their related keynotes stored in the external database.
ii. Energy analysis and lighting simulation - the 3D geometric model must be converted to an analytical model, then the energy analysis can be executed.
iii. Analysis of energy embodied in building components.
iv. Calculation of the potential LEED points.

An optimization cycle can also aid in sustainable design. After analyzing the building profile, geographic location and climate characteristics, the designer creates an architectural scheme. Then, parameters are inserted in the model, and the evaluation is performed. If the green building requirements are not met, a new design must be developed (JIE et al., 2014).

BIM-based performance optimization, BPOpt, was proposed by (RAHMANI et al., 2015) as an integrated framework to establish multidisciplinary optimization in the process of performance-based design. It integrates the information stored in parametric BIM with performance analysis to make design and performance optimization more accessible in the design process.

Another factor related to design lifecycle is Green Retrofit design (GRD). It aims to reduce carbon emissions and improve energy efficiency when rebuilding existing constructions. Four main measures should be involved in GRD. The first topic is to improve the energy-saving building plan and design, and to enhance maintenance of the heat insulation. The second aspect is to develop new energy-saving measures. After that, system maintenance and management and of energy saving technical measures should be considered. Finally, the indoor environment should be improved (BU et al., 2015).

Another relevant aspect of BIM are families. Green materials must be researched and identified, and its specification collected. Then, the families must be designed and converted to BIM format files and added to the database (JRADE;

JALAEI, 2013), this topic correlates to sustainability issues, especially when considering materials and resources.

Construction

The greatest goal of developing and promoting BIM is to develop built environments with the least possible construction and operation costs, also minimizing resource consumptions (WANG; ZHAI, 2016). During the construction stage, the greatest BIM potential in sustainability may come from the application of lean construction. Also, it is important to notice that design and construction can be fully integrated and dynamic through BIM (GORDON; HOLNESS, 2008).

Authors (SHADRAM et al., 2016) even suggest that the use of BIM during the construction stage may minimize embodied energy, automating the tracking of distances between suppliers' facilities and the construction site. This way, distances can be reduced, dropping levels of embodied energy.

When submitting a building for LEED ratings, during construction the design documentation is submitted to the USGBC. Based on that information, it is determined whether or not to award the LEED points. However, certification is not received until the construction is finished, and any changes made during construction stage require documents to be re-submitted (AZHAR et al., 2011). BIM can aid in this process of as-built documentation, (ZANNI et al., 2014), even through photogrammetric technology (KLEIN et al., 2012).

Operation

Especially in the construction of industrial plants, as-built design documents often are incomplete or flawed. This results in operational problems once the plant is handed over from construction to operation. To improve this situation, the utilization of automatic planning technologies and of sensory devices in quality control may aid users to handle a dynamic operation environment (CHI et al., 2015). Complex green BIM models generate big amounts of data. This information can be used for managing and monitoring a building's sustainability performance. An impact on the lifecycle costs can be noticed if dynamic operational and maintenance plan is used (WONG; ZHOU, 2015).

Building specific data along with detailed building energy simulation can be used to virtually test different system/ building operation strategies. These strategies can afterward be implemented in the actual building. Some barriers to this occurring are still interoperability issues, such as IFC problems and lack of data (COSTA et al., 2013).

Some models and systems are especially limited in the operation phase, because they only represent construction activities. So, methods can be developed in order to allow automatically linking the construction and operation activities through BIM (KIM et al., 2015). Also, to implement BIM in for building and construction operation, users must first find the practical applications of BIM in infrastructure management, shifting to an easier management of the operation. (COSTIN et al., 2018)

Maintenance

The building sustainability analysis and management should not be just limited to the design as well as construction stages, but also extend to the entire lifecycle of a building, including maintenance (WONG; ZHOU, 2015).

The maintenance of facilities is a multi-domain problem encompassing financial accounting, building maintenance, facility management, human resources, asset management and code compliance, affecting different stakeholders in different ways (CURRY et al., 2013).

Another relevant aspect of Maintenance is the measurement of the level of emitted gases and fuel and electricity consumption (WU et al., 2014). By measuring a building's energy consumption, its possible draw up a GRD (Green retrofit design), which consists of the following technical measures: (i) development of energy-saving building plan and design, as well as the enhancement in maintenance structure of the heat insulation performance (ii) development of new energy-saving technical measures, such as cold storage technology and cooling tower technology; (iii) performance of system maintenance and management of energy-saving technical measures; renewable energy; and indoor environment enhancement (BU et al., 2015).

When considering sustainability, for existing buildings to achieve energy efficiency goals, energy-retrofitting of great importance. By applying BIM practices to this problem, this process can become more efficient. (SANHUDO et al., 2018).

Demolition/deconstruction

Re-use of building components and disassembly have numerous advantages over traditional demolition and/or recycling. Deconstruction activities include concrete demolition, hacking, breaking of it into smaller pieces, removal of reinforcing bars and steel components, transportation of rubble to steel and concrete recycling plants, and finally the recycling process itself. Adopting more sustainable deconstruction strategies as reuse and recycling may also result in economy and energy savings, eliminating the need for traditional demolition and landfilling of rubble. With the aid of BIM, this cost may be estimated by calculating the size of the work required, using the attributes that assign the activity to the components, and multiplying it by the unitary cost (either entered manually by the user or imported from data libraries) (AKBARNEZHAD et al., 2014). A building´s primary life is enveloped by the traditional lifecycle (design until the extraction of raw materials until demolition). However, the secondary life begins when concrete is recycled and used in a new construction (WU et al*.*, 2014). Another relevant concern in sustainability in this stage of the lifecycle are the gas emissions generated from dust from soil disturbance and demolition (AZZI et al., 2015).

By using BIM with a higher level of detail, it can be possible to estimate the types and quantities of demolition waste with greater accuracy. This can serve not only as an estimation tool for the demolition waste, but also to provide tools to calculate recycling practices and environmental impact assessment, improving sustainability in the end-of-life stages of buildings. (KIM et al., 2017).

4.4 INTEROPERABILITY

Authors (Chen, 2008) interpret interoperability through three axes: concerns, barriers and approaches. Approaches can be understood as interoperability levels, them being: integrated, unified or federated. The next axis consists of interoperability barriers. They can be conceptual, technical or organizational. This means that there is more to interoperability then systems and technical issues. Finally, the final axis presents interoperability concerns: Business, process, service and data. This section presents interoperability main issues in the construction industry, especially related to BIM and sustainability, structured based on Chen´s (2008) concerns.

Business

The demand for sustainable construction is growing all over the world, and many companies are discovering the green building design and construction business. In addition, new environmental policies and regulations have been created in the business of civil construction. The use of energy efficiency is a new topic in the construction market and with the current competitive scenario in business, companies have been looking for new ways to stand out (AZZI et al., 2015.). The implementation of BIM can help in this competitiveness and the adoption of sustainable measures. But the implementation of BIM requires a significant change in the way the construction business functions in virtually its entire process. The company needs to improve its integration and production capacity with other disciplines in the production process (ARAYICI et al., 2011).

One of the improvements of BIM is the need to have a fully collaborative environment, which changes the traditional way of the business, and this needs to take the various levels of the company to adapt to technological improvements (ZANNI et al., 2014). Nevertheless, there is little research that can contribute to a better understanding of BIM implementation in the business process, or how the implementation of BIM can influence sustainable project outcomes (WU; ISSA, 2014.).

Process

The entire process of a construction (briefing, design, construction, use, re-use and recycling) requires a participation from its designers, builders and users. The complexity of this architectural design in the constructions due to the fact that various parties are involved in different areas, with professionals with different knowledge, and different means of interaction. (GOÇER et al., 2015). Authors show that the development of specifications for the design process can increase flexibility, share understanding between stakeholders about what information pieces should be provided at what stage, from whom to whom, also aiding in the tool selection. (ARAYICI et al., 2017).

In the early stages, buildings can be modified through digital technologies, and become part of the architectural design process (NEGENDAHL, 2015). One of these technologies that modify the civil construction process is BIM, which is a new topic in the AEC, but there is still a lack of standard business processes to execute green projects, especially for LEED (WU; ISSA, 2014). Some studies show parametric process optimization tools through energy simulation. In order to find solutions for the projects, the energy simulation process uses the information stored in BIM, such as its geometries, material information and location (ASLA et al., 2015).

Despite the efforts to create a framework for helping professionals perform sustainability analyzes in the early stages of design, there is still no fully structured process. The process is not to be a prescription of what should be done, but to aid professionals to take sustainability into account during the design process (ZANNI et al., 2014).

Services

Services interoperability can be defined as the ability of an enterprise to dynamically register, aggregate and consume composite services of an external source (CHEN et al., 2008). Authors even suggest the concept of resource sharing within the design of new cloud-based data services like external sources (CURRY et al., 2013; WONG; ZHOU, 2015).

Services interoperability is also present in the exchange of information between multidisciplinary teams that are geographically distributed (e.g., owners, architects, consultants, contractors, sub-contractors, suppliers, and engineers) (JIAO et al., 2013) (KIM et al., 2015). Any information related to the green materials can be stored in an external database in the form of predefined design families that can be recognized by the BIM tool. These databases can also be called external libraries (JALAEI; JRADE, 2014).

Data

In recent years, BIM is climbing positions in building representation, being settled as the paradigm for data collection (DIAZ-VILARINO et al., 2013). To integrate sustainable data into BIM is critically important. In some cases, a team may need to import information to the BIM model from an outside source, such as a database of weather data or material properties, and this information must be easily available for users (ILHAN; YAMAN, 2016).

Data interoperability can occur through the extension IFC (Industry Foundation Classes). It is a data model, and also is the standard data specification for exchanging information throughout the entire lifecycle of a building. XML defines a set of rules for encoding documents in a human-readable and machine-readable format (JRADE; JALAEI, 2013). One relevant way to structure information, achieve representation, manage of heterogeneous data and enable the automated compliance checking is to structure building ontologies. Such ontologies can be especially useful for environmental monitoring and compliance checking. (ZHONG et al., 2018).

The BIM for a large-scale development must include the data at the building level and multi-disciplinary professionals. (J.I. KIM et al., 2015). Because of this, the concept of centralizing building information data in a shared data schema is necessary and typically associated with the early influences of the BuildingSmart initiative (K. NEGENDAHL, 2015).

4.5 INTEGRATED ANALYSIS

From the literature review, it was noticed that each LEED field presents an influence on a lifecycle stage. For example: In the demolition stage, materials present a high impact, since the disposal of the material can be hazardous to the environment, however, the same concrete structures present little to no environmental influence in the operational stage. This degree of influence can be called a relational factor (RF) and can be used to verify which field presents more influence on each stage.

Through the qualitative analysis of the selected papers, it was possible to determine which lifecycle stage correlates the most with which LEED field. Nodes where added to each topic studied in Lifecycle stages and LEED fields. Whenever the terms appeared, a mark called node was added to the paper on a QDA software. The articles with 10% most nodes in each topic were identified, (in the case, 12 papers in each category represent the top 10%). Finally, the results crossed, so if a paper was in the top 10% in a LEED field, it was analyzed if it was well classified in the lifecycle stages well. Papers that also had a high score on the lifecycle topics were awarded 12 points for the one with the most nodes, 11 points for the second and so on. Then, the scores were added, and a relational matrix was developed by dividing the scores by the highest value, generating a proportion (Table 16).

For example, it can be noticed that water efficiency has great importance in the operation stage, while material and resources must receive special consideration in the design, construction and demolition parts of the lifecycle. Also, the most important connection is from sites to construction phase, however there is 0% connection between sites and the design stage. Energy is strongly connected to design and interestingly to maintenance, since apparently energy retrofitting can provide interesting results (SANHUDO et al., 2018). Finally, both innovation and regional priority and indoor environmental quality are closely linked to the design stage.

Table 16 - Relational matrix LEED x Lifecycle stages

	Sustainable Sites	Water efficiency	Energy and atmosphere	Materials and resources	Indoor Environmental Quality	Innovation in operation and regional priority
Design	0.00	0.00	0.66	0.49	0.31	0.46
Construction	1.00	0.14	0.00	0.34	0.00	0.00
Operation	0.17	0.49	0.00	0.00	0.11	0.00
Maintenance	0.00	0.11	0.49	0.09	0.00	0.00
Demolition/deconstruction	0.00	0.00	0.00	0.20	0.20	0.37

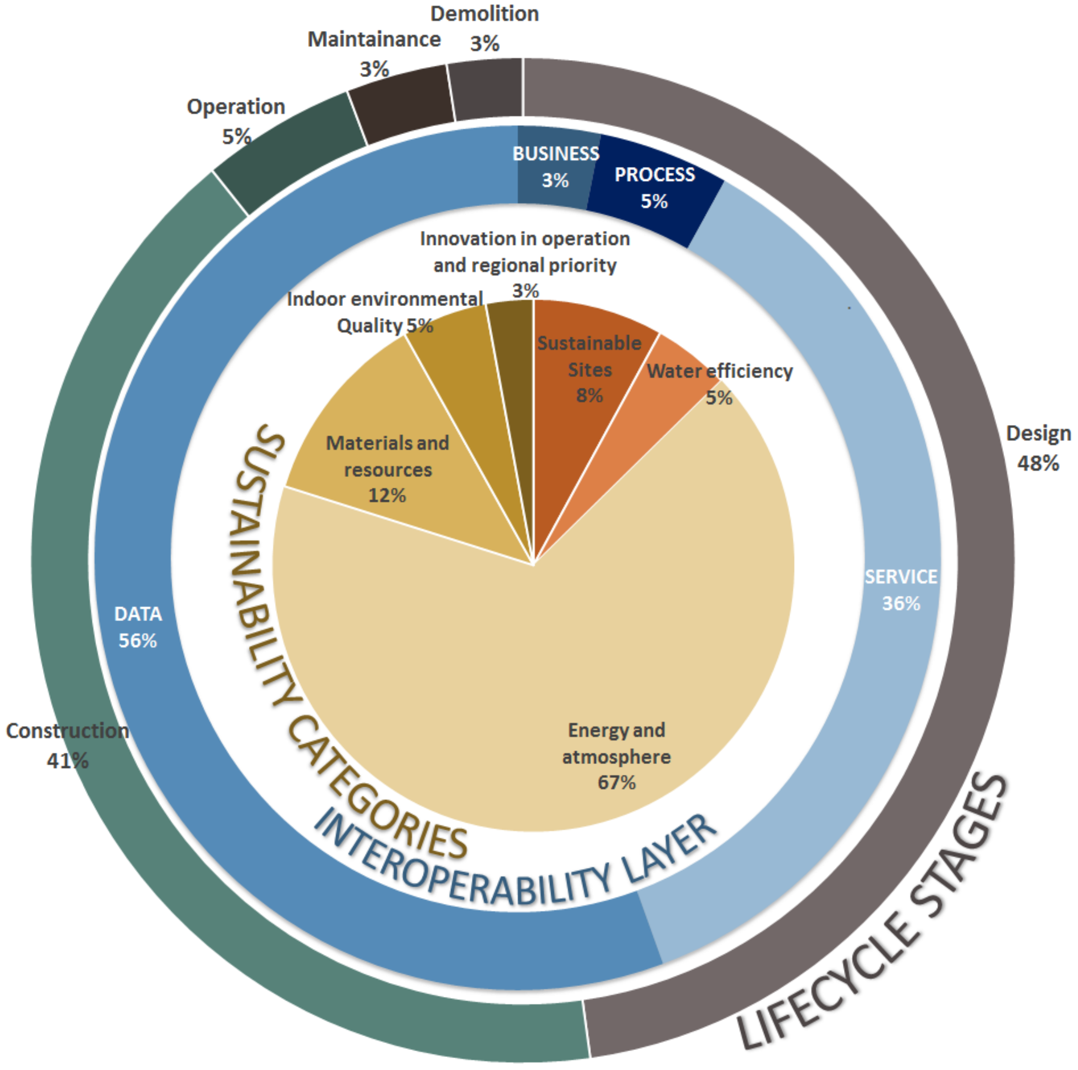
Source:The Author

To better demonstrate and understand the interoperability for sustainability in the BIM lifecycle, a simple framework can be used: one must first consider the BIM lifecycle enveloping all fields in the construction industry, demonstrated in the exterior lane. Then, as a goal to improve sustainability, the LEED domains are placed in the innermost lane. Between the sustainability lane and the BIM lifecycle lane, there is the lane of interoperability, that presents the interoperability concerns. This lane bridges the other two, connecting the lifecycle to sustainability aspects. This schema can be seen in Figure 34.

These relational factors can be used, for example, as criteria on a multicriteria decision process, to evaluate the maturity level of each construction industry domain. It is possible to apply other weights to the areas studied as well. These weights can come from specialist and domain data and can be used to aid decision making toward more sustainable buildings, and even in sustainable framework developments (CALISTA; CHANG, 2012; MARZOUK et al., 2018).

The research also showed an inclination for researchers to develop studies focusing in the design stage (about 48%). Also, it was noticed that operation and maintenance are profoundly linked in the construction industry, and are underrepresented in the considerations of a building´s lifecycle. This highlights a need to consider the entire lifecycle of a building since, for example, the three final stages (demolition/deconstruction, maintenance and operation) make up less than 10% of papers. Also, more LEED topics should receive attention as well, while energy and atmosphere receive great attention, (67%) Innovation and regional priority make-up 3% of the journals considered. Interoperability, however, presents a more even distribution among all concerns.

Figure 34 – Framework model for interoperability maturity in the green BIM LC.



Source: The Author

Concomitantly to other reviews such as performed by (JUNG et al., 2017), that demonstrate that the current practice of BIM utilization tends to focus more on ‘performance of a project’ than the ‘performance of the building’, this research also showed that there is an extensive focus on design and planning. However, the building´s lifecycle and sustainability aspects and these should be considered simultaneously.

When considering sustainability aspects, efficient interoperability in the use of BIM can lead to improved sustainability in the AEC industry. The minimization of information loss and better-defined processes allow users to perform more extensive analysis, improving energy use, quality of the indoor environment and water efficiency. Some important suggestions to link the interoperability layer with sustainability concepts is the use of ontologies to structure information and improve environmental monitoring (ZHONG et al., 2018).

4.6 CONCLUSION OF THE SECTION AND FUTURE RESEARCH

This study presented a systematic literature review. Papers from 2006 to mid-2018 concerning sustainability, BIM and interoperability were searched. The searches were limited to three main in academic databases (Scopus, Engineering Village and Proquest). Through Methodi Ordinatio and a multicriteria decision method the papers were ranked and analyzed with the aid of a QDA system. A total of 272 papers were downloaded, some were excluded due to duplication and a final pool of 230 papers were ranked. The top 50% (115 papers) were analyzed and included in the literature review.

This research presented relevant issues for the advancement of the AEC industry, such as sustainable buildings and digitalization, mainly in the forms of BIM and interoperability, and especially the connection of both fields. Also, the gaps in the fields could be used to support further research and the relational factor could even aid professionals in their decision-making processes, directing where the focus should be on each stage.

From this research it was possible to notice that the Green BIM lifecycle has been studied thoroughly in the past couple of years, representing an exponential growth on the topic. Even with this growth, it can be noticed that papers tend to focus on one stage of the lifecycle alone. Also, it can be noticed that more than half of the papers are concerned with the design, a few consider the construction stage, but very few consider the final stages of the lifecycle.

When considering sustainability, credits related to energy and atmosphere also make-up more than half of the studies. Topics related to materials and resources also receive some attention, but the other four LEED topics (Indoor environmental quality, innovation and regional priority, sustainable sites and water efficiency) are also very under-covered.

Technological innovation is presented through BIM and interoperability. However, the broader aspects of interoperability, services and business, are often not studied, while more technical aspects of data interoperability receive more attention. Interoperability is the field that can connect and improve both the lifecycle and sustainability, opening doors for innovation, economic and sustainable buildings.

So, along with this lack of a holistic view of the system, such analysis of these topics in the light of interoperability is needed. In the future, this review can be used to structure a framework for interoperability in the Green BIM lifecycle, to present solutions and patterns to organize knowledge and data and systematize processes. These tools can even aid and improve decision-making processes, to further develop sustainability in the construction industry. For example, future researches can use the relational factor calculated in section five can be used as weights for a multicriteria decision system, that can aid users to choose where to prioritize for better sustainable results.

4.7 CHAPTER ALIGNMENT IN THE THESIS

This review was structured to identify the convergence of studies in interoperability, sustainability and BIM lifecycle. From this research it was possible to notice that the Green BIM lifecycle has been studied thoroughly in the past couple of years, representing an exponential growth on the topic. Even with this growth, it can be noticed that papers tend to focus on one stage of the lifecycle alone. Also, it was noticed that more than half of the papers are concerned with the design, a few consider the construction stage, but very few consider the final stages of the lifecycle. Therefore, the framework proposed was designed to consider the entire lifecycle of a construction.

Also, the review demonstrated LEED as the ideal certification to apply the framework model, since it is not only the most used worldwide, but also presents important characteristics in the development of a framework, such as clarity, openness and versatility.

Furthermore, the broader aspects of interoperability such as services and business, are often not studied, while more technical aspects of data interoperability receive more attention. So, considering this lack of a holistic view of the system, an analysis of these topics in the light of interoperability is needed, and will be provided in the framework proposed.

Summarizing, this literature review confirmed the need for a framework to structure BIM interoperability with a broad approach, considering sustainability and developing it for the entire lifecycle, as was proposed in the objectives.

5 INTEROPERABILITY FRAMEWORK FOR BUILDING INFORMATION MODELING BASED ON SUSTAINABILITY

The construction industry, or from a broader perspective – the AEC, has several characteristics that distinguish it from other industrial activities, either for its temporary character, or for the fact that every construction is a unique product. One of the challenges to ensure interoperability is the great quantity of professionals involved in its entire lifecycle. According to Wong et al. (2015), effective communication between professionals, interested parties, and companies must occur throughout all phases of a construction work lifecycle.

The lifecycle of the AEC industry can be divided into the following phases — design, construction, operation and maintenance, and finally, demolition/deconstruction. Therefore, the range of such lifecycle is also challenging in terms of ensuring sustainable interoperability. (MULLER, 2019).

The design phase of a concrete structure, according to the NBR 6118 standard (ABNT, 2014), consists of a structural solution that must meet the requirements regarding the resistance to the applied loads, the intended service performance, and the durability in face of the environment. With regard to the execution of the structure, it is specified by the respective NBR 14931 (ABNT, 2004).

During the operation phase, the use of the structure over the years should always respect what was established in the design and by the construction through the owner's manual. Maintenance is also essential in this phase, once the omission or the poor maintenance plan execution may interrupt the operation, and thus even cause the premature demolition/deconstruction of the structure. The final phase of the lifecycle is marked by the demolition or deconstruction, which is the complete elimination of structure elements at a specific date and time. This entire lifecycle may present great environmental impact, and BIM can aid its management and improvement. (WONG; ZHOU, 2015; MULLER et al., 2019).

Given the importance of interoperability within the construction industry, the goal of this research is to measure, from a process perspective, the interoperability gain between the building lifecycle phases of a cast-in-place concrete structure and its external agents, using BIM in relation to the traditional process while in the current scenario. This assessment were developed through interoperability requirements associated with business prospects, processes, services and information, using Chen’s framework (2008) as a base.

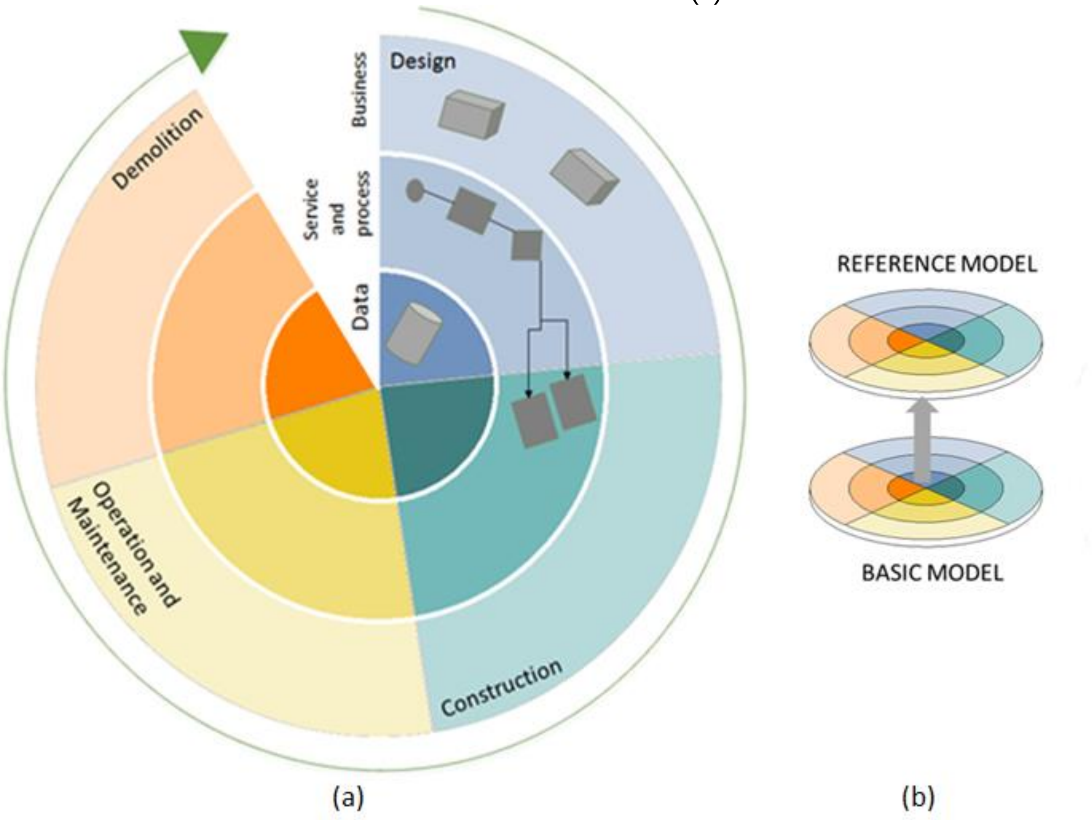
The lifecycle modeling of cast-in-place concrete structures was chosen due to its widely used function in civil works of all categories, covering a large area within the AEC. In Brazil, cast-in-place concrete is employed as one of the main construction systems, being that the Brazilian concrete standard NBR 6118 (ABNT, 2014) is recognized by ISO 19338:2014 (International Organization for Standardization) as a standard that can be used anywhere in the world.

5.1 FRAMEWORK STRUCTURE

To organize and structure concepts of interoperability and sustainability in the construction industry through BIM, a framework is proposed. This framework presents a disk structure as seen in Figure 35. Each slice represents the stages of the building´s lifecycle: Design, construction, operation and maintenance, and demolition/deconstruction. The transversal layers are structured to organize interoperability concerns as follows:

- Business: The outermost layer of the disk presents the standards and certifications used on the field. This information will present decision support factors to influence the process toward more sustainable constructions. In this case, LEED will be used as a reference, since it provides a well-structured scoring system, however any certification or standard can be used. The LEED manual will be 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 will be 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).

Figure 35 - Framework for interoperability in the green BIM lifecycle –general overview (a) and reference and basic models (b)



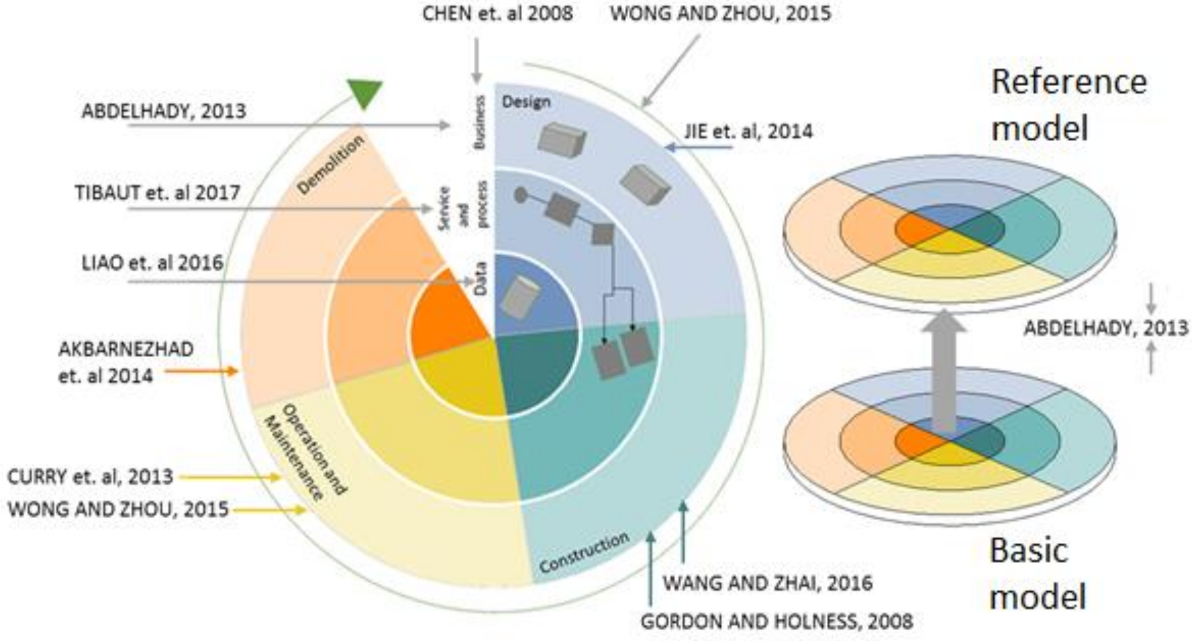
Source: The Author

- Data: The innermost layer is where data will be structured through IFC based ontology. There is a need to develop interoperability in this section (Muller, 2017), and ontologies can be an important tool to organize information to be shared through the process lifecycle. As shown by Liao et al. (2016), processes can use the ontology to create an understanding of the semantics and exchange knowledge to improve the semantic interoperability. This layer will work as a repository for knowledge to feed the other layers.

Also, this framework can support two phases related to two different moments: first a basic model is developed, observing companies and structuring the current state of the AEC industry in the interoperability and sustainability field. After that a reference model is developed, presenting the scenario with ideal BIM use and efficient interoperability (ABDELHADY, 2013), as seen in figure 26 b.

These literature influences on the development of the framework, are presented in Figure 36.

Figure 36 - Literature influences on the Framework

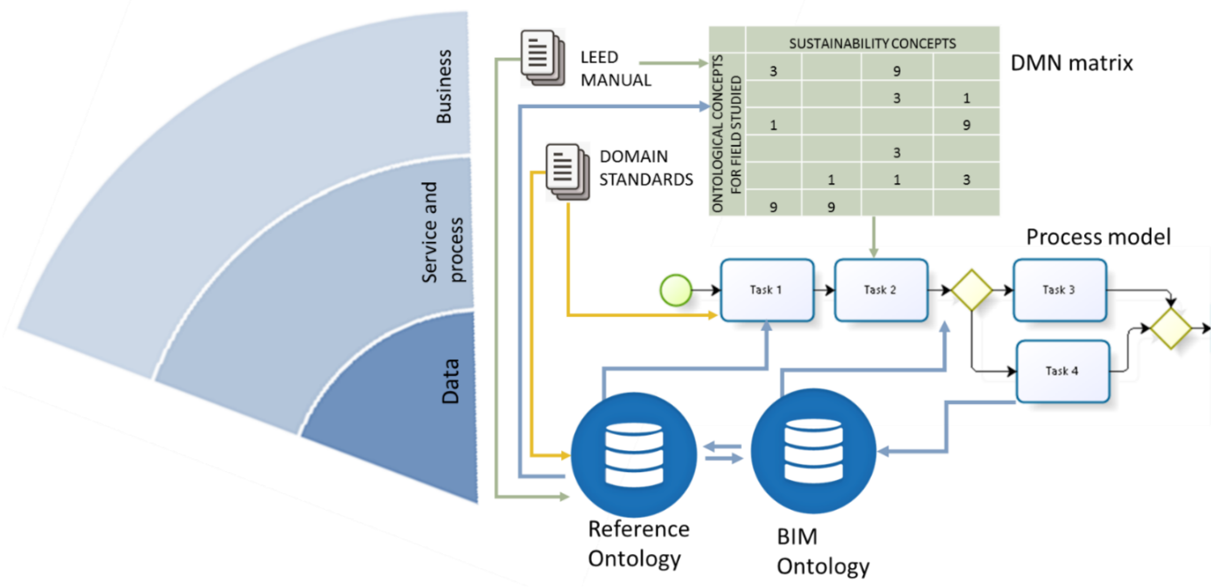


Source: The Author.

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 will support the other layers acting as a semantical reference. This data will allow the semantic annotation of the processes and the DMN matrix, so it will be possible to observe information bottlenecks and analyze LEED influence on each process task. This DMN relational matrix will be based on LEED points and on the influence of the ontological concepts used on each task of the process on sustainability. These influence factors throughout the process can support decision making considering the most sustainable options for a building. For instance: In the design stage, when the designer is on a task “Define slab type”, he may opt for a plan slab or a waffle slab type. The waffle slab usually creates less residue and also presents a better thermal insulation for a construction, so it would present a higher influence LEED factor, suggesting him to follow the path to the task “select waffle slab type”. This schema is demonstrated in Figure 37.

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 catheterized by its own ontology, process and matrixes. Thereby, companies from specific fields will be able to focus on their interoperability and sustainability goals and to compare their current situation to the ideal on each area and verify new ways to improve on each task of the process to achieve a higher interoperability maturity level on sustainability. An example was developed in this study using cast-in-place concrete structures. Concrete structures were chosen for this purpose since structures represent a big part of the building´s cost and embodied energy and cast-in-place concrete structures specifically tend to influence a building´s sustainability through all stages, even until the demolition/deconstruction. (MEHTA, 2011).

Figure 37 - Framework Detail



Source: The Author

5.2 FRAMEWORK BUILDING METHODOLOGY

To structure such framework, a set of methodological steps must be taken. The structure is presented for both the basic model and the reference model (figure 37). IDEF0 diagrams show the methodological process and steps of the framework, considering inputs, outputs, programs used, etc. (CHENG-LEONG et al., 1999). Then, figures x and x present the methodology proposed in further detail.

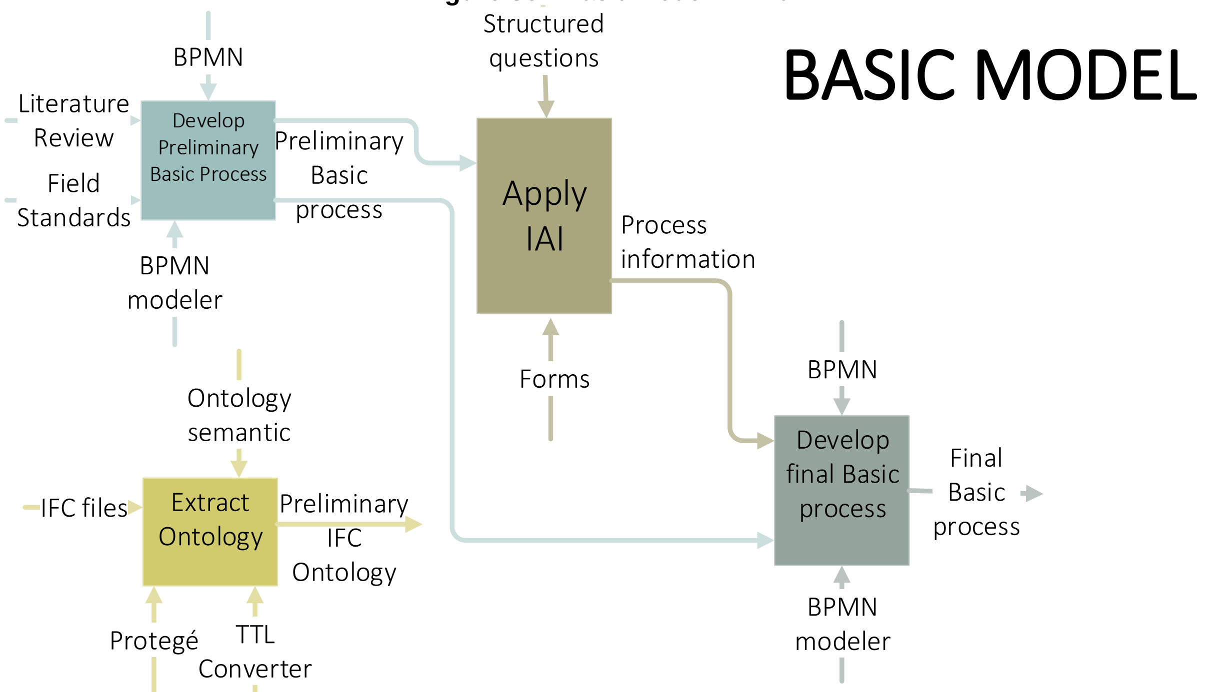
5.2.1 Basic model

The basic model considers the state of pre-BIM or early BIM. Figure 38 describes the process of developing the processes and ontologies represented 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.

The Business layer in the basic model influences only the processes sequencing, as an input for the preliminary process model, through the standards from the field studied. The first step is to develop the ontology for the data layer. This ontology can be extracted from IFC files. First, native files from BIM programs containing elements from the field studied can be exported to IFC. For example: for concrete structures, models such as concrete beams, slabs and columns can be used. These files can be exported as an ontology on the Terse Triple Language (TTL) format, containing elements as structure types, concrete characteristics, reinforcement bars diameters, etc. These TTL files are readable by ontology editors (DI MASCIO et al., 2013) and can be presented in an ontology graphic called ontograph.

Meanwhile, a preliminary process can be modeled based on literature and standards from the specific field. This process will later be refined into a final process by an Information Acquisition Instrument (IAI -1), containing a set of questions sent to companies specialized on each of the lifecycle stages. This IAI 1 provides the process modeler modeling the process with information on tasks, sequences and professionals involved in each process.

Figure 38 - Basic model IDEF0



Source: Author.

5.2.2 Reference model

The reference model is the model for full BIM use, considering interoperability efficiency throughout the lifecycle. The process can be developed in a similar manner to the basic process. First, the preliminary processes are developed based in the basic processes, literature and in the standards of the field in question are refined as well. However, the IAI in this case is submitted to specialists instead of professionals, going through Delphi rounds, either until the specialists reach consensus on the processes or until a predefined number of rounds (HSU, 2007).

The ontology can be developed based on the literature and standards of the field. A common method for ontology development is the Seven-Step method, which is an already established ontology development methodology (GAO at al., 2017). The seven steps that structure this method are:

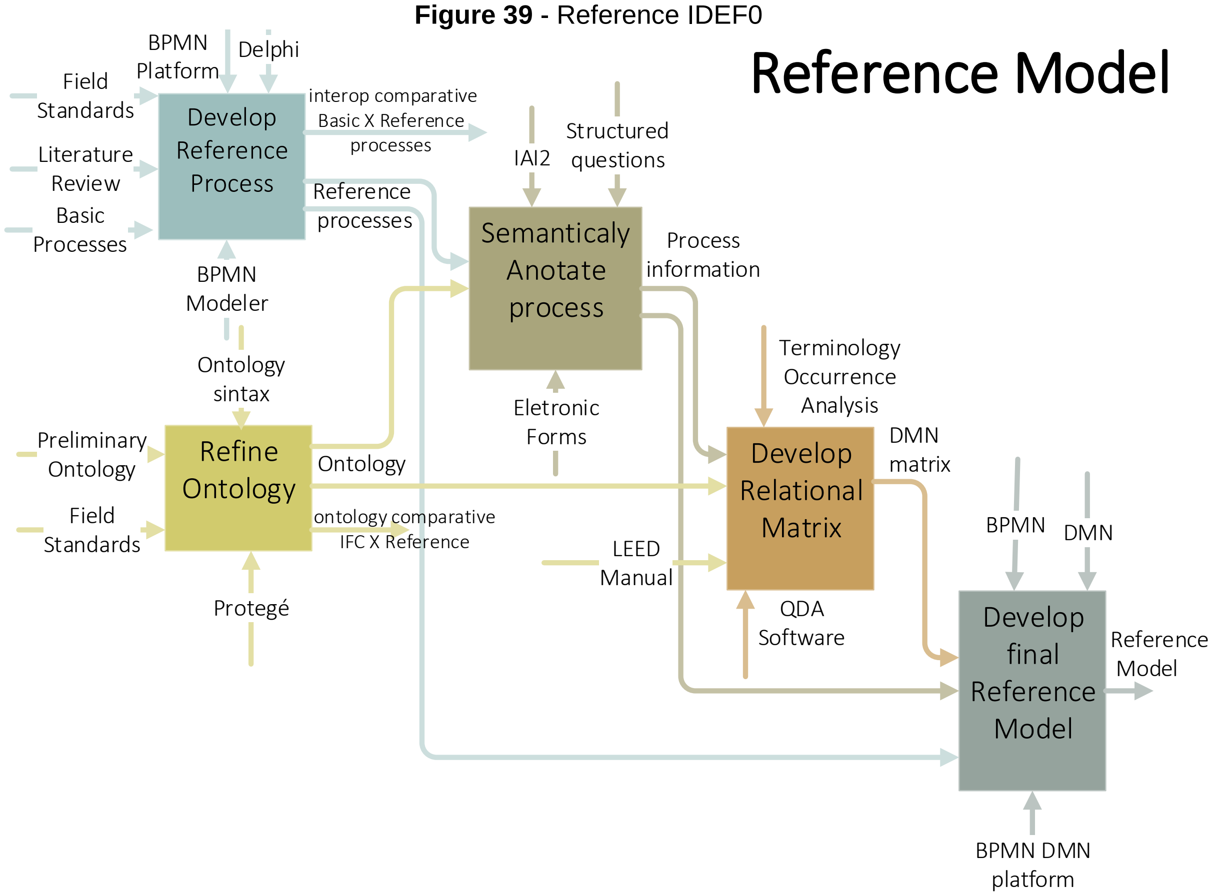
i. Determine the scope and domain of the ontology;
ii. Consider re-using pre-existing ontologies;
iii. Enumerate Terms in the Ontology;
iv. Define Classes and the Class Hierarchy;
v. Define the Properties of the Classes;
vi. Define the ontology rules;
vii. Create instances (Individuals).

It is possible to enrich process models with semantic annotations from domain ontologies to formalize of both the structural and information domain in a shared knowledge base (DI FRANCESCOMARINO, 2011; LIAO et al., 2016). Thus, the process model will receive 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 BPMN modelers to enrich the process semantically.

Finally, 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 software, and each ontology class can be configured as a knot on the program. A search is performed, and a relation between each ontology class and each field or area of the manual can be presented.

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. Figure 39 describes this process.

Figure 39 - Reference IDEF0



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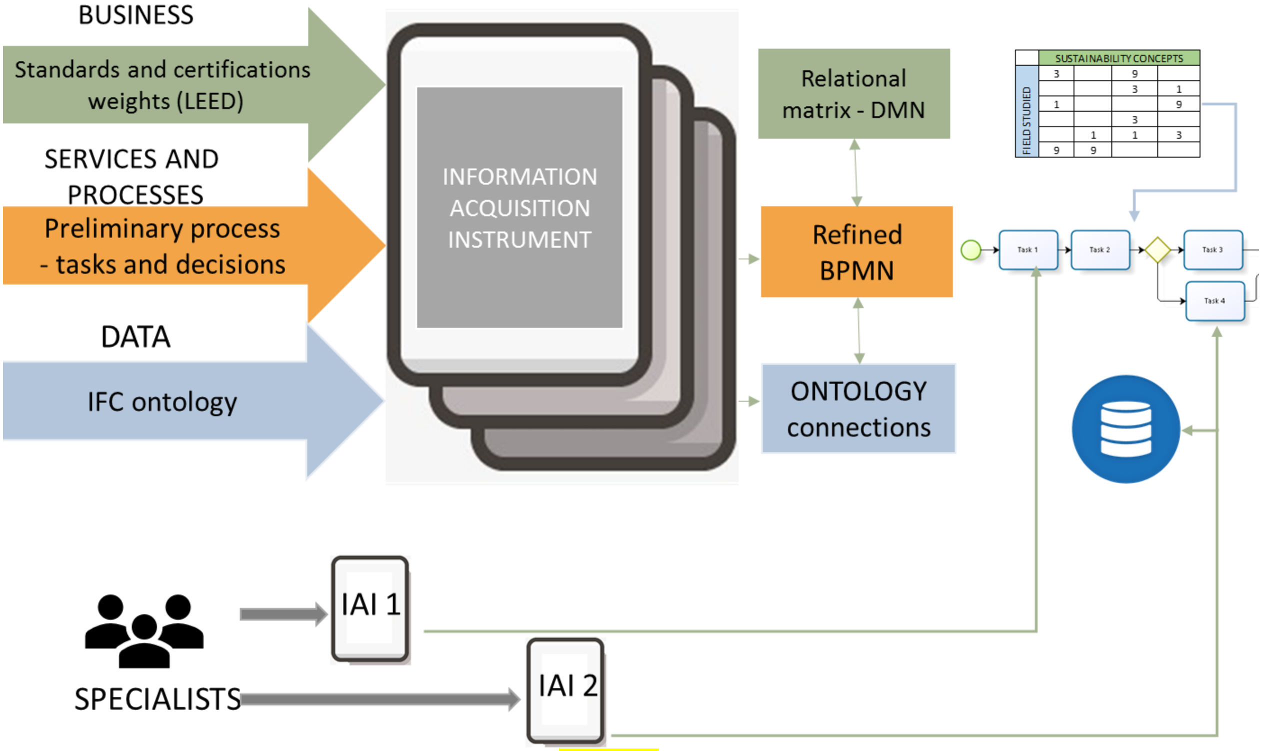
5.3 FRAMEWORK IMPLEMENTATION

An example for the framework will be developed by interviewing several companies and specialists, each answering according to their fields of expertise in the lifecycle stages. This case will be structured using LEED for the business guidelines and cast-in-place concrete structures as the case for the study, however, any sustainability certification and any construction field can be used.

5.3.1 Information Acquisition Instrument

To develop the process maps for the processes and services layer, an instrument to be sent to companies and specialists is necessary. 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 will be used to verify the inputs, outputs and performers for each task of the processes, as well as its sequence, as seen in Figure 40. 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.

Figure 40 - Information acquisition instrument



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This instrument will be useful not only to structure the processes, but it will also support the annotation of the ontology in the data layer developed previously to 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 through digital media such as Google Forms or Qualtrics. A simplified example of an IAI for cast-in-place concrete structures is presented in Table 17.

Table 17 - Information Acquisition Instrument.

IAI 1 - Process modeling form

Activity 1	
Task name:	
Task description	
Origin of task:	
Task Inputs	
Task Output:	
Receiver of output:	
Execution time:	
..	

Activity 2	
Task name:	
Task description	
Origin of task:	
..	

..

IAI 2 - Semantic Annotation form

Task 1: Evaluate Architectural Design	
Information consumed:	(mark with x)
Action	
Combination	
ConcreteElasticModulus	
CoverDepth	
EnvironmentalAgressionClass	
Rebar	
RebarSurfaceGeometry	
Stress	
StructuralElement	
WaterCementRatio	

Task 2: Visit Construcion Site	
Information consumed:	(mark with x)
Action	
Combination	
ConcreteElasticModulus	
..	

Source: The Author

5.4 FRAMEWORK OUTPUTS AND RESULTS

The information collected will be used to structure three main artifacts 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 take decision 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.
- 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 from 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 user may find the best solutions for each project.

These artifacts will be developed for both the basic and reference phases, except for the decision support matrix, that will consider only the reference stages already considering BIM. These artifacts will structure knowledge and aid companies to structure a more sustainable and interoperable lifecycle for buildings, providing users with tools to improve processes, organize information and to take better decisions, taking into consideration environmental and sustainable issues in an interoperable manner.

The span of the lifecycle of the construction industry requires special attention when considering sustainability. Since BIM can aid in the management of this lifecycle, a framework can be developed to organize the knowledge and aid users in the decision-making processes. This framework is based on interoperability concerns, in order to ensure that the information flow is well-structured. Its disk-like structure is comprised of three layers. It considers the innermost layer as a data repository based on the ontology. The second layer presents the process and the outermost layer contains the decision support to guide the processes to more sustainable directions.

This framework can be employed by construction industry professionals, organizing and structuring processes, decision making and data storage. This Frame 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.

5.5 CHAPTER ALIGNMENT IN THE THESIS

In this chapter, the framework was proposed. Since the SLR showed a lack of studies encompassing all stages of a building's lifecycle, this model was developed to consider all stages of a building, from design to demolition. Also, the span of the lifecycle of the construction industry requires special attention when considering sustainability, since, for instance, a building may take years to be demolished, postponing the environmental impact of that stage. To solve these issues, a BIM-based model was proposed. Since BIM objects store information and data, these properties can aid in the management of the lifecycle and its issues mentioned before.

Considering interoperability concerns, the framework is structured in three main artifacts: To solve the data transference issues observed in the preliminary studies, an ontology is used to structure this information, considering it a central IFC based repository. To organize the processes and services, process modeling used, and BPMN is suggested to formalize such processes. This process can be semantically annotated, and this annotation can be used afterwards to guide processes and decisions. Finally, in the business concern, LEED manuals were selected to guide a decision model. LEED was selection as this instrument is justified in the SLR. Finally, to structure this decision model, DMN is selected, since it can be used with BPMN.

Though the framework can be used to any areas in the construction industry, this study applied it to cast in place concrete structures, considering its relevant environmental impact and its well-described standards throughout the lifecycle.

PART B

DEVELOPMENT AND VALIDATION

6 ONTOLOGY FOR CAST-IN-PLACE CONCRETE STRUCTURES

Concrete is currently the most used construction material in the world, due to several factors, among them, the main one, its possibility to create different shapes (HANNA, 1998). The possibility of designing buildings at lower costs, faster, with more durability and with greater safety has made professionals in Architecture, Engineering and Construction (AEC) adapt to the new technologies in the market.

With the development of BIM many software were created aiming to supply the demands of the market in different fields of the knowledge. Nevertheless, most of this software do not communicate well with each other, or yet, when data transfer occurs between them, a large amount of data is lost or incorrectly sent. Interoperability issues are widely studied in the construction industry (MULLER et al., 2017); (SACKS et al., 2010) (KARAN et al., 2015) (EASTMAN et al., 2015) (YANG, 2006). The existence of a common model, where all participants in the same project can access and modify it according to the needs of each professional is essential to the synergy and efficiency in a project execution (EASTMAN, 2008).

One of the premises of the Building Information Modeling (BIM) system is to be an interoperable architecture, providing a secure way of storage, transmission, access and use of project information. This provides for the processes of the lifecycle of a building to be based on documents and information extracted from computer models. The standard model for the exchange of BIM information between agents involved is through the IFC files. Today IFC is published, maintained and updated by the buildingSMART alliance, an open and non-profit institution (buildSMART, 2019). In the field of cast-in-place concrete structures, there are a lot of software that have the possibility to transfer IFC files – for structural analysis software there are 34 software cited on the buildingSMART website. However, researchers such as Muller *et al*. (2017) show that cast-in-place concrete structure elements modeled on BIM, when transferred through IFC, have significant data loss. Other studies (VANDECASTEELE, 2017) show incomplete or fragmented BIM data to supply the BIM lifecycle.

Thus, to improve interoperability it is necessary to understand the data that is transferred by the IFC files. In this work, an ontology is created from an IFC file with various structural elements modeled in BIM, through a direct conversion tool. This automatically generated ontology based on the IFC file does not have structural completeness[1] being the motivator of the development of a method of creating new ontologies manually. To avoid loss of information during file exchange between the professionals involved in the lifecycle of a cast-in-place concrete structure building, it is required that the IFC files have all the requested information. This way, a single model can be used until a demolition/deconstruction. This study is structured as follows: first, the background is established and in section three the methodology is presented. Then, the automatic IFC ontology extraction is presented and after that the development of the ontology according to the standards is shown. In the next section the comparative structure is presented, and after that the results are discussed. Finally, the study is concluded.

6.1 BACKGROUND AND RELATED WORKS

The method chosen for this systematic literature review is the *Methodi Ordinatio* (PAGANI et al. 2015), which is a variation of the ProKnow-C (Knowledge Development Process - Constructivist) method of the Multi Criteria Decision Supporting Methodologies Laboratory (LabMCDA) (ENSSLIN et al*.* 2010). Through this method, 120 articles were identified, 20 of which were excluded because they had no relevant impact factor. Of the 293 authors who wrote these 100 articles, we can highlight Charles M. Eastman with largest production of articles in this theme, with 06 articles of his authorship. The selected articles were analyzed with the aid of a QDA software. As a result, it is possible to see in Figure 41 a wordcloud that presents words very similar to the search terms.

To understand the distribution of articles in relation to the BIM lifecycle, the words Design, Construction, Operation, Maintenance and Demolition/deconstruction were also analyzed in the QDA. The knowledge around BIM and Ontology is concentrated in the Construction and Design stages of the BIM lifecycle, while the demolition/deconstruction phase is cited in only 10% of the articles and mentioned very few times.

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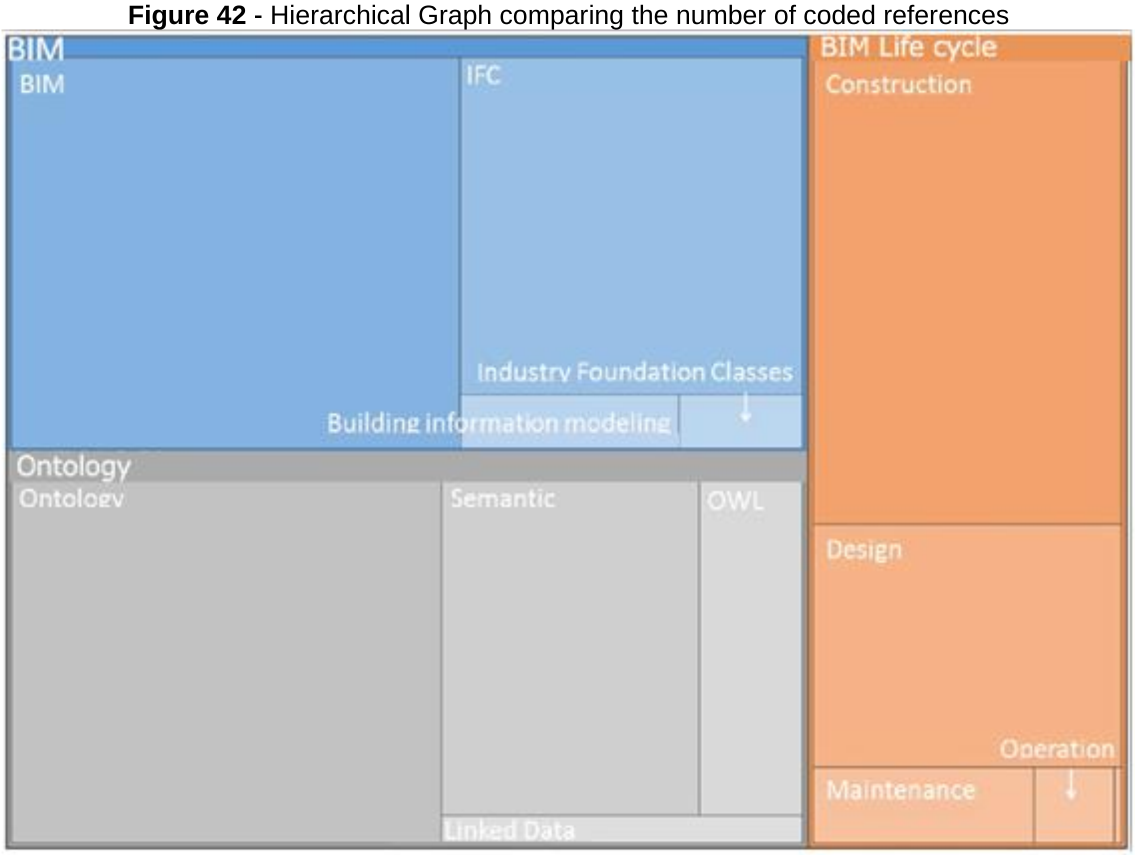
[1] Ontology that has no semantic connectors, is presented without hierarchical criteria and all modeled elements are expressed with their properties mixed in a single instance. There is no connection between the classes.

Figure 41 - Wordcloud of most recurrent terms.

Source: The Author

With word quantification, a hierarchical chart comparing the number of coded references can be created, resulting in Figure 42, where the proportion of each rectangle is related to the number of times the word appears in all articles.

Figure 42 - Hierarchical Graph comparing the number of coded references



Source: The Author

Some articles have been added to this search in addition to those catalogued in the database. As the author of RSL InOrdionatio himself quotes, some works are "classics" in his field, since they have been cited many times over the years and therefore should not be left out. The main concepts of these articles are described in this section.

Interoperability and lifecyle

One of the issues that BIM aims to address is the interoperability problems that exist between the various disciplines of the AEC industry, since they all should represented in a single model. In addition, it is possible to work in parallel on the same model, which facilitates the identification of conflict points. This is a point in which project productivity is increased (LEE et al., 2016). In this sense, with the large volume of data that is exchanged between professionals in the area, it is necessary to ensure that the information related to objects is interoperable between one software and another correctly throughout the building's lifecycle. This is still a barrier applicable to BIM, since interoperability between applications is insufficient to ensure information exchange (MULLER et al., 2017).

The lifecycle of a building tends to be more complex than any other product as it takes many years to reach the point where it is demolished and subsequently recycled, therefore, all stages should be tracked through BIM (WONG; ZHOU, 2015).

Consequently, information modeling of a building during its lifecycle addresses the problem of information heterogeneity exchanged between actors. This demonstrates the need to homogenize the representation of these exchanges with the construction of knowledge throughout its the whole lifecycle (PITTET et al., 2014).

BIM is commonly used as data sharing and knowledge repository to support planning/design, construction, management, utilization/operation, revitalization/maintenance, and demolition/deconstruction activities (KOCH, 2017). Each step will be addressed and contextualized in the following sections. To provide interoperability throughout the BIM lifecycle, IFC is adopted as a neutral format for information exchange. IFC is currently considered the most appropriate scheme for improving information exchange and interoperability in the construction sector (MACIT et al*.,* 2017), (BUILDINGSMART, 2018).

IFC (Industry Foundation Classes)

The Industry Foundation Classes (IFC) is a neutral file model that can be read across different AEC industry software and can be used throughout a building's lifecycle (LEE et al., 2016). This file model is supported by about 150 software applications worldwide to enables better workflows for the AEC industry. In the field of cast-in-place concrete structures, less than 34 software programs are known to have the ability to communicate with others software through IFC (BUILDINGSMART, 2018).

With the implementation of the IFC file model, projects that previously consisted of applications that did not communicate with each other, due to a lack of similarity in the information exchange pattern (EASTMAN, 2008), today can use the model to improve communication between professionals in the area. The IFC is an open extension present since 1994 and its extensions and additives are frequently updated (BUILDINGSMART, 2018).

IFC4 (formerly named IFC2x4) was released as the new IFC platform since march 2013, being the current IFC platform (with due addeduns). It incorporates several IFC extensions into the building: building structural and service areas, geometry enhancements and other feature components as well as quality improvements, fully integrated with ifcXML specifications and a new record format (BUILDINGSMART, 2018). In addition, IFC enables several new BIM workflows - including 4D and 5D model exchanges, product libraries, BIM and GIS interoperability, enhanced thermal simulations, and sustainability assessments. It is fully integrated with new mvdXML technology and allows easy definition of data validation services for IFC4 data environments, fixes technical issues encountered since IFC2x3 release, allows IFC extension to infrastructure and other parts of the internal environment. In addition, it incorporates multilingual property definitions linked to the buildingSMART (IFD) data dictionary (BUILDINGSMART, 2018).

The second IFC4 addendum (IFC4 addendum 2) was released in July 2016 and is the last available version of IFC. The main change is related to improvements in geometry. It has also been updated because the MVD version became 1.1 (BUILDINGSMART, 2018).

The language used for the development of IFC was the EXPRESS, also used in the STEP standard, and overseen by ISO 10303-11. The language consists of elements that allow unambiguous data definition and specification of constraints in defined data (ISO 10303-11: 2004).

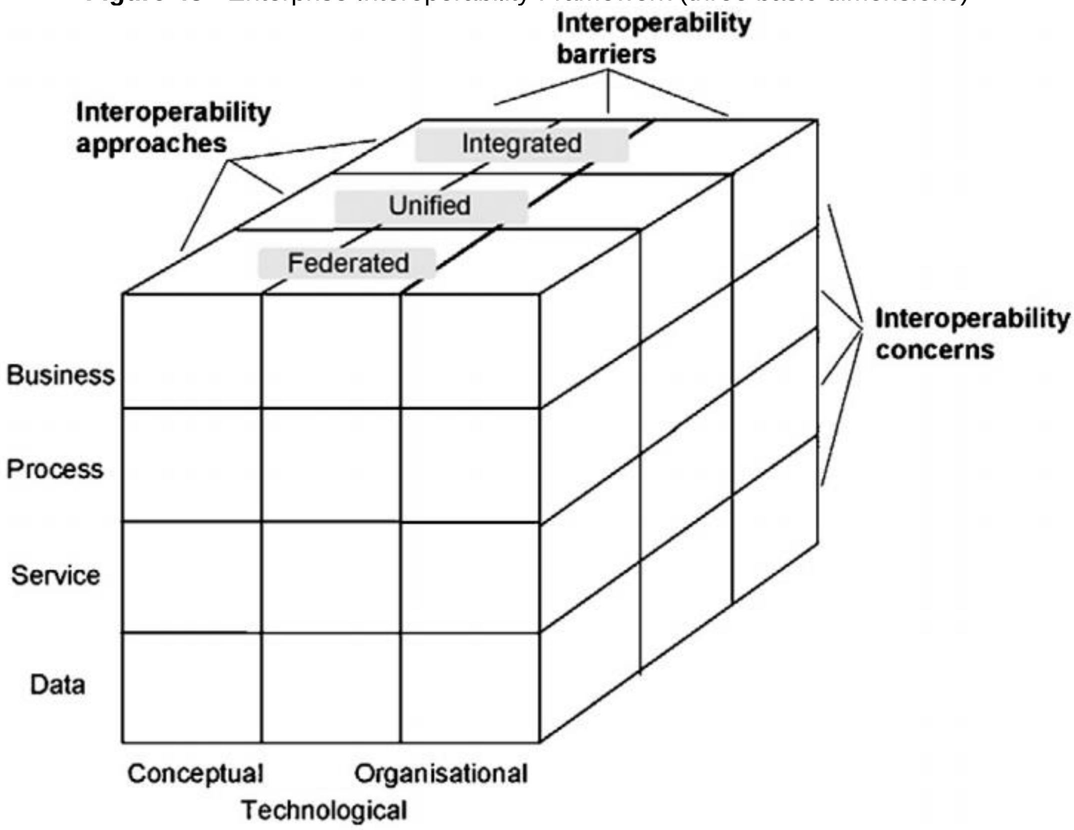
Because of this, regarding the IFC file data structure, there are three fundamental entity types in the IFC model: objects, relations, and properties. The IFC model has a hierarchical structure per module. Each module groups a series of entities where concepts are defined (BUILDINGSMART, 2018). In the IFC4 documentation (present on the buildingSMART website, 2018) there is an introduction field that presents the IFC layers. At the base of the IFC architecture, that is, at the resource layer the entities defined in this layer can be referenced and specialized by all the entities above in the hierarchy. In this first layer, there are entities common to many AEC objects such as cost, materials, geometry, representation, measurements, date and time. The nuclear layer, also known as the core layer provides the basic structure, fundamental relationships and the common concepts to all layers. All entities defined at the nuclear layer and above are derived from an IfcRoot, having unique information of change control, name, description and information. The organization of all entities of the IFC model, as coming from the IfcRoot entity, was developed to create a stable superstructure that would enables the conciliation of the new entities that are being included in the model. The third layer, shared elements layer, is composed of objects and/or concepts common to two or more domains. This layer is also known as the interoperability tier because it bridges common objects across different domains. The top layer, called the domain layer, organizes the definitions according to the 08 disciplines of the sector. The entities defined in this layer are independent and cannot be referenced by any other layer. Inside this layer two disciplines are addressed in this project: IfcStructuralAnalysisDomain and IfcStructuralElementsDomain.

The IfcStructuralAnalysisDomain describes the structural analysis model for integrating the structural engineering domain. It uses existing building element and spatial structure definitions and associates structural assumptions with it. The focus is to ensure that structural engineering information is captured and made visible to other related domains (BUILDINGSMART, 2018). This area will be detailed and thoroughly analyzed during the course of the work. Both schemes need have enough information to support the entire BIM lifecycle.

Interoperability

Chen (2008) interprets interoperability through three axes of a cube structure shown in Figure 43: concerns, barriers and approach. Approaches can be understood as levels of interoperability: integrated, unified or federated. The next axis consists of interoperability barriers, which may be conceptual, technical or organizational. This means that there are more dimensions to system interoperability and technical issues. Finally, the final axis presents concerns for interoperability: business, processes, services and data.

Figure 43 - Enterprise Interoperability Framework (three basic dimensions)



Source: CHEN, 2008.

In the axis of barriers, this research is framed in both the conceptual and the technical barriers. In the conceptual barriers, through ontologies, the syntactic and semantic differences of the information to be exchanged are conceptualized. On the technical barriers it is connected to presenting, storing, exchanging, processing and communicating data using computers.

In the concerns axis, this project is located along with data, which encompasses the use of different models of information, that can be exchanged between databases or systems without data loss. Data interoperability can occur through Industry Foundation Class - IFC, which is a data model and also represents the standard data specification for information exchange throughout the building's entire lifecycle.

Sheth (1999) suggests that systems interoperability solutions are at different levels, which 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 the data structures adopted by each system and the semantic issue refers to the adoption of divergent interpretations for the information exchanged between the systems.

Semantic interoperability is the ability to communicate information between two or more software and have this information correctly interpreted by the receiving system, with consistency in its representations according to the context of use, as predicted by the transmitting system. Just as buildingSMART stands for the IFC standardization, W3C stands for standardization of information organization on the WEB. One of the semantic Web tools for representing data in a domain is ontology Miller (2001).

Unicode and URI layers ensure the use of international character sets and provide means for identifying objects on the Semantic Web. The XML layer with namespace definitions and schemas ensures integration of Semantic Web definitions with other XML-based standards. With RDF [RDF] and RDFSchema [RDFS] object declarations with URIs can be made and vocabularies that can be referenced by URIs can be defined. The Ontology layer supports vocabulary evolution as it can manage and define relationships between different concepts.

Kim et al., 2013 describe that to use BIM-based data relationships in a semantic inference procedure, IFC files can be converted to Web ontology language (OWL) to input to Semantic Web applications. Also known as ifcOWL, this ontology is automatically generated from the 'IFC4' EXPRESS schema using the 'IFC-to-RDF' converter developed by Pauwels; Terkaj (2016). This technique will be developed in this research.

In this sense, Mignard et al. (2014) shows that semantic BIM is the use of ontologies to manage models. Ontologies unify the knowledge generated during each stage of the building's lifecycle. For this purpose, users describe real-world elements and their interactions with each other in the model.

According to Pauwels; Terkaj (2016), an IFC ontology, or ifcOWL, is explored and researched because it allows:

a) The use of the already consolidated IFC standard to represent construction data.

b) The exploration of the software of semantic Web technologies in terms of data distribution, data model extensibility, query and reasoning.

c) The reuse of software implementations for general purpose data storage, consistency checking and knowledge inference.

Ontology

Ontology is one of the semantic web technologies for representing, exchanging, and reusing domain concepts, relations between concepts and rules. Ontology has begun to be used in the area of AEC for knowledge representation, information interoperation, and rule-based reasoning because of its better adaptability and efficiency (MA et al., 2018).

Ontologies are used to document understanding of various concepts in a formal and explicit manner (PETRINJA et al., 2007). However, from the authors' point of view, the best definition that capture is the essence of an ontology is given by Gruber: "an ontology is a formal and explicit specification of a shared conceptualization" (REZGUI et al., 2011).

For the ontology creation guide by Noy et al. (2000), an ontology is an explicit formal description of concepts in a discourse domain (classes, sometimes called concepts), properties of each concept that describes various attributes and attributes of the concept (slots, sometimes called roles or properties) and slot constraints (facets, sometimes called role constraints).

An ontology together with a set of individual instances of classes, constitutes a knowledge base. In fact, there is a fine line where ontology ends and the knowledge base begins (NOY et al., 2000).

Corcho et al. (2007) show that there is a data organization common to all ontologies even though the form of knowledge representation and the corresponding language vary. There are 04 common elements: classes, relations, axioms and instances.

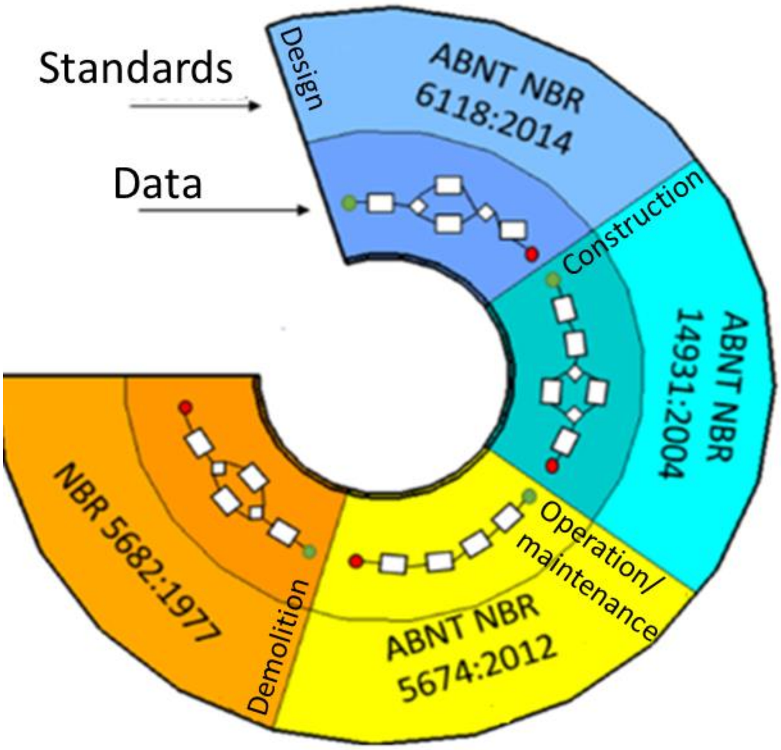
Concrete Structures

In Brazil, the main design standard for cast-in-place concrete structures is ABNT NBR 6118, which in 2015 was recognized by ISO (International Organization for Standardization) as a technical standard that meets international requirements and can be used anywhere in the world. According to NBR 6118: 2014, cast-in-place concrete elements are those that, in order to achieve the necessary strength for an adequate structural performance, depend on the adherence between the concrete and the reinforcement bars, having the initial deformations applied only after the consolidation of the materials.

In BIM, all cast-in-place concrete structural information must be represented on modeled concrete structure objects in the IFC File (MULLER et al., 2017). All cast-in-place concrete structural information is associated with a phase of the BIM lifecycle, for example, structural analysis information is consumed in the design phase, quantitative and details are used in the execution/construction phase, and so on.

The criteria used to base the knowledge of cast-in-place concrete structures followed the standards established by the Brazilian Standard - NBR, as shown in Figure 44.

Figure 44 - BIM Lifecycle and Standards



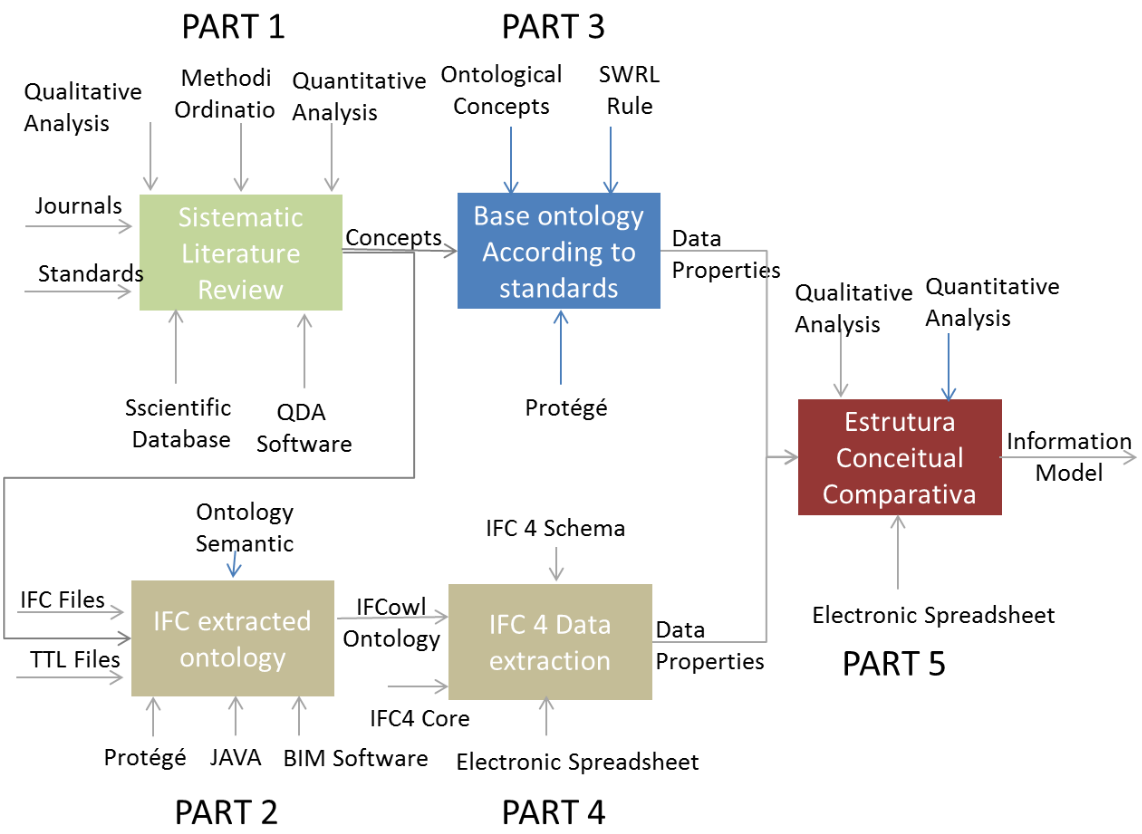
Source: The Author

6.2 METHODOLOGICAL APPROACH

The methodological approach was developed in five parts, described in Figure 45. These parts are structured in an IDEF0 diagram. The left to right arrows represent the information inputs, the upper arrows are the controls (plans, specifications, methods, rules...), the lower arrows are the mechanisms (people, software, tools) and the right side of each frame are outputs from each step.

In general, the result of this research depends on comparing the data properties present in the cast-in-place concrete structures standards and the data properties present within IFC4 add2, and a result is presented as diagnosis of whether the IFC4 information structure can supply all data properties required throughout the lifecycle of a cast-in-place concrete structural building.

Figure 45 - IDEF0 Diagram - Research Methodology



Source: The Author

In the first part of the project, a systematic literature review is carried out, with the input of scientific articles and standards. Through the ordinatio method, qualitative and quantitative analysis, the articles were mapped with the QDA software. By reading these results it was possible to stipulate the research objectives, knowledge gaps, methodologies, as well as to determine the methodological steps to set up the presented IDEF0.

Next, an ontology was developed through an IFC file. To assess the structure of the information contained in an IFC file, the main structural elements and their possible variations were initially modeled in Autodesk's Revit Structure 2018 software, and after being modeled, the file is saved in IFC4 ADD2 (latest version of IFC) format. The modeled cast-in-place concrete structural elements were based on cases previously approached by MULLER et al. (2017). The results obtained showed that elements that required presented errors when being exported and imported to IFC files.

Pauwels; Terkaj (2016) describe that the base of the EXPRESS language (used in IFC) is similar to the base of the OWL language (used in Ontologies), and the semantic structure of an IFC file is to some extent comparable to the semantic structure of an RDF chart. Through this IFC-RDF similarity, developers Jyrki Oraskari, Mathias Bonduel, Kris McGlinn have created an IFC-to-RDF converter, freely available from a GitHub repository, which aims to create a TTL file to track W3C proposed ontologies. The purpose of this tool is to represent IFC information through ontology, but without later application.

Then the TTL file can be opened directly in Protégé software, and its ontological framework can be analyzed (Protégé is a free and open source ontology framework editor for building intelligent systems, created at Stanford University). Outcome analysis consists of finding out how and what are the information that the IFC is organizing in this structure.

In the third stage, through the Systematic Literature Review it was possible to identify cast-in-place concrete structures standards and where they are inserted in the lifecycle phase of a building (design, construction, operation/maintenance, demolition/deconstruction). To develop the relevant ontologies all concepts, relations, properties and axioms must be identified and organized. So all requirements have been extracted from the standards.

Although there are several classifications for requirements in the literature, it is indicated that each organization defines its own classification (SOMMERVILLE, 2004). Because of this, the requirements defined in the standards are: Restrictions; Taxonomies; Default values and Data Inputs (values entered by the user). With this information, four basic ontologies will be built in Protégé, one for each phase of the lifecycle.

There are several methods for building domain ontologies, such as TOVE, IDEF5, Skeleton, KACTUS, SEN-SUS, METHONTOLOG, and Seven-Step. Among them, the Seven-Step method is considered to be a well-established approach and suitable for the purpose of this research and will be used in this work (GAO et al., 2017). Like Protégé, this seven-step method was developed by Stanford University School of Medicine.

The seven steps are:

i. Determine the domain and scope of ontology;
ii. Consider the reusing existing ontologies;
iii. List important terms in ontology;
iv. Define the classes and the hierarchical classes;
v. Define the properties of the classes;
vi. Define the rules;
vii. Create instances (Individuals).

In order to extract class properties from the standards all data that needs to be inserted or is already preloaded into the IFC base must be considered: data entry values, text, values, or information that the BIM user needs to enter and/or the BIM software needs to load in order to perform the calculations, define finishes, to model structures and generate documentation.

For validation, individuals (single element composed of multiple data properties) will be created to test the SWRL Semantic Web Rules, and an inference engine will be used to classify this instances according to standard. For this purpose, an individual is created and assigned Data Property values, these values are tested and validated according to the rules present in the SWRL, and in response the individual is classified into a class. However, the objective of this research is not to make knowledge inference about the cast-in-place concrete structures domain, this rules were created only to test the ontology.

In Protégé, at the end of the ontology validation test, the “Data Properties” of each Standard Ontology will be listed. It contains the information that the IFC schema needs to carry in order to be able to supply a certain phase of the lifecycle.

In the data extraction step, the documentation for the latest release of IFC4 can be accessed openly on the buildingSMART website, which specifies a conceptual data schema and a swap file format for BIM data. The conceptual schema is defined in the EXPRESS data specification language. The graphic scheme is given by EXPRESS-G.

EXPRESS-G charts feature IFC specifications that include terms, concepts, and data specification items that stem from use within the disciplines of the construction and facility management industry. Terms and concepts in the documentation use data items within the data specification following a naming convention. With the completion of the previous parts, a comparative conceptual framework is created between data resulting from ontologies and standards and the data extraction from the IFC4 add2 documentation.

6.3 IFC ONTOLOGY EXTRACTION

To perform the assessment offre the structure of the information contained in an IFC file, cast-in-place concrete structures were initially modeled on Autodesk's Revit Structure 2018 software. The geometric model represents the physical structure of the building, while the analytical model consists of the structural elements, their geometries, material properties, loads and combinations, which unified represent a structural engineering system (LIU et al., 2016).

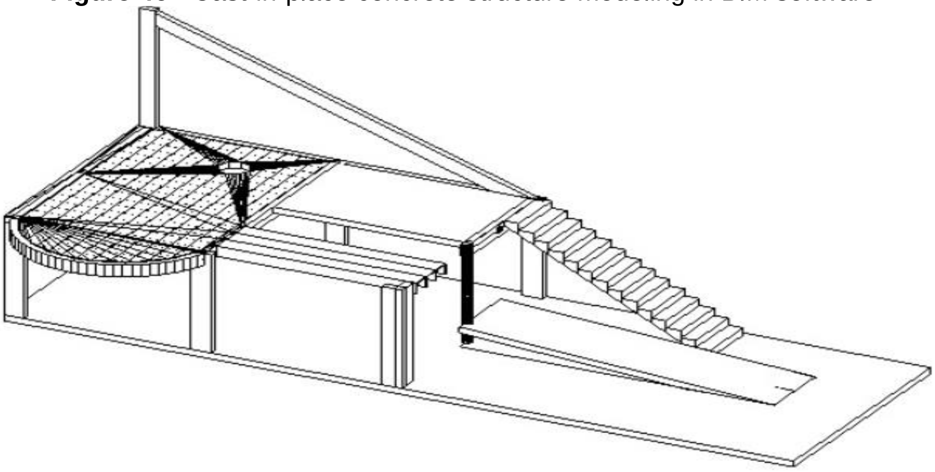
A BIM digital model with the main structural elements of the supra-structure of cast-in-place concrete and its possible variations was modeled and can be observed in Figure 46:

(i) Beams: Beam with one span ; Beam with two or more spans; Beam with section variation; Beam with hole; Curved beam; Sloped beam;

(ii) Pillars: Pillar of only one floor; Pillar of two or more floors; L-shaped section pillar; Circular section pillar; Pillar with section change;

(iii)Slab: Flat slab; Free edge slab; Slab with hole; Stairs; Ramp; Curved slab; Waffle slab.

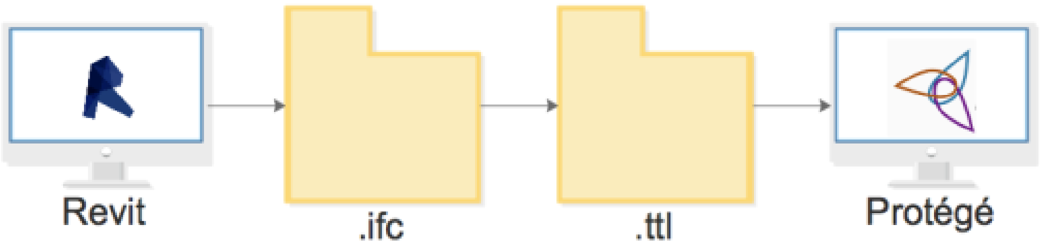
Figure 46 - Cast-in-place concrete structure modeling in BIM software



Source: The Author

This list was based on an IFC and cast-in-place concrete structures interoperability study developed by Muller (2017), who analyzed interoperability between cast-in-place concrete structure design CAD systems and BIM modelers through IFC files. After being modeled, the file was saved in IFC4 add 2 format. From this point it was defined that the IFC structure would be analyzed based on Resource Description Framework (RDF) charts, which generate a TTL file format. And with the help of Protégé it was possible to visualize the resulting structure. This script can be seen in Figure 47:

Figure 47 - Experiment Script

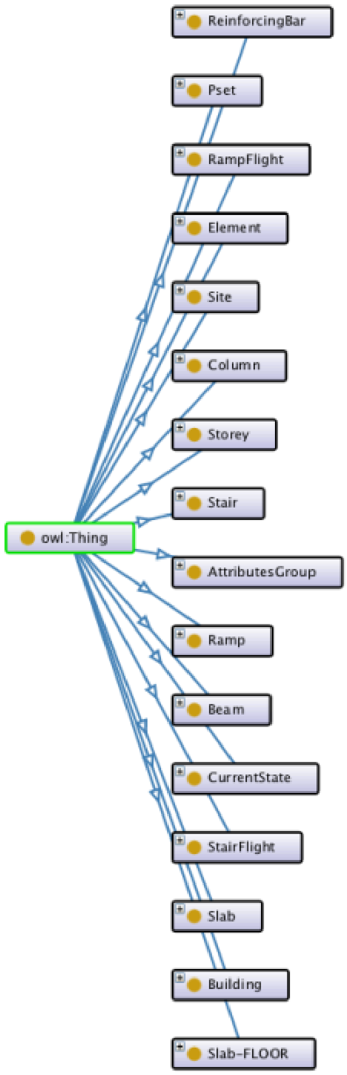


Source: The Author

After conversion to RDF in TTL format, the file can be opened directly in Protégé, and an ontology chart called “ontograph” was generated (Figure 48). This figure shows that structural elements such as pillars, ramps, stairs, and slabs appear as classes, and have no subclasses. The program generated a total of 16 classes, and for each of these classes there were annotations and individuals linked to them.

There were no relations in the generated ontology; relations represent a type of association between concepts in a domain. There were also no formal axioms, which are usually used to represent knowledge that the other components cannot formally define. They are useful for inferring new knowledge, for verifying the consistency of the ontology itself or the consistency of the knowledge stored in a knowledge base.

Figure 48 - IFC4 Ontograph of Cast-in-place concrete Structures



Source: The Author

6.4 DEVELOPMENT OF ONTOLOGIES ACCORDING TO THE STANDARDS

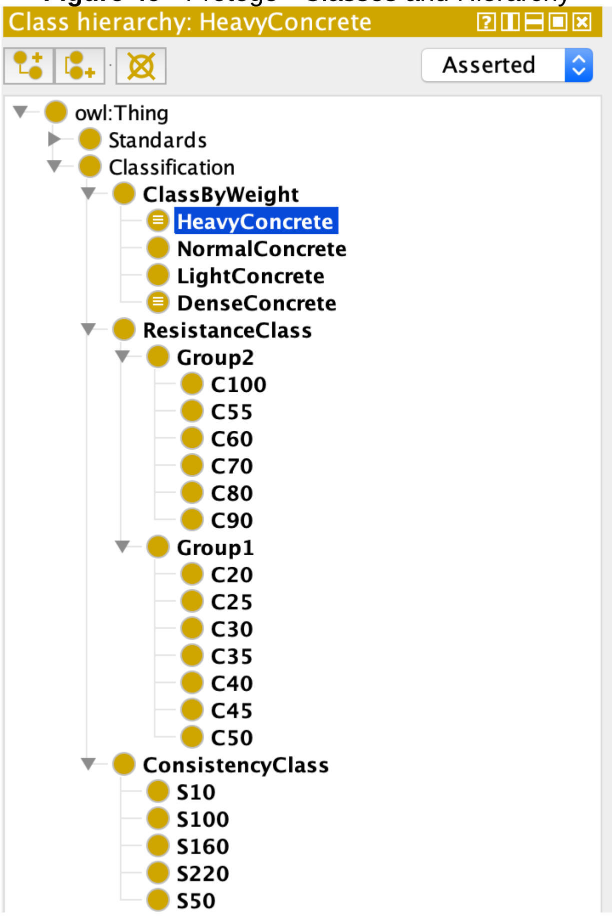
The development of the ontologies was based on each of the building´s lifecycle standards, and an ontology for each stage was developed. In this section the development of the design stage ontology by the sevenstep method will be demonstrated.

For the design stage, the standard NBR 6118 /: 2014 - “Design of concrete structures - Procedure” was used. In addition to this, the standard ABNT NBR 8953/2015 - Concrete for Structural Purposes was also used. It establishes the concrete classes according to their specific masses, axial compression strengths and consistencies. This stage was developed through the seven step methodology mentioned previously.

First, important terms were enumerated in the ontology, which in the standard in question are: Terms and Definitions; Resistance classes and Consistency classes. In the definition of hierarchical classes, the first was defined as the Specific mass, divided in concretes types classified as normal, light and heavy or dense. The second class refers to the resistance classes. Structural concretes are classified in groups I and II according to the characteristic compressive strengths (fck) determined from analysis.

Thus, Group I and Group II are subclasses of the Resistance class. The third class, Consistency, refers to the classification of the concrete according to its consistency in fresh state, determined from of the slump test, and has five subclasses (s10, s50, s100, s160, s220). As a result, in the Protégé software these hierarchy classes were built as shown in Figure 49.

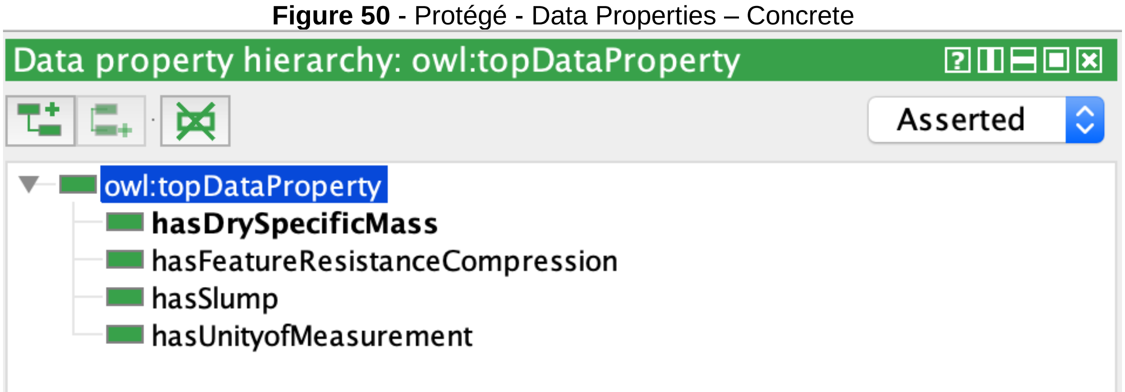
Figure 49 - Protégé - Classes and Hierarchy



Source: The Author

Class properties are distributed into two types: Object Properties and Data Properties. Object properties represent binary relations between two individuals, however this standard did not require this feature. Data properties connect an individual with basic data (such as strings or numbers), as shown in Figure 50, and the same individual can have multiple class properties attached to it.

Figure 50 - Protégé - Data Properties – Concrete



Source: The Author

These data entry needs are system requirements necessary to be implemented in BIM software so that the information needed to know if concrete data belongs to the classification required to be used as structural concrete, for example.

The rules were written using the SWRL language. For example, the strength class C45 which has a compressive strength greater than 45 Mpa and less than 50, since at 50 it is already considered C50, should be written as follows in the SWRL, as a rule:

ResistanceClass (?p) ^ FeatureResistenceCompression (?p,? x) ^ swrlb: greaterThanOrEqual (?x, 45) ^ swrlb: lessThan (?x, 50) -> C45 (? p)

Thus, when running the Protége's inference engine, it understands that if an individual has a data property named "FeatureResistanceCompression" between 45 and 50, he will categorize this invidual as a C45 subclass of "Class 1" of the standard, and is in turn subclass of "ResistanceClass". The other rules created can be seen in Figure 51.

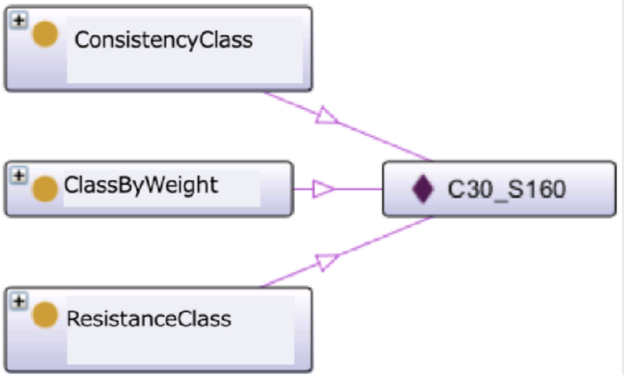
Figure 51 - Protégé - SWRL - NBR 8953/2015

ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,45)^swrlb:lessThan(?x,50)->C45(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,40)^swrlb:lessThan(?x,45)->C40(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,50)^swrlb:lessThan(?x,55)->C50(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,55)^swrlb:lessThan(?x,60)->C55(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,60)^swrlb:lessThan(?x,70)->C60(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,70)^swrlb:lessThan(?x,80)->C70(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,80)^swrlb:lessThan(?x,90)->C80(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,90)^swrlb:lessThan(?x,100)->C90(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,100)->C100(?p)
ConsistencyClass(?p)^hasSlump(?p, ?x)^swrlb:greaterThanOrEqual(?x,10)^swrlb:lessThan(?x,50)->S10(?p)
ClassbyWeight(?p)^hasSpecificMass(?p, ?x)^swrlb:greaterThanOrEqual(?x,2000)^swrlb:lessThan(?x,2800)->NormalConcrete(?p)
ConsistencyClass(?p)^hasSlump(?p, ?x)^swrlb:greaterThanOrEqual(?x,50)^swrlb:lessThan(?x,100)->S50(?p)
ConsistencyClass(?p)^hasSlump(?p, ?x)^swrlb:greaterThanOrEqual(?x,100)^swrlb:lessThan(?x,160)->S100(?p)
ConsistencyClass(?p)^hasSlump(?p, ?x)^swrlb:greaterThanOrEqual(?x,160)^swrlb:lessThan(?x,220)->S160(?p)
ConsistencyClass(?p)^hasSlump(?p, ?x)^swrlb:greaterThanOrEqual(?x,220)->S220(?p)
ClassbyWeight(?p)^hasSpecificMass(?p, ?x)^swrlb:lessThan(?x,2000)->LightConcrete(?p)
ClassbyWeight(?p)^hasSpecificMass(?p, ?x)^swrlb:greaterThanOrEqual(?x,2800)->HeavyConcrete(?p)
Classification(?p)^Belong_to_normal(?p, ?s)^ClassbyWight(?s)->NBR_15823_1(?s)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,20)^swrlb:lessThan(?x,25)->C20(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,25)^swrlb:lessThan(?x,30)->C25(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,30)^swrlb:lessThan(?x,35)->C30(?p)
ResistanceClass(?p)^hasFeatureResistanceCompression(?p, ?x)^swrlb:greaterThanOrEqual(?x,35)^swrlb:lessThan(?x,40)->C35(?p)

Source: Author.

In the last step the creation of individuals is used to test the rules created in SWRL. If the inference engine manages to process the rules and generate knowledge through categorization according to the standard, it is implied that the built ontology does not present errors. In this standard 02 individuals were created to test the ontology through the SWRL rules, in which these rules classify the individuals according to consistency class, class per weight and resistance class, which are classes present in the ontology, as shown in Figure 52:

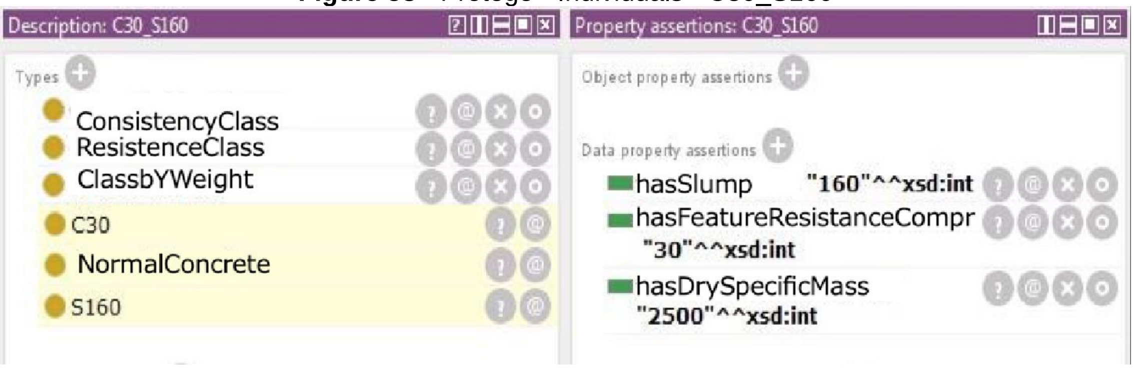
Figure 52 - Protégé - Link between Individuals and Classes - C30_S160



Source: Author.

The reasoning engine automatically identified in yellow (according to Figure 53) that one of the two individuals created, Concrete C30 S160 inserted in the resistance class C30, is considered a normal concrete (C) and has S160 slump.

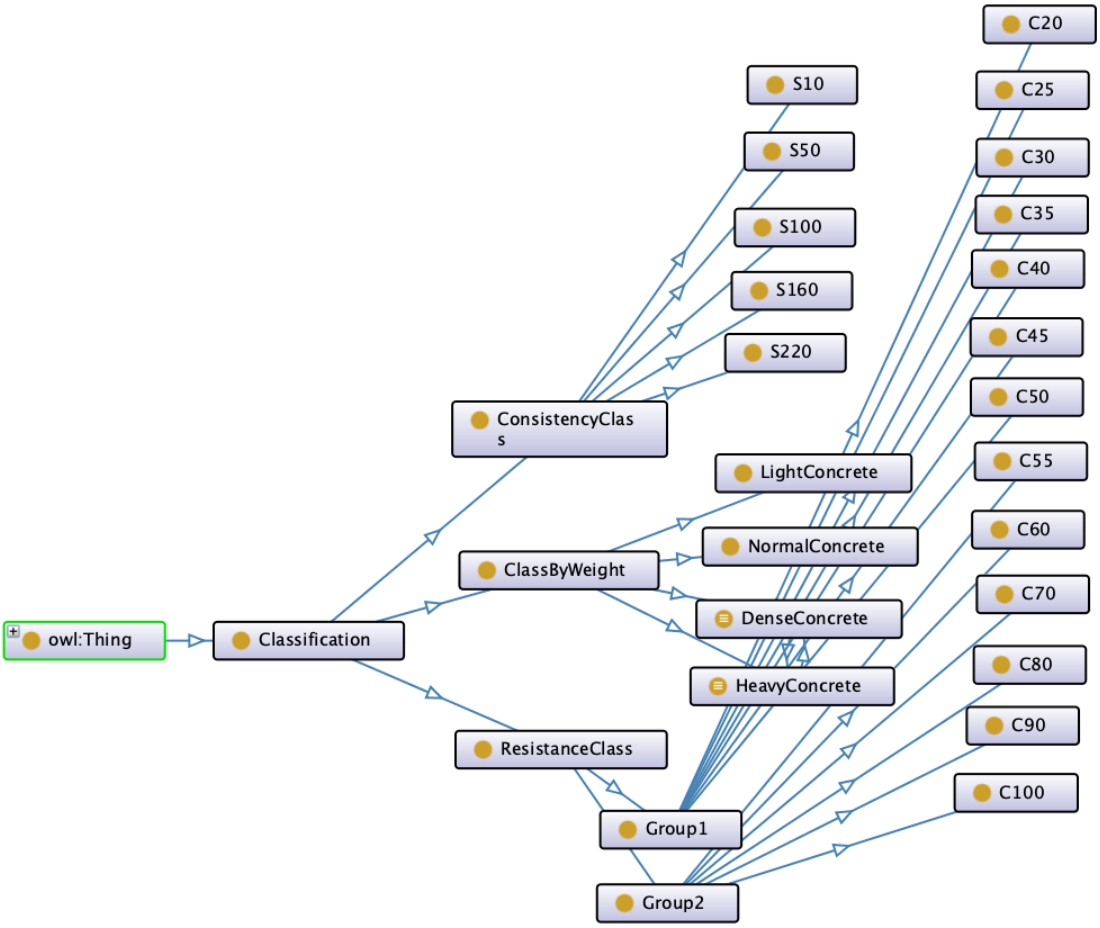
Figure 53 - Protégé - Individuals - C30_S160



Source: The Author

As a result of ontology, Ontograph presented the taxonomy of the cast-in-place concrete classes as shown in Figure 54 showing the possibilities of classification as inference engine responses. All other standards were mapped following the same methodology.

Figure 54 - Protégé - OntoGraph - NBR 8953/2015



Source: The Author

6.5 IFC 4 DATA EXTRACTION

The data extraction from IFC4 was performed through the IFC4 add2 HTML Documentation. It contains the subset of entities, properties, and concepts, that IFC specifies for the exchange of information between BIM systems.

IFC organizes its data according to the domains that are embedded in the information. For example, within the structural element domain “ifcFooting” represents foundations and has a property called “IfcFootingTypeEnum”, which represents the type of foundation that will be chosen by each user. The type of foundfation can be “Caisson_Foundation”, “Footing_Beam”, “Pad_Footing”, “Pile_Cap”, “Strip_Footing”, “Userdefined” or “notdefined”. When choosing the foundation type, in addition to the attributes of the structural element domain, each foundation type will also use attributes common to various domains, such as "shared property sets", "representations", "materials", "composition of elements". That is, each foundation type represents a complex link between all domains with some attributes of the Structural Elements domain.

Only the elements inside of domains of Structural Elements (“IfcStructuralElementsDomain”) and Structural Analysis (“IfcStructuralAnalysisDomain”) were cataloged in this project. Therefore the EXPRESS-G graphics present in the IFC4 add4 documentation were analyzed for each domain.

The IfcStructuralElementsDomain schema provides the ability to represent different types of building elements and to structure parts of elements that are generally structural in nature. In addition to the commonly used building elements already defined in the IfcSharedBuildingElements schema, this schema contains entities to represent foundation parts, such as foundations and piles, as well as some important structural subparts included in other building elements.

The EXPRESS-G chart example shows foundation types and pile types. It also shows as indicated in Figure 55, a surface treatment feature and an annulment feature that is a modification of an element that reduces its volume, such as adding “hollow” volumes within concrete structures, or chamfers. As shown in section 3.4, all data properties that are located on the dotted lines are taken from the EXPRESS-G graphs, except when they are “PredefinedType”, which lists the items pre-defined by IFC4. Users can choose any of the predefined alternatives, as well as use the option "Userdefined" and write a new option themselves.

According to buildingSMART documentation, IfcStructuralAnalysisDomain describes the structural analysis model for integrating the structural engineering domain. The focus is to ensure that structural engineering information is acquired and made visible to other related domains. Included in this domain are:

- Straight or curved structural elements, flat or curved structural surface elements, point, curved, and surface connections and supports.
- Load specification including point, curved, surface loads, temperature loads, their assignment to load groups, load cases, and load combinations.
- Specification of different structural analysis models to describe different aspects or parts of the building.
- Analysis results defined by forces and dislocations.

Figure 55 - IfcStructuralElementsDomain (1/4)

Source: The Author (2019), adapted from BuildingSMART (2018).

This domain has four EXPRESS-G charts. The first of them is composed of the structural analysis model, Structural Load Group, Structural Result Group and Structural Load Case.

The second and third EXPRESS-G graphs present the Support conditions, the connections between structural elements and structural members connected. The last EXPRESS-G graphic of Structural Analysis is about actions (such as forces, displacements, etc.) and reactions (support reactions, internal forces, deflections, etc.) that the structural elements cause in each other.

Finally, the mapping and extraction of data properties of all EXPRESS-G graphs related to the structural element domains and structural analysis was developed.

Table 18 - Data Requirements in IFC4 Documentation add2

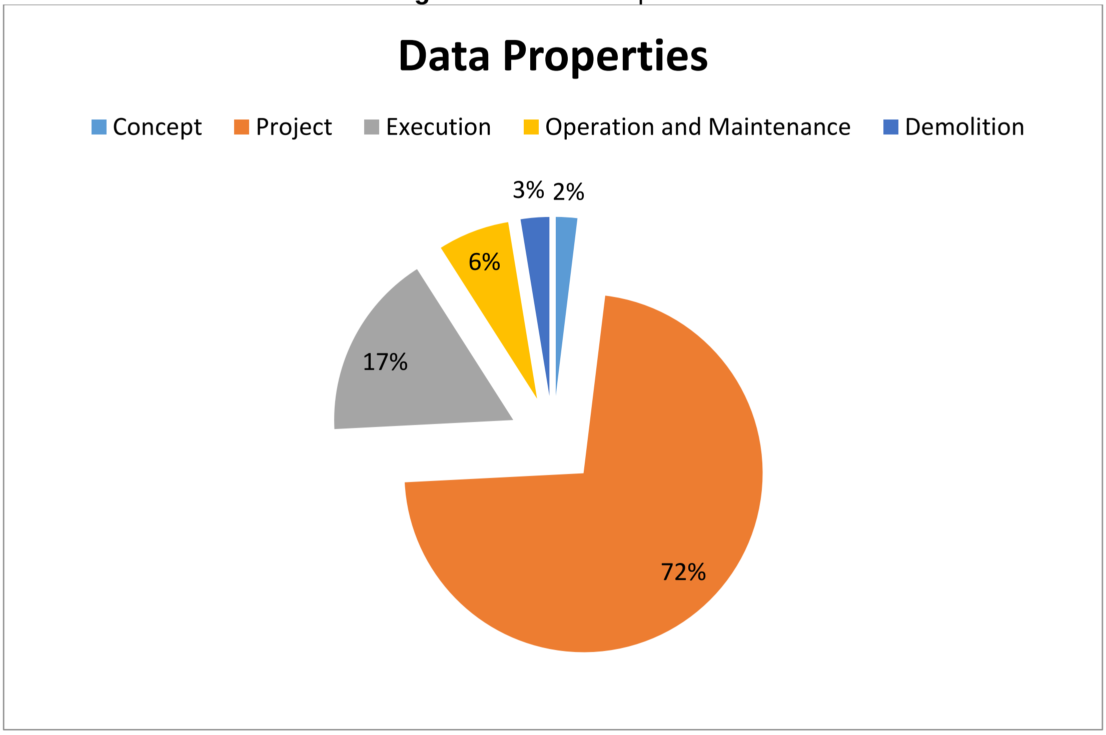
Domain	No.	Requirement	Domain	No.	Requirement
Domain of Structural Elements	1	Prefefined Type Of Footing	Domain of Structural Analysis	25	Predefined Type Of Analysis Model
	2	Predefined Type Of Pile		26	Orientation Of 2D Plane
	3	Construction Type Of Pile		27	Shared Placement
	4	Predefined Type Of Surface		28	Predefined Type Of Load Group
	5	Predefined Type O fVoiding		29	Action Type
	6	Nominal Diameter		30	Action Source
	7	Cross Section Area		31	Coefficient
	8	Bar Legth		32	Purpose
	9	Predefined Type Of Reinforcing Bar		33	Self Wheight Coefficients
	10	Bar Surface		34	Theory Type
	11	Mesh Lenght		35	Additional Conditions
	12	Longitudinal Bar Nominal Diameter		36	Applied Conditions
	13	Tranverse Bar Nominal Diameter		37	Supported Lenght
	14	Longitudinal Bar CrossSection Area		38	Condition Cordinate System
	15	LongitudinalBar Spacing		39	Axis
	16	Transverse Bar Spacing		40	Predefined Type Of Surface
	17	Predefined Type Of ReinforcingMesh		41	Thickness
	18	Predefined Type Of ReinforcingBar			
	19	Bending Shape Code			
	20	Bending Parameters			
	21	Predefined Type Of ReinforcingMesh			
	22	Mesh Width			
	23	Mesh Lenght			

Source: The Author (2019).

6.6 RESULTS

Regarding the scope of this research in cast-in-place concrete structures, the requirements were found and specified after the analysis of the IFC4 ADD2 standards and documentation. Regarding the number of requirements found in each lifecycle stage through the ontology tool, there were 03 in pre-project, 112 in Project, 26 in Execution, 10 in operation and maintenance and 4 in demolition. Figure 56 shows the percentages.

Figure 56 - Data Properties



Source: The Author (2019).

Regarding the data properties present in the IFC4 add2 documentation, 23 were found in the Structural Elements Domain and 17 in the Structural Analysis Domain. Requirements can be unique or collaborative. There are several phases of the project with information collaborative to the other phases of the lifecycle, such as, the “overloads”, which are used: to dimension the structure in the design phase, to size casts in the execution phase, to check the overloads in the operation phase, and maintenance and also must know them prior to the demolition/deconstruction phase of the structure.

As for the data properties found in the IFC4 add2 documentation survey, the data contained in the Structural Elements Domain (IfcStructuralElementsDomain) was described as the same way it was described in the created ontologies, such as for example “Longitudinal Bar Diameter” (LongitudinalBarNominalDiameter), which is a requirement that can be informed or calculated at the design phase and consulted at the execution stage.

In the requirements found in the Domain of structural analysis, the requirements identified are generalists, such as for example (ActionType), which has a predefined list of types of actions such as permanent actions, variable actions, extraordinary actions. However, in addition to those previously set by the program, the user can define new types of actions.

Altogether 23 different types of data properties were found in the Structural Domain and 17 in Structural Analysis, in addition to the predefined items within the data properties, which add 32 more in the Structural domain and 38 in the Structural Analysis domain, totaling 52 properties and 70 pre-defined items.

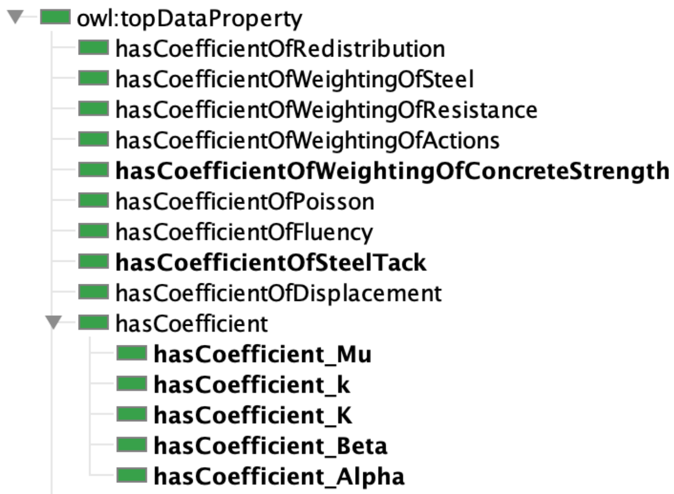
In conclusion, there are 155 data properties present in cast-in-place concrete structures ontologies and standards versus 52 in IFC documentation. These numbers do not portray that 2/3 of corresponding properties are missing within IFC, since IFC data properties are generalist and may comprise more than one data property. This comparison will be described next.

6.6.1 Ontologies X IFC4 ADD2 Comparision

In order to identify which data properties present in the 155 properties found in the standards are present in the IFC, a comparison is made item by item, correlating the context that each property has with its counterparts.

Context is important, as some data properties present in the IFC4 documentation are generalist, have multiple meanings and multiple analysis possibilities, such as for example “coefficient”, which is linked not only to one type of coefficient, but to all coefficients that apply values. A list of types of coefficient can be seen in Figure 57.

Figure 57 - Types of Coefficient present



Source: The Author (2019).

Still in the matter of context, the data property called “Purpose” present in the IFC4 documentation refers to a label, the term by which something can be referred to. It is a string that represents the name of something that can be interpreted by humans and must have a natural language meaning. For example, beam numbering is a label that the standard cites that should be carried out in structural design.

As a result of this item-by-item evaluation, in Table 19 the “standard” column shows the data properties present in project ontology and compares which IFC4 Requirement, if there is a correspondence. The comparison was developed for all stages, however only the project stage is shown here as a demonstration.

Table 19 - Comparison Table Standards x IF4 – Project

Phase	Standard	IFC4 ADD2
Project	hasCrackOpening	
	hasActions	ActionType
	hasPermanentActions	ActionType
	hasVariableActions	ActionType
	hasHeight_d	ConditionCordinateSystem
	hasHeight_H	ConditionCordinateSystem
	hasHeight_h	ConditionCordinateSystem
	hasNeutralLineHeight	ConditionCordinateSystem
	hasTotalStructureHeight_H	ConditionCordinateSystem
	hasTotalStructureHeight_h	ConditionCordinateSystem
	hasHeightd	ConditionCordinateSystem
	hasBeta_Angle	ConditionCordinateSystem
	hasaAlpha_Angle	ConditionCordinateSystem
	hasaDeclinationAngle	ConditionCordinateSystem
	HasFullSectionArea	CrossSectionArea
	hasCompressionRebarSectionArea	LongitudinalBarNominal-Diameter
	hasTractionRebarSectionArea	LongitudinalBarNominal-Diameter
	hasConcreteSectionArea	TranverseBarNominal-Diameter
	hasLeverDistsance	AppliedConditions
	hasResistenceCategory	ActionType
	hasCoverDepth	
	hasMu_Coefficient	Coefficient
	hasBeta_Coefficient	Coefficient
	hasAlpha_Coefficient	Coefficient
	hasK_Coefficient	Coefficient
	Hask_coefficient	Coefficient

	hasSteelAdherenceCoefficiento	Coefficient
	hasDeformationCoefficient	Coefficient
	hasCreepCoefficient	Coefficient
	hasPoissonCoefficient	Coefficient
	hasConcreteResistanceWeighting-Coefficient	Coefficient
	hasActionWeightingCoefficient	Coefficient
	hasPrestressResistanceCoefficiento	Coefficient
	hasSteelWeightingCoefficient	Coefficient
	temCoeficienteDePonderacaoDoAco	
	hasRedistributionCoefficient	Coefficient
	hasLength	SupportedLenght
	hasLengthofSupportParalleltoSpan	SupportedLenght
	hasSpecificDeformation	
	hasSpecificActiveRebar- Deformation	
	hasSpecificDeformationofPassiveRebar-Steel	
	hasPlumbDeviation	
	hasMaximumDisplacement	
	hasVibratorNeedleDiameter	
	hasRebarDiameter	NominalDiameter
	hasLongitudinalRebarDiameter	LongitudinalBarNominal-Diameter
	hasTransverseRebarDiameter	TranverseBarNominal-Diameter
	hasDiameterofSteelBarBendingPins	
	Hasdimension_a	ConditionCordinateSystem
	Hasdimension_ b	ConditionCordinateSystem
	hasParallelDimensionorDistanceTo- Width	ConditionCordinateSystem
	hasDistance_z	ConditionCordinateSystem
	hasDistance_e	ConditionCordinateSystem
	hasDistance_d	ConditionCordinateSystem
	hasDistance_a	ConditionCordinateSystem
	hasResilientCalculationStress	ActionType
	hasSolicitantCalculationStress	ActionType
	hasSpacingBetweenRebars	LongitudinalBarSpacing
	hasEccentricityofCalculationfromthe SolicitingStrains	ActionType
	hasaFactorThatDefinesSupport-Conditions	AppliedConditions
	hasStrength	ActionType
	hasCalculatedShearStrain	ActionType

	hasNormalReducedAdimensional-Strength	ActionType
	hasNormalResistantCalculationForce	ActionType
	hasNormalAppliedCalculationForce	ActionType
	HasCast	PredefinedTypeOfSurface
	hasHour	
	hasaSlimnessIndex	Coefficient
	hasWidth	ConditionCordinateSystem
	hasOneBeamWebWidth	ConditionCordinateSystem
	hasAgressionLocation	ActionType
	hasConcreteSpecificMass	SelfWheightCoefficients
	hasSmallerDimensionofaRectangle_a	ConditionCordinateSystem
	hasSmallerDimensionofaRectangle_b	ConditionCordinateSystem
	hasElasticityModule	Coefficient
	hasConcreteTransverseElasticity- Module	Coefficient
	hasMomentofInertiaoftheConcrete-Section	Coefficient
	hasBendingrMoment	ActionType
	hasFletorMomentof1order	TheoryType
	hasFletorMomentof2order	TheoryType
	hasAdimensionalReducedBending-Moment	ActionType
	hasBendingMomentResistantOf-Calculation	ActionType
	hasAppliedBendingMomentCalculated	ActionType
	hasNumber	Purpose
	temNumero	
	hasNumberOfCollumLines	Purpose
	hasParameterDuetotheNatureofthe-Gravel	Coefficient
	hasConcreteCompressionResistance ReducingParameters	AdditionalConditions
	hasPerimeter	ConditionCordinateSystem
	hasInternalHookCurvatureRadius	
	hasaMinimumRadiusOfGyrationofthe GrossConcreteSection	Axis
	hasSupportReactions	AppliedConditions
	hasResistance	ActionType
	hasRigidity_EI	Coefficient
	hasRigidity_r	Coefficient
	hasRotation	Axis
	hasPassiveAdherentRebarGeometryRate	LongitudinalBarNominal-Diameter
	hasLongitudinalRebarGeometricRate	LongitudinalBarNominal-Diameter

	hasMinimumGeometryRateof LongitudinalARebarsofBeamsAnd-Collumns	LongitudinalBarNominal-Diameter
	hasTemperature	
	hasTime	
	hasTensiontoCompressionIntheConcrete	ActionSource
	hasTensiontoTractionintheConcrete	ActionSource
	hasCalculationShearStress	ActionSource
	hasDirectShearStress	ActionSource
	hasTorsionalShearStressCalculation	ActionSource
	hasShearStressResistantCalculation	ActionSource
	HasNormalStressInPassiveRebars	ActionSource
	hasNormalActingStressCalculation	ActionSource
	hasSpan	ConditionCordinateSystem

Source: The Author

In the project phase out of the 115 properties, 13 ontology data properties were left without a correspondent within IFC4 add2.This comparison was developed for all stages of the lifecycle, presenting the following results: At the construction stage of a building, eight of the 25 data properties did not match in the IFC4 documentation. This represents 1/3 of the data properties of this phase. Following the lifecycle, the comparison of the operation and maintenance phase resulted in four data properties out of 10 that had no correlation with the IFC4 documentation. Finally, the comparative analysis of the demolition/deconstruction phase, presented correlation of all four data properties present in standard in the IFC4 file. This can be seen in Table 20.

Table 20 - Properties present in the developed ontology that have correspondence in IFC4.

	Total properties	**Properties with IFC4 correspondence**
Design	115	102
Construction	25	17
Operation and Maintenance	10	6
Demolition/Deconstruction	4	4

Source: Author.

6.6.1 Analysis of Results

Altogether, 25 ontology data properties were not represented IFC4 add2. This corresponds with BuildingsSmart´s already planned updates and improvements in In the domain of structural analysis and structural elements, especially in: Dynamic analysis, description of prestressed loads, finite element topology and deformations in structural elements.

In summary, the results point out that in the previously reported analysis items, all data properties that indicate deformation, expansions, or soil consolidation are not available in IFC4. In addition, there are temporal data properties such as date, time, period that are not present in the element domain or structural analysis, but are present in the common element domain of IFC4. Other unmatched items do not actually exist in the body of the IFC4 add2 documentation and are required to complete all phases of the lifecycle of a cast-in-place concrete structure building. The elements needed in IFC4 are:

- hasDeformation
- HasSpecificActiveRebarDeformation
- HasSpecificPassiveRebarDeformation
- hasMaximumDisplacement
- hasMaterialDeformation
- hasMaximumDeformation
- hasSoilSettlement
- hasTotalVerticalisplacement
- hasHour
- hasTime
- hasDateofInspection
- hasSlump
- hasCrackOpening
- hasNominalCover
- hasDiameterofVibratorNeedle
- hasPlumbDeviation
- hasDiameterofSteelBarBendingPins

- hasInternalHookCurvatureRadius
- hasPlumb
- hasQuantityOfReleaseAgent
- hasCracking

IFC4 add2 considers infrastructure elements such as blocks, footings, piles, and foundation elements with the superstructure elements. Foundation elements have not been analyzed in the cast-in-place concrete structures standards in this study, therefore some of this itens were present IFC4l but no on the ontology based on the standards.

Furthermore, since the IFC file enables the creation of new data properties directly by the user, semantic errors can be generated as the user can create a new property called “NewConcreteProperties” and by default the system uses “NewConcretsProperties”. This one letter difference is enough for the system not to understand that it is the same property. To avoid this kind of situation it is convenient for the IFC4 file to always have as many options as possible in its PredefinedTypes. This way, if all data property information cataloged in standards through ontologies had direct correspondents within the IFC documentation, it would prevent the user from having to enter new information into the system, increasing interoperability between systems as it would standardize property nomenclature.

6.7 CONCLUSION OF THE SECTION

A systematic literature review showed that one of the main characteristics of cast-in-place concrete structures that must be considered when it comes to interoperability of BIM modelers is their presence throughout the lifecycle. Because of this, there is a clear need for a single IFC file that holds all this information to improve interoperability between software and BIM agents. To verify if all available documentation data from the IFC4 File add2 file is sufficient to meet the information demand at all stages of the building lifecycle, a mapping of requirements properties is needed. To this end, ontologies were used as tools for requirements mapping and formalization of the knowledge involved.

In order to avoid loss of information, the ontologies were developed manually based on the Brazilian technical standards for cast-in-place concrete structures. The data properties of the ontologies were analyzed for all phases of the building's lifecycle. Some properties are repeated at different times of the cycle. It is also noted that the design stage is the phase that has the most data properties.

By comparing the data requirements present in the extraction through the ontologies and documentation of IFC4, most requirements have an associated structure within IFC4 add2, provided by the addition of the structural analysis domain in version 3x2. However, there are improvements to be added to this extension in order to ensure greater semantic interoperability of data, mainly concerning the deformation of structural elements. This research presents the domain of cast-in-place concrete structures, however, the methodology used for the creation of ontologies and extraction of data requirements can be adapted to the different types of structures and materials of civil construction, provided that there are relevant standards for them.

6.8 CHAPTER ALIGNMENT IN THE THESIS

This chapter presented the first part of the development and application of the framework, in which the development of the ontology for cast-in-place concrete structures was presented. In this chapter a comparative of the ontology from IFC models to an ideal ontology extracted from cast-in-place concrete standards is described. By comparing the data requirements present in IFC and the ontologies developed from the standards, it was noticed that most requirements have an associated structure within IFC. However, there are improvements to be developed to ensure greater semantic interoperability of data, mainly concerning the deformation of structural elements. This need for IFC standard improvement was demonstrated in the preliminary studies of this thesis.

When considering the lifecycle and the flow of data through it, it was noticed that some properties are repeated at different times of the cycle. It is also noted that the design stage is the phase that has the most data properties, concomitant to what had been seen in the SLR, where the design stage had received more attention from scientific papers, the same occurring for standards.

This application was developed for cast-in-place concrete structures, as was discussed in the framework. However, as also proposed by the framework, the method can be used for the creation of ontologies and extraction of IFC can be adapted to the different areas of the construction industry.

The ontologies will later be consumed to semantically annotate the processes. Then, these enriched processes can support decision toward sustainable efficiency for buildings through DMN. These ontologies my also serve to support data interoperability improvements via IFC.

7 PROCESS MODELS FOR CAST-IN-PLACE CONCRETE STRUCTURES LIFECYCLE

The construction industry, or from a broader perspective – the AEC (Architecture, Engineering and Construction), has several characteristics that distinguish it from other industrial activities, either for its temporary character, or for the fact that every construction is a unique product. One of the challenges to ensure interoperability is the great quantity of professionals involved in its entire lifecycle. According to Wong et al. (2015), effective communication between professionals, interested parties, and companies must occur throughout all phases of a construction work lifecycle.

The lifecycle of the AEC industry can be divided into the following phases — design, construction, operation and maintenance, and finally, demolition/deconstruction. Therefore, the range of such lifecycle is also challenging in terms of ensuring sustainable interoperability. (MULLER, 2019).

The design phase of a concrete structure, according to the NBR 6118 standard (ABNT, 2014), consists of a structural solution that must meet the requirements regarding the resistance to the applied loads, the intended service performance, and the durability in face of the environment. The execution of the structure is specified by the respective NBR 14931 (ABNT, 2004).

During the operation phase, the use of the structure over the years should always respect what was established in the design and by the construction through the owner's manual. Maintenance is also essential in this phase, once the omission or the poor maintenance plan execution may interrupt the operation, and thus even cause the premature demolition/deconstruction of the structure. The final phase of the lifecycle is marked by the demolition or deconstruction, which is the complete elimination of structure elements at a specific date and time. This entire lifecycle may present great environmental impact, and BIM can aid its management and improvement. (WONG; ZHOU, 2015; MULLER et al., 2019).

Given the importance of interoperability within the construction industry, the goal of this research is to measure, from a process perspective, the interoperability gain between the building lifecycle phases of a cast-in-place concrete structure and its external agents, using BIM in relation to the traditional process while in the current scenario. This assessment will be made through interoperability requirements associated with business prospects, processes, services and information, using Chen's framework (2008) as a base.

The lifecycle modeling of cast-in-place concrete structures was chosen due to its widely used function in civil works of all categories, covering a large area within the AEC. In Brazil, cast-in-place concrete is employed as one of the main construction systems, being that the Brazilian concrete standard NBR 6118 (ABNT, 2014) is recognized by ISO 19338:2014 (International Organization for Standardization) as a standard that can be used anywhere in the world.

The research is structed as follows. First, the lifecycle in the construction industry and BIM importance in it are described. After that, the methodology is presented and in section then the literature is explored even further, presenting the documents used to develop processes. The, the assessment of the processes is presented on section. Finally, in the conclusions are presented.

7.1 LIFECYCLE IN THE CONSTRUCTION INDUSTRY

The great particularity in the construction industry resides in the lifecycle of its products. A construction may last for an undetermined period, as long as it undergoes proper maintenance. Reazei et al. (2019) describes the construction work lifecycles as quite long, and with extensive environmental impact, in order of decades. It may comprise several phases such as operations setup, disposal, rehabilitation, designs, construction, use, and maintenance.

In this regard, the author also says that these phases are conducted by independent agents, with different roles and objectives in the construction work. In this study, the following phases were adopted for the cycle and life of an edification, according to Wong (2015): I) Design, II) Construction, III) Maintenance, IV) Operation and V) Demolition/deconstruction. Such phases are described next.

7.1.1 Design

The first stage of a construction work considered for this analysis is the design phase, comprising since the most preliminary studies until the actual delivery of the elements planned in the scope. According to BuMamdan et al. (2019), throughout a construction design phase there is great room for performance improvement, thus promoting cost reduction. Great integration among professionals is therefore needed in this phase in order to improve the construction’s performance in all related areas.

The construction market is no longer interested in simply adopting tools, but now implements the BIM as a guarantee of success in the accomplishment of projects (WON; LEE, 2016). That is because, according to Abdelhady (2013), the BIM also supports the study of more agile and sustainable alternatives, resulting in a better cost benefit and optimizing the construction stage.

From all the stages of the lifecycle, the design stage is the one with the most emphasis on academic studies and researches, mainly due to the fact that it is the area that will influence all other throughout the lifecycle (MULLER et al., 2019).

7.1.2 Construction

A high-quality construction may be the result of a well-conducted and information-rich design that supports its execution. In this scenario, the lack of adequate integration between the construction and design phases could give rise to. The lack of compatibility between the structural elements and the other complementary designs can increase a buildings cost and cause extensive trouble. (HU et al., 2019)

The execution of a building concrete structure is one of the most relevant stages in the construction process, upon which lies the critical path of all subsequent activities of a work. The execution of this structure, in a wrong or inappropriate way, impacts not only on its delivery timeframe, but also on its performance, once it makes easier the outbreak of possible pathologies such as corrosion of rebars in the future (GEIKER, 2012). That is to say, the entire lifecycle is affected when the edification is poorly conducted, reinforcing the need to bring all stages of the lifecycle closer, in favor of the quality of the structure to be executed.

In the work planning stage, the junction of a complete database with a high level of detailing makes the anticipation of occurrences that may negatively affect the timeframe possible. That means, agile responsiveness is guaranteed, correcting, preventing and relieving possible deadline- and cost-related losses. These factors will ensure the high construction performance (ATKINSON, 1999).

Volkov et al. (2016) claim that when deploying the building information modeling tool for an effective construction management control system, the assignment and distribution of functions among participants in their respective phases of the process is crucial. Likewise, authors support that the representation of the information flow among participants is essential, as well as the functions assigned to them and the process progress.

7.1.3 Maintenance and Operation

Facilities management is a multiple-domain issue that includes financial accountability, building maintenance, installations management, human resources, asset management, and code conformance, affecting different interested parties in different ways (CURRY et al., 2013). Furthermore, the team that normally designs and raises the building is not the same one that carries out the building maintenance, thus resulting in the need for adequate storage of maintenance data, which can be no through cloud-based BIM (REDMOND et al., 2012).

One of the greatest difficulties faced in planning and determining solutions for maintenance operations is the lack of background information about the edifications, for instance: specifications and characteristics of the structure, a fact sheet with the maintenance history, a list of previously involved professionals and possible specialists that may coordinate future repairs, no traceability of the components that were held and those still requiring assistance.

This way, maintenance management lacks a database that can provide and store information about the edification elements. Such base would provide access to data related not only to the current phase of the construction lifecycle, but also to previous phases, and even to the simulation of future experiments (NUMMELIN et al., 2011).

Volk and Schultmann (2014) point out that the BIM provides a database serving both as a repository and as a data enabler agent for management and planning of maintenance procedures of existing and new edifications.

7.1.4 Deconstruction or Demolition

The demolition phase of a building lifecycle needs to approach some questions that might guarantee an appropriate planning for the demolition/deconstruction execution. The British Standard (2011), points out that before the mobilization of teams for the demolition of a structure, the planning and analysis of the existing designs is required, as well as the environmental footprint and the impact on the neighborhood.

For this last stage of the lifecycle, it is important to have means to obtain the designs, specially the structural ones, so that a safe demolition/deconstruction can be conducted. It is observed that despite the temporal distance between design and demolition/deconstruction, it is necessary that information remains accessible throughout the entire lifecycle, maybe even with the same cloud-based BIM approach proposed for the maintenance stage (REDMOND et al., 2012).

Is this way, NBIMS (2007) mentions that the BIM is a virtual model composed of geometrical characteristics directly linked to a database, thus providing data related to other phases of the construction lifecycle. Information contained in the model and vastly used in the design and construction phases can be recycled for the demolition waste management, resulting in more efficient planning and execution of the structure demolition (HAMIDI et al., 2014).

7.2 METHODOLOGY

The methodological approach in this research is divided into three main stages, namely Exploration, Development, and Analysis & Conclusion. Based on the Design Science Research (TAKEDA, 1990), Figure 58 shows the method used to assess interoperability under the process perspective, serving as a guide of what will be presented in this study.

The development stage includes the modeling of BASIC and REFERENCE processes. The basic processes consider the traditional methods of the construction industry without BIM or low BIM use. The reference process model develops an ideal scenario in the industry considering high or full BIM use.

Stage 1: Exploration

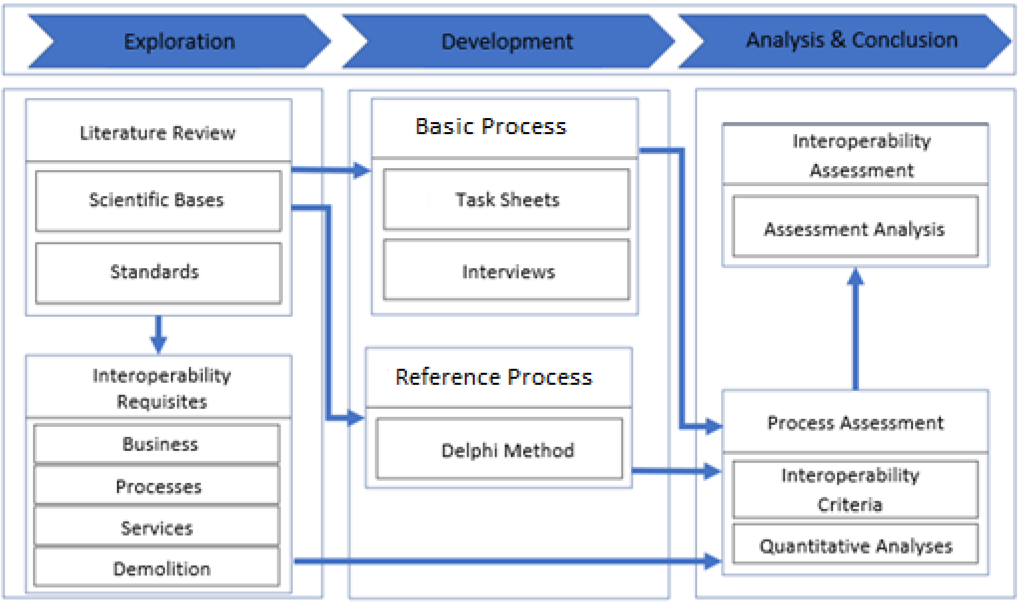
Literature review was based on the Science Direct, in which definitions and interoperability, BIM, and process state-of-the-art were found. In addition, a wide review of concrete structures standards was conducted. Such literature and standard review aims to identify which elements must exist in order to ensure interoperability of a cast-in-place concrete structure lifecycle.

The identified elements become interoperability requisites and base for the assessment, as presented in the next stage. Still in this stage, interoperability requirements were defined:

- Business Requirement: compatibility with existing standards for each lifecycle phase, once the technical standards must be applied to the processes regardless their size or work method of the company or specialist under analysis.
- Process Requirement: The detailing level of the lifecycle business processes can influence greatly in intereoperability and in the collaboration of processes. (ALEMANY et al., 2010).
- Service Requirement: communication among internal and external agents in the lifecycle for the information acquisition, defined as in Chituc et al. (2007).

Information Requirement: information fragmentation throughout the lifecycle as perVerdanat (2006), Howard (1989) and Eastman (2001).

Figure 58 - Methodology



Source: Author.

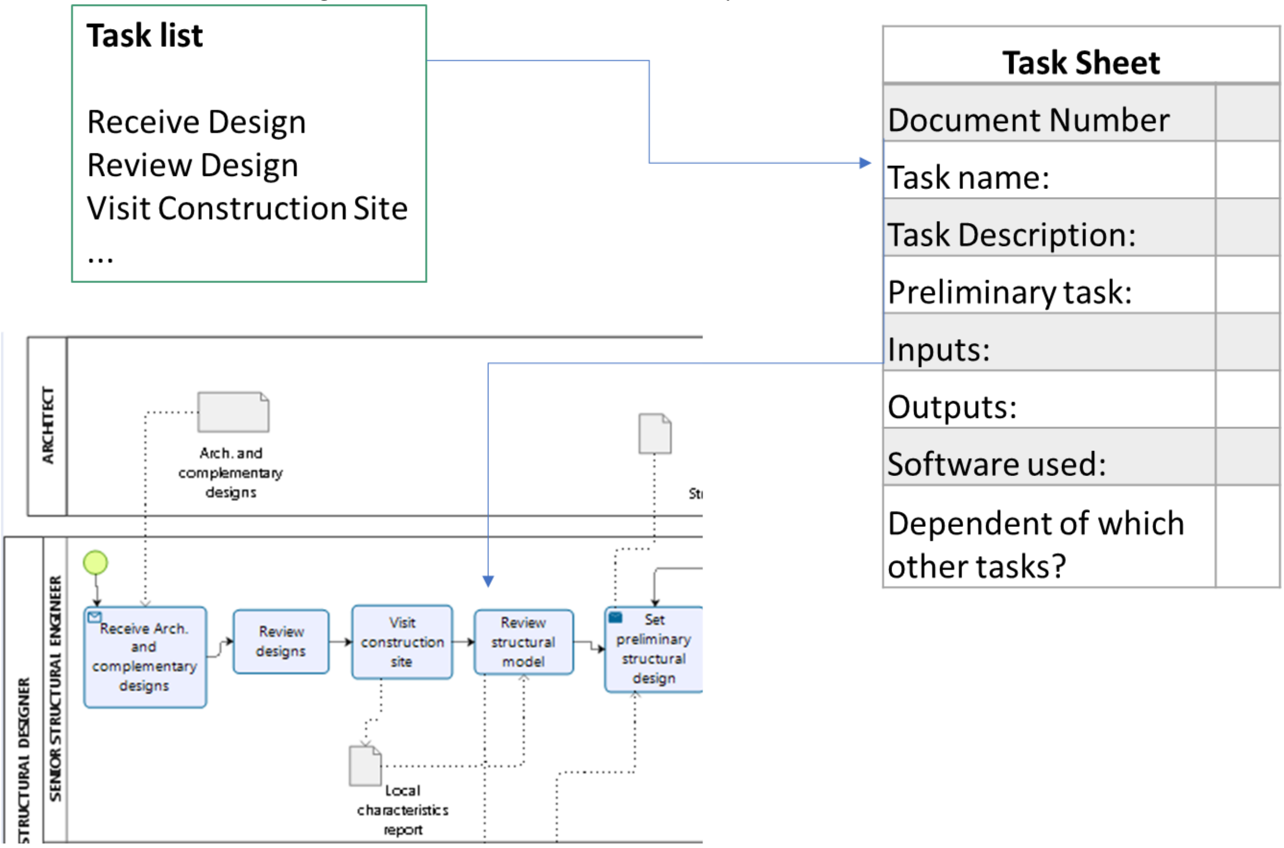
Stage 2: Development

Cast-in-place concrete structures were chosen to illustrate the method of process modelling and assessment due to its comprehensiveness throughout the lifecycle of a building. Also, concrete is one of the most widely used construction materials in the world, with a yearly consumption of about 11 billion tons, and behind water consumption only (IBRACON, 2009). The cast-in-place concrete structure is the link between concrete and steel, and whose aim is to support the forces stemming from traction and compression, i.e., in general, concrete is resistant to compression and steel to traction (PARK; PAULAY, 1975).

According to the NBR 6118:2014 standard, cast-in-place concrete elements are those that, in order to obtain the necessary resistance for an appropriate structural performance, depend on the adherence between concrete and the steel frame, and whose initial stretching is applied just after the materialization of the raw components junction.

The development stage includes the modeling of BASIC and REFERENCE processes, which are mapped with task sheets and the Delphi method, respectively. The creation of the BASIC model is carried out in two phases – the first phase regards the development of the task sheets with information and characterization of the company, existing tasks, and resources assigned accordingly. In its turn, in the second stage the task sheets become surveys sent to the companies involved in each phase of the cast-in-place concrete structure lifecycle. Figure 59 show an example of the task sheet and its use. If this sheet is sent directly to the company without the researcher to provide explanations, a small explanation can be added to each section.

Figure 59 - Task sheet for the basic process models.



Source: Author.

For the REFERENCE process framework using the BIM the Delphi Method was used, once it is an interactive research and survey process that aims to collect knowledge and assumptions about the development of a process or topic under study. Processes based on the literature review were modeled for the design, construction, maintenance, and demolition/deconstruction phases of the lifecycle of a cast-in-place concrete structure, validating questionnaires in two rounds with BIM specialists and professionals.

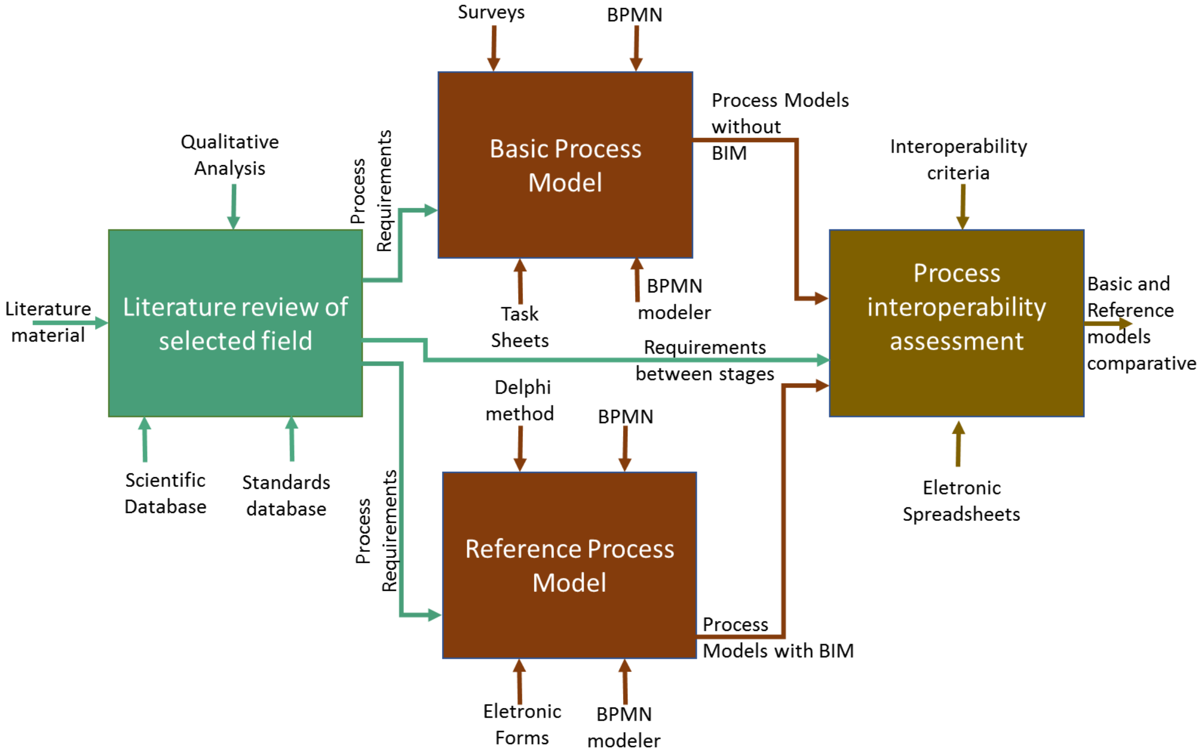
Stage 3: Analysis and Conclusion

Quantitative criteria based on interoperability requisites for each one of Chen´s (2008) concerns were established, and then, based on such criteria the two processes of the BASIC and REFERENCE lifecycle were assessed. The objective consists in evaluating the interoperability gain under the process perspective – the REFERENCE process in relation to the BASIC process. The methodology used to assess interoperability is based on the creation of criteria and the identified requisites provided by the standards. Such criteria allowed the interoperability quantitative definition of the

BASIC and REFERENCE processes. After such analyses, results were normalized to determine a final value to measure the interoperability gain to adopt the BIM. Conclusion of such assessment will show which of the two processes (BASIC or REFERENCE) is more interoperable, quantifying such difference.

The methodology procedural steps can be seen in Figure 60, that present 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.

Figure 60 - Methodology IDEF0 model.



Source: Author.

7.3 INTEROPERABILITY IN THE BIM LIFECYCLE

According to the ISO/IEC 33001:2015 standard, interoperability is the ability of two or more systems or components exchange and make use of information. The Australian Department of Finance and Administration (2007) defines processes, through its framework, as a group of tasks or operations needed in order to achieve objectives in a company. In this scenario, the trigger to pursuit interoperability of processes is the great need for collaboration among all participants.

This way, Xu et al. (2009) mention that, in order to improve process efficiency, a high level of collaboration among all professionals and companies involved is required. Such collaboration, however, can only be achieved if all related processes are interoperable. That means, in order to achieve the quality needed for any building component, interoperability within its lifecycle process must be ensured, and thus the identification of existing issues plays an important role. Under this perspective, Xu et al. (2009) say that one of the first steps consists in identifying the interoperability requirements.

Interoperability issues can occur in different ways within the lifecycle processes of a cast-in-place concrete structure – process intrinsic difficulties, inadequate communication among the agents, communication failure among the software used, adaptation issues with the related standards, among others. These issues can be categorized by using the Chen framework (2008) - Framework for Enterprise Interoperability (FEI), adapted by Cestari et al., (2018), in which the concepts of barriers and concerns are defined as illustrated in Table 21.

Table 21 - Interoperability concerns

	Conceptual	Technical	Organizational
Business	Business models, enterprise visions, strategies, objectives, policies	Infrastructure, technology	Work methods, business rules, and organizational structure.
Process	Processes models	Tools supporting processes modeling and execution	Responsibilities, Process management and rules
Service	Services models	Tools supporting services and applications	Responsibilities, service and application management and rules.
Data	Data models, (semantic, syntax).	Data storage and exchange devices	Responsibilities, data management and rules.

Source: Chen, 2008

Interoperability barriers are divided in:

- Conceptual: related to the syntax and semantic differences in the information transmission.
- Technological: related to the information technology incompatibility, i.e., issues regarding storage, exchange, processing, and communication using computers.

- Organizational: related to definition of responsibility or authority for each task and the incompatibility among the organization structures. Organizational interoperability is crucial, given that in each phase of the lifecycle different companies and teams take part in processes and require a wide range of information, in addition to the common normative understanding.

7.3.1 Business Concerns

Chen (2006) defines business interoperability as the effort involved in adjusting methods, laws, standards, and culture so that businesses can evolve along with other companies. When applied to the lifecycle process of a cast-in-place concrete structure, it can be observed that there are specific standards to be followed in each of the cycle's stages.

Cast-in-place concrete structures play a key role in all phases, given their structural function, and thus the building quality is deeply dependent on the quality of its structure. In this context, the lifecycle phases of a structure is interpreted as "organizational entities", as defined by Chen (2006), once each stage regards different tasks and usually involve different companies executing the different phases.

The NBR 6118 (2014) standard defines the minimum requirements that a cast-in-place concrete structure execution must observe during construction and service:

i. Resistance capacity: safety against rupture.

ii. Service performance: capacity of the structure to be used for its intended function throughout its life time, without material loss or damage that impact such utilization.

iii. Durability: capacity to resist to the environment for which the structure was designed.

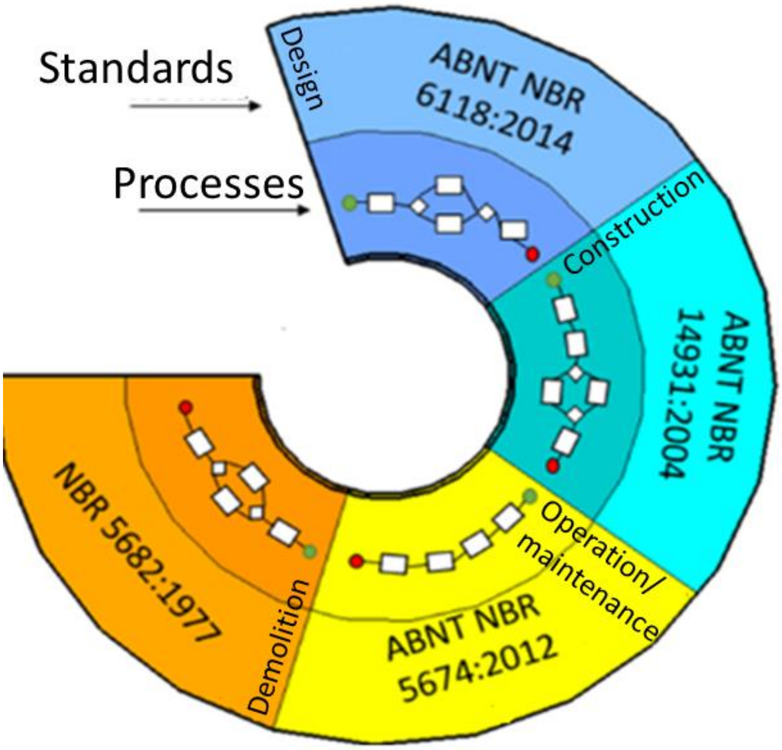
In order to fulfill such requirements, and thus the quality criteria imposed, all phases of the lifecycle must comply with the business interoperability concern. The 6118:2014 standard clearly states that durability of concrete structures depends on the cooperation and commitment of all lifecycle phases.

By analyzing the most important Brazilian standards for each lifecycle stage, it is possible to observe several criteria that highlight the need for interaction among other cycle phases or external professionals (called "external agents" in this work) for the achievement of quality and safety, as shown in Figure 61. The standards chosen for each stage of the lifecycle were:

- Design Stage: ABNT NBR 6118:2014.
- Construction Stage: ABNT NBR 14391:2004.
- Maintenance Stage: ABNT NBR 5674:2012.
- Demolition Stage : NBR 5682:1977

In the following sections, each of these standards will be discussed and detailed, presenting requirements, identified activities, agents involved and so on.

Figure 61 - Lifecycle Standards



Source: The Author

Design – NBR 6118

In Brazil, the main standard applied to cast-in-place concrete structures is the ABNT NBR 6118, which in 2015 was recognized by ISO (International Organization for Standardization) as a technical standard that complies with international requisites, and thus can be used worldwide.

Based on the current NBR 6118 revision, approximately 28 tasks and 9 agents were identified as external to the design stage and yet necessary to keep the construction quality in accordance with durability, performance, and resistance criteria.

For instance: the responsible for each operation in each subject and their respective design, approval, and recruitment tasks.

Construction – NBR 14931

The current Brazilian standard for the execution of concrete structures is the ABNT NBR 14931:2004. This standard lists the requirements for the execution of a concrete structure, assuming that projects were designed according to the standard mentioned in the previous topic.

Based on the current standard revision, 18 tasks and 2 agents were identified as external to the construction stage and yet necessary to keep the construction quality in accordance with durability, performance, and resistance criteria. For instance: the execution of each stage of the project, installations, assembly, and receipt in the construction work.

According to the standard, the only lifecycle phase that requires interaction is the design, more specifically the need of a design, specifications, and information provided in this phase. Also, it is possible to identify divergences about requisites for the design stage pointed out by the execution standard, but not by the design standard itself. For instance: work site specifications, impermeabilizations, quality plan for the structure execution, firefighting installations.

The design standard mentions that the construction stage is responsible, together with the design stage, for creating the operation and maintenance manual, though not mentioned in the execution standard. The document that must be developed and attached to the manual in the construction stage is the “as-built”.

Maintenance – NBR 5674

Building maintenance is standardized by the ABNT NBR 5674:2012 standard. It defines scopes for the maintenance process of the building elements, including its structures. The standard claims that it is important to overcome the culture that defines edification delivery is concluded as the construction process is over, once the building and its structure are designed to serve users for many years, providing services and resisting to environmental agents.

The need for maintenance results from the fact that disposable edifications are unconceivable, given their high value as well as the environmental footprint involved.

Based on the current standard revision, 10 tasks and 1 agent were identified as external to the maintenance stage and yet necessary to keep the construction quality in accordance with durability, performance, and resistance criteria. Some of these tasks interact with the design, construction, and operation stages.

The maintenance and operation stages are deeply linked, once maintenance is a reoccurring process throughout the entire life time of the building, while operation keeps the maintenance records to support future interventions in the structure.

Demolition – NBR 5682

The demolition standard used in this study is the NBR 5682 from December 1977. It establishes the requisites for contracting and licensing of demolition work as well as procedures and preventive measures to be considered prior to and after demolition works and methods.

This standard was valid through November 2008, after which it has been cancelled and no successor released so far. Foreign standards can be adopted substitute it, or even other standards that focus on related areas.

Based on the revision from 1977, 6 tasks and 2 agents were identified as external to the demolition stage and yet necessary for a safe execution. The lifecycle phases that interact with this one are the design and construction stages. Demolition is at the end of the structure lifecycle. In this stage, the required interaction with the previous phases, as per the standard, consists of the structural designs and the "as-built" design. In spite of having just few interactions, attention must be paid to such interoperability, given the long period of time from the beginning through the conclusion of the structure.

7.3.2 Process Concerns

This interoperability concern aims at making several processes work together so as to define the sequence of tasks to fulfill the needs of a company. Besides the internal processes, interoperability with other companies or professionals is necessary in order to create a single process (CHEN, 2010).

For such collaboration to take place, however, participants are required to be aware of their tasks as well as information they need to provide. O'Brien et al. (2007)

mention that the construction industry imposes challenges regarding integration among companies due to restrictions commonly related to the short-term aspect of the organizational environment in question. In other words, companies in the construction industry cycle may interact during a specific work only, and they often employ different practices. One aspect pointed out by the author regards the existence of a high level of detailing in the companies' business processes. This is necessary so that it is possible to detect in which part of the process information is provided and who is responsible for it.

Such detailing can be done through the process mapping in the discussion section. It is possible to say that the main goal of the process mapping consists in providing subsides and information required for the study and understanding of the existing processes. BPMN and BIM can be used to facilitate management, however, there is a lack participation in the industry in this area (WU et al., 2014).

This way, one of the process interoperability requisites regards the business process detailing level of a cast-in-place concrete structure lifecycle in terms of successfully representing the information flow and relations among the involved agents. In so doing, the lifecycle process analysis is possible (traditionally and using the BIM), indicating which process is the most detailed, i.e., providing a diagnosis of the understanding of companies and professionals about the process on which they act.

7.3.3 Service Concerns

Interoperability under the service concern is related with how to identify, arrange, and make several independent functions work together, i.e., comprising not only the use of computers, but also the organizational functions within the companies. One of the main points that can be affected by the interoperability of services refers to the communication infrastructure. As per Chituc et al. (2007), a messaging system is required for the communication among companies, thus ensuring that information is exchanged appropriately. Such information exchange system can be created from a database, in which companies and professionals can obtain information without necessarily making calls or sending e-mails.

In this context, interoperability of services represents a reduction in the need for direct communication among participants in order to obtain information. Muller et al. (2017) demonstrate how such data repository operates within a design process of a concrete structure, suggesting that all information provided throughout the process is concentrated into a place called BIM repository. In their turn, participants of the modeled process make use of the data repository directly, instead of communicating with each other to get such information.

Therefore, in the context of a concrete structure lifecycle, the service interoperability requisite will be considered in the analyses of the two process models (with and without BIM), in terms of how many times an agent needs to communicate with others and how many times such communication could be replaced by a service such as the BIM repository.

7.3.4 Information Concerns

It is the capacity to find and provide information from different bases, either computers, software or devices in different locations. The integration of information within processes in companies was for a long time considered an information technology issue only. But, according to Vernadat (2009), the actual challenge resides in providing the right information at the right time. This challenge is even greater inside the construction industry because, as said previously, the lifecycles in a construction work are quite long, this time dimension makes information integration more difficult throughout this cycle (JIAO et al., 2013).

One of the reasons pointed out by Howard (1989) is that, even though every phase of the lifecycle has its own specialist, they continue to exchange information and take decisions in the same way as a century ago. In other words, they keep using sketches and paper documentation, not bearing in mind the change in the information exchange method employed by companies and lifecycles in the construction industry.

Howard (1989) also says that in 1989 it was common for professionals and companies to own powerful design, calculation, and graphical analysis software. However, regarding the information exchange between professionals and companies of the lifecycle, information passed on through paper documents that would degrade and get lost during the lifecycle timespan. If there would be any need for maintenance or even demolition/deconstruction of the structure, it would be less probable to have any available information. On the same hand, Pärn (et al. 2018) mentions that there is some difficulty in obtaining information from other phases or areas of industry, since information is fragmented among different agents.

With the utilization of the BIM, where Eastman (2011) described a change in the industry – the use of 2D documentation and paper was replaced by a single model, created in a digital environment through a collaborative work method in all phases of the edification.

Based on that, the information interoperability requisite is interpreted as the number of documents fragmentally generated. Therefore, analyzing the traditional and the BIM-based process, the number of digital or paper documents is measured, separately generated and not aggregated in a single file, as proposed by Eastman (2011).

7.4 INTEROPERABILITY ASSESSMENT APPROACH

This section will present the development of the BASIC and REFERENCE processes. The basic processes consider the traditional methods of the construction industry without BIM or low BIM use. The reference process model develops an ideal scenario in the industry considering high or full BIM use. Then an interoperability assessment is performed for all processes, presenting in which areas interoperability was improved with the use of BIM.

7.4.1 Modeling of the BASIC Processes

As previously mentioned, the methodology adopted in the modeling of the basic processes is founded on the use of characterization and task sheets for the process definition. An example of this Sheet model is presented in the appendix.

Professionals of companies acting on each stage of the lifecycle of a cast-in-place 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 all tasks that take part in the Design, Construction, Maintenance, and Demolition/deconstruction phases. In this study, 4 distinct companies were considered:

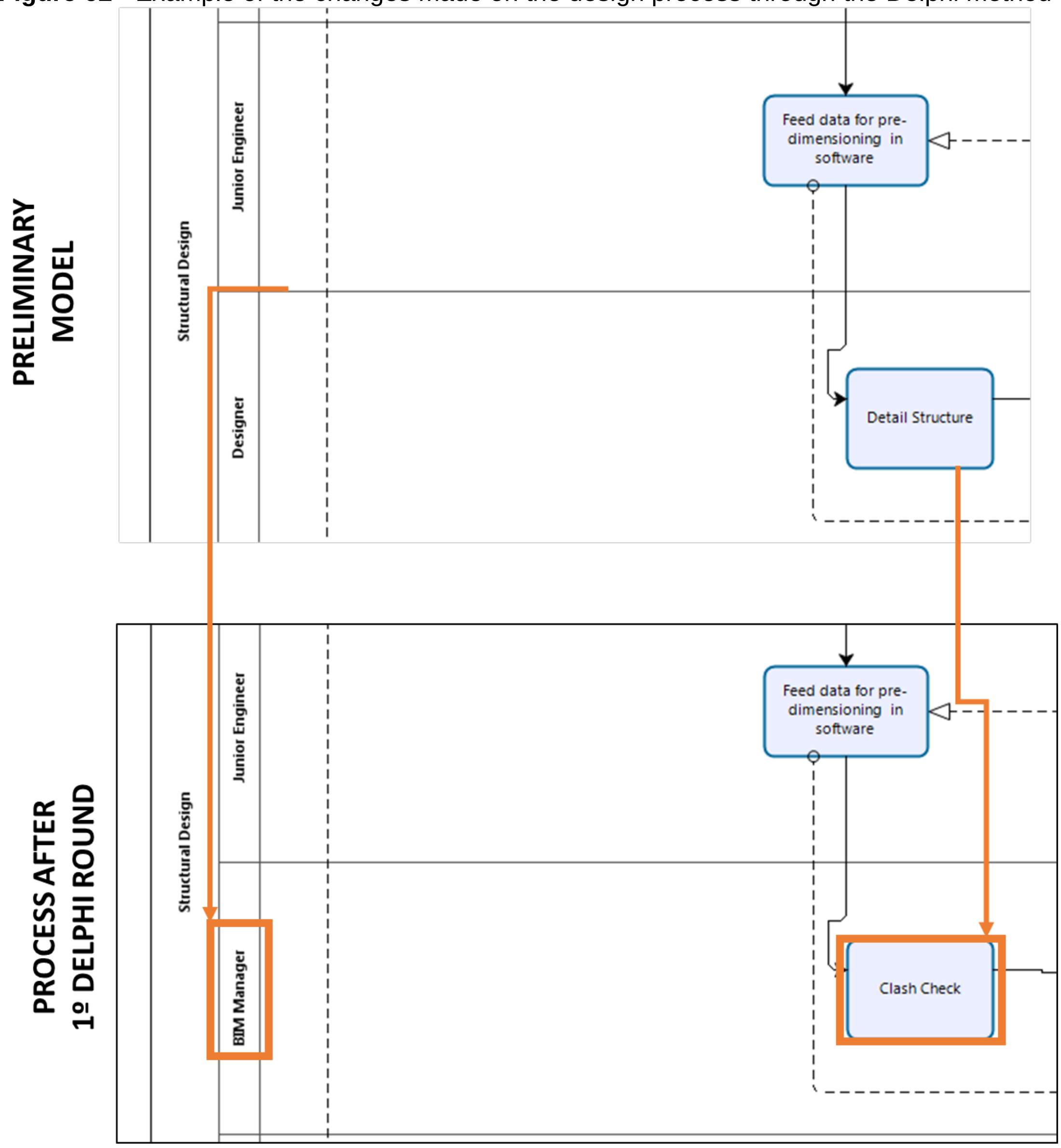
2 small-sized for the design and demolition stages interview, 1 micro-sized for the maintenance stage, and 1 large-sized for the construction stage.

This mapping did not aim to propose a lifecycle process standard that serves all company sizes, but provide a diagnosis about how some companies taking part in the cast-in-place concrete lifecycle work. The methodology in question, however, can be replicated to any company in the cycle, no matter its size. Figure 3 illustrates the modeling of the design stage.

7.4.2 Modeling of the REFERENCE Processes

For reference processes, the Delphi method was used for validation and improvement of the preliminary proposals. The preliminary processes were developed based on the literature, including all processes in the cast-in-place concrete structure lifecycle using BIM. 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 Process, Construction, Maintenance, and Demolition areas, and just after three rounds the specialists reached a common understanding. Figure 62 shows an example of the changes made on the design process through the Delphi method, where clash detection was facilitated and a BIM manager lane was included.

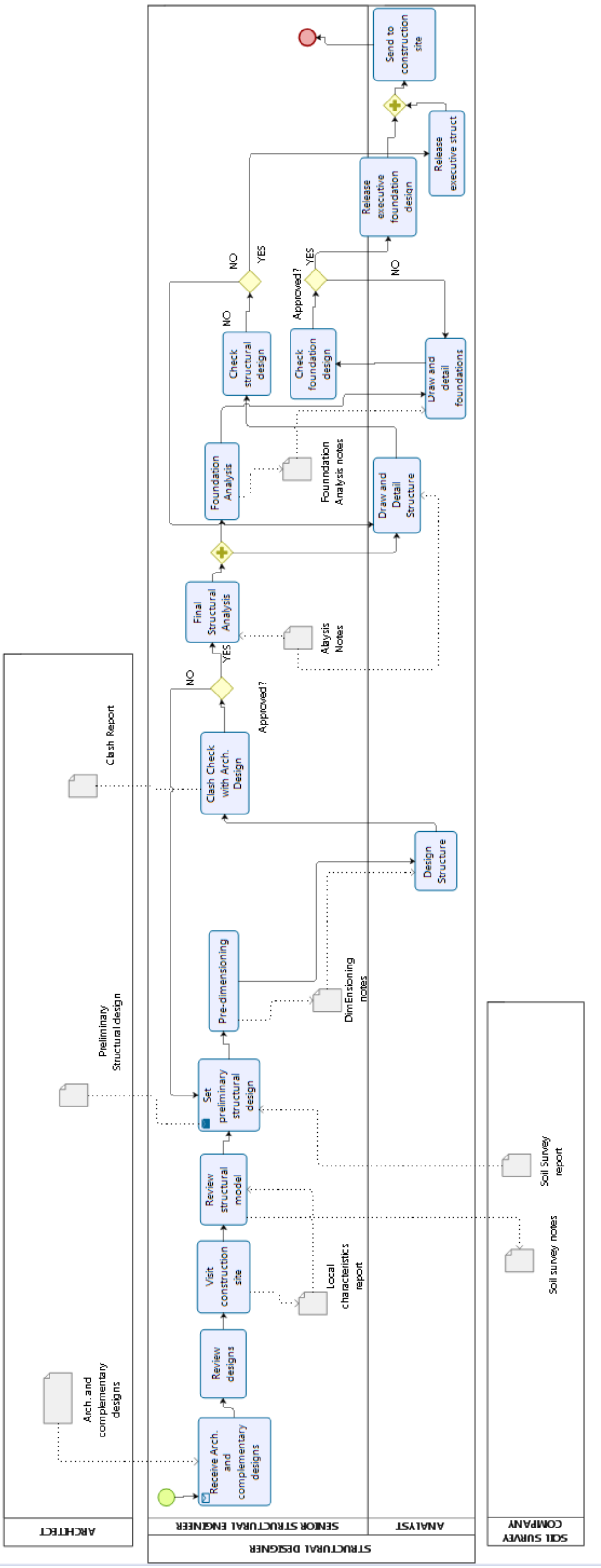
Figure 62 - Example of the changes made on the design process through the Delphi method



Source: Author.

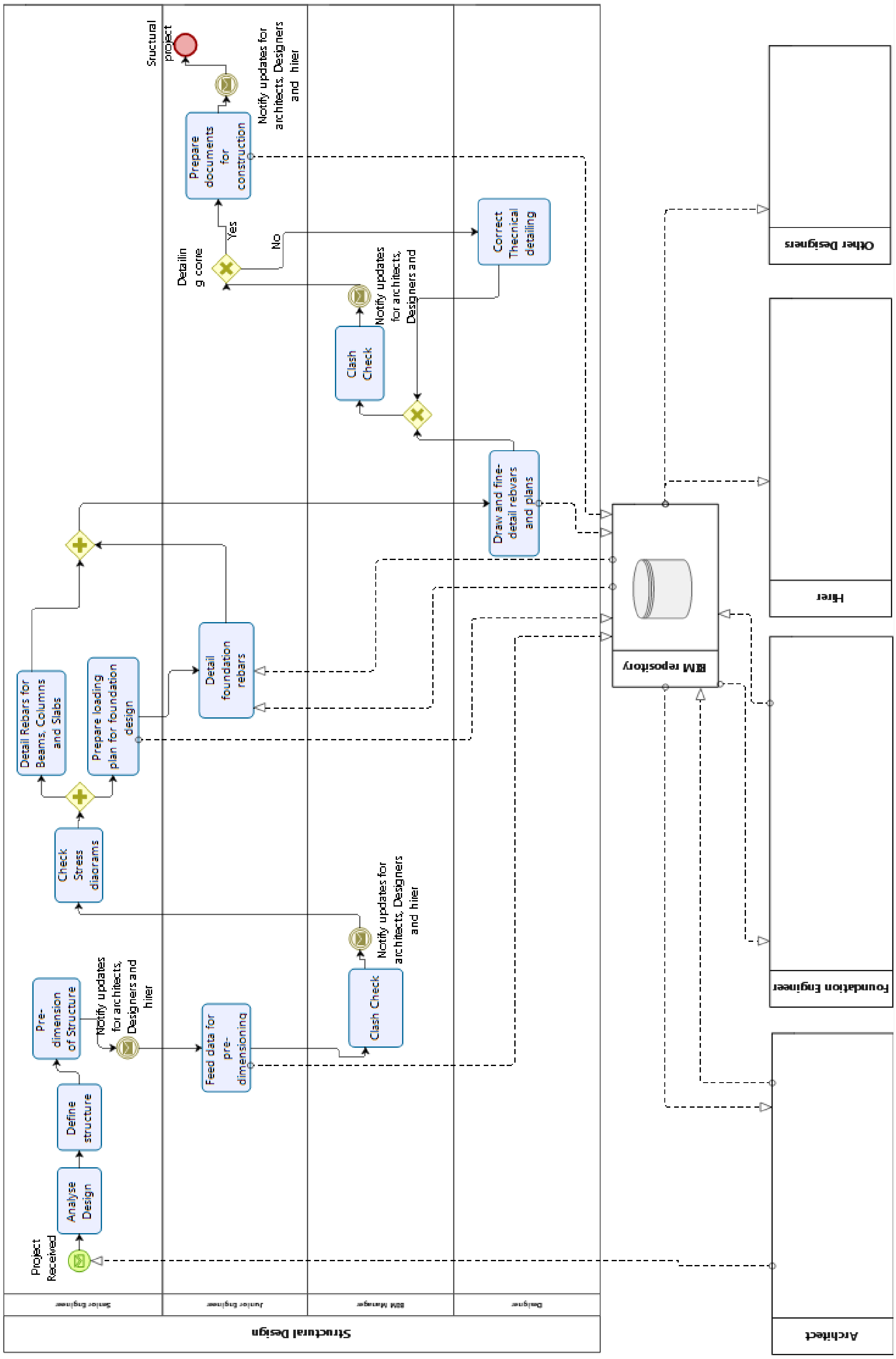
As a matter of fact, most changes suggested in the presented processes are not related to the BIM utilization. From a total of 20 changes recommended by specialists, only 6 are related to BIM, being that from these, only 2 propose significant changes – as in the design process that foresees the insertion of a professional called BIM Manager, and yet pursuing the function to make the structure and other processes compatible. Figure 63 illustrates the modeling process of the design stage in the Delphi final version.

Figure 63 - Design Stage - BASIC MODEL



Source: Author.

Figure 64 - Design Stage - REFERENCE MODEL

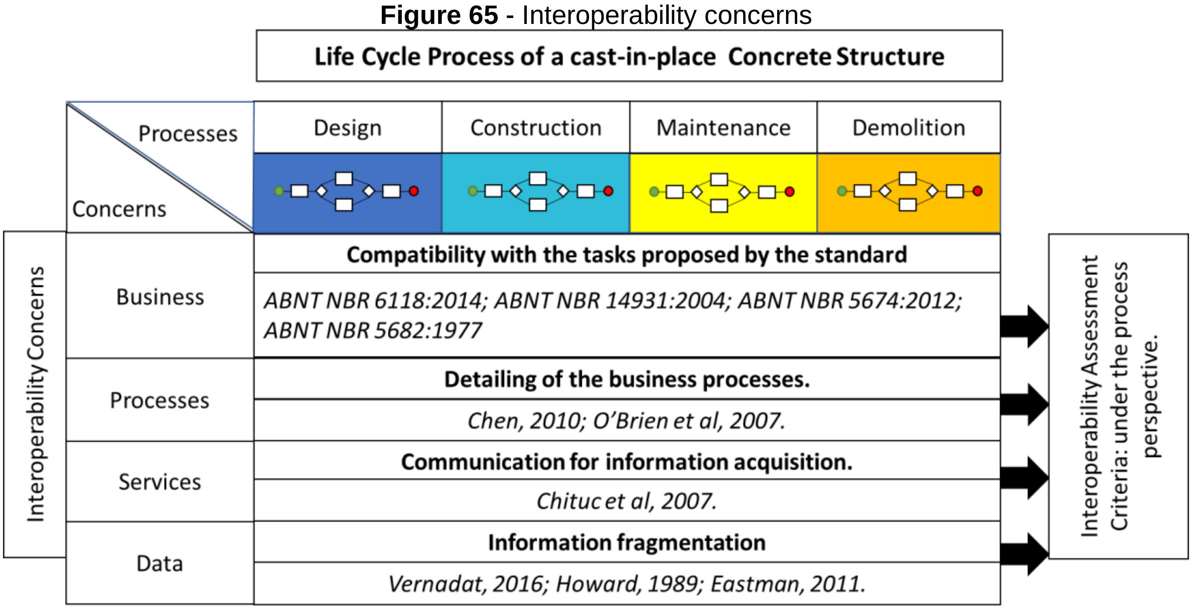


Source: Author.

7.4.3 Interoperability Assessment

The individual analysis of each standard and the correlation with the requisites resulted in the interoperability requirements, which are summarized in Figure 65, representing the interoperability concerns as well as authors and standards that share this vision.

Figure 65 - Interoperability concerns



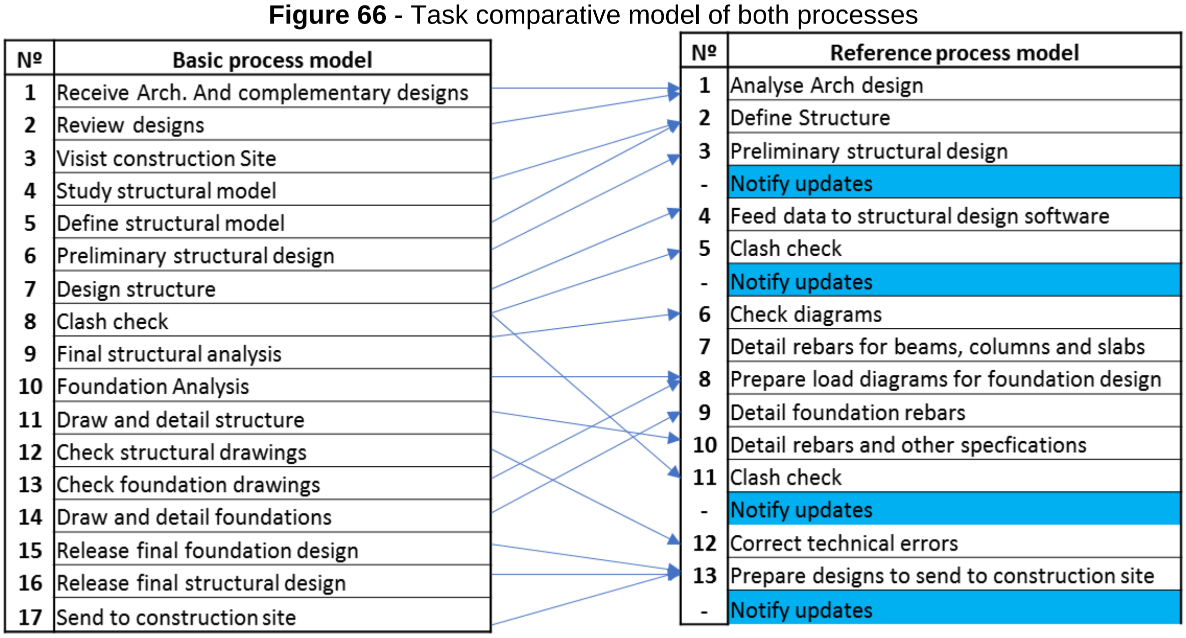
Source: Author.

For the business layer, it was established that in a more interoperable scenario, there is a higher adherence of the processes tasks to the tasks proposed in the standards. The process layer indicates that a more detailed process tend to be more interoperable, therefore this evaluation item is connected to the number of tasks (CHEN, 2010; O'BRIEN et al., 2007). For the service layer, a higher number of connections between different agents, indicated a poorer interoperability (CHITUC et al., 2007). Finally, in the information layer, the information fragmented represented less efficient interoperability, therefore, the higher the number of files generated, the poorer the interoperability as well (VERNADAT, 2016; HOWARD, 1989; EASTMAN, 2011). This results are described in Table 22. the REFERENCE lifecycle process achieved best performance in all criteria evaluated in comparison to the BASIC PROCESS model.

At the end of the analysis of the business criteria of all the stages of the lifecycle of a reinforced concrete structure, 15 tasks of the Basic model meet the standards and 24 of the reference do so. Therefore, reference model is more compliant with the standards than the version without the use of BIM. This way, it is possible to verify that the professionals who use BIM in their processes are able to describe a more interoperable process in the business aspect.

In the final result of the analysis of the process criteria, the basic model presented an average of fewer tasks then the reference model, when considering that some tasks are equivalent to others or many others. It can be noticed that the lifecycle with the use of BIM has a better-defined process than that without the use of BIM. A comparative model of tasks in both design processes can be seen in Figure 66. Even that the total number of tasks are fewer, some tasks of the reference model comprehend up to three tasks in the basic model, making the reference model a more complete process.

Figure 66 - Task comparative model of both processes



Source: Author.

For the service interoperability assessment the basic model had 25 interactions for information exchange, and the reference model had only 5 interactions, totaling five times less. This result was expected since with a BIM database to provide service support throughout the lifecycle, each participant can use the model to extract the information they need.

Finally, concerning the information assessment, all the documentation analysis generated over the traditional lifecycles and with the use of BIM. In the basic model 30 documents were generated, against 9 documents generated in the reference processes. This way, it was is possible to perceive a reduction of the information fragmentation, since BIM allows the union of information of the entire process in a single model. This results are detailed in Table 22

Table 22 - Interoperability criteria by lifecyle stage.

Information Criteria- Number of documents generated		
Stage	**Basic**	**Reference**
Design	10	1
Construction	4	1
Maintenance	8	4
Demolition	8	3
Total	30	9

Business criteria - number of tasks that meet the standards		
Stage	**Basic**	**Reference**
Design	3	10
Construction	2	1
Maintenance	7	8
Demolition	3	5
Total	15	24

Service criteria - number of interactions outside the process		
Stage	**Basic**	**Reference**
Design	4	0
Construction	5	1
Maintenance	3	2
Demolition	5	3
Total	17	6

Process Criteria - Points related to number of tasks		
Stage	**Basic**	**Reference**
Design	5,5	4
Construction	4	9
Maintenance	4	4
Demolition	7	5
Total	20,5	22

Source: Author.

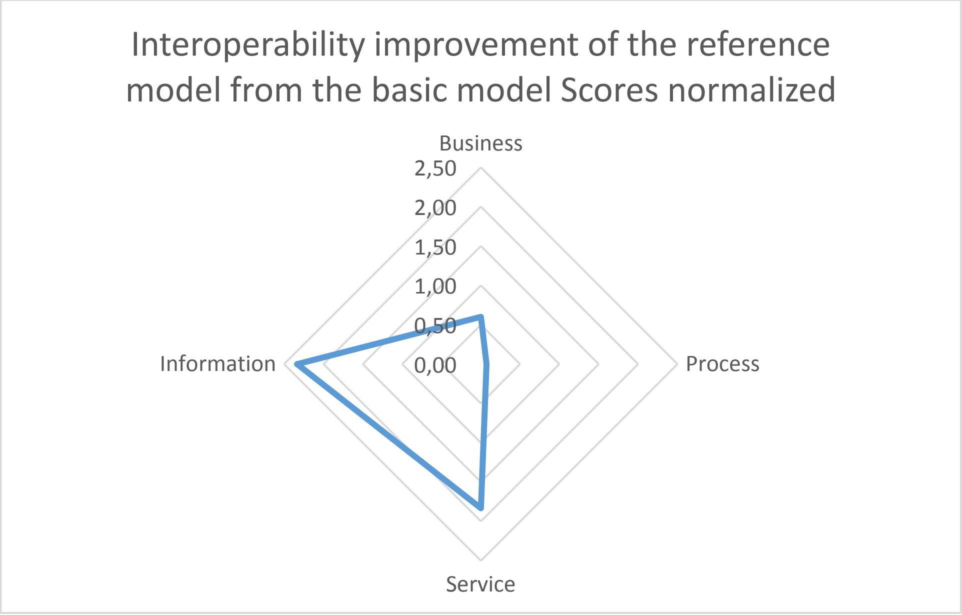
Due to different ranges of the criteria, in order to quantify how much more interoperable the REFERENCE process is in relation to the BASIC process, the obtained results had to be normalized. For that, a percentage of process improvement was established in relation to the other, and the results obtained are described in Table 23**,** and the graphic is displayed in Figure 67.

Table 23 - Interoperability improvement of the reference model from the basic model

Interoperability improvement of the reference model from the basic model	
Criteria	Scores normalized
Business	0,60
Process	0,07
Service	1,83
Information	2,33

Source: Author.

Figure 67 - Interoperability improvement of the reference model from the basic model



Source: Author.

The result obtained was that the REFERENCE process is more interoperable than the BASIC process in all aspects. Considering all stages of the cast-in-place concrete structure lifecycle based on businesses, processes, service, and information requirements. Therefore, the results of this research lead to the conclusion that the BIM-based process is more interoperable than the traditional process, showing that, in fact, the BIM is a significant change to the AEC sector with regard to its processes.

Also, it is demonstrated that information and service gain the most with the use if BIM, ensuring that data is transferred more smoothly amongst all professionals involved.

7.5 CONCLUSION OF THE SECTION

The main objective of this research consisted in evaluating the lifecycle interoperability of a cast-in-place concrete structure (BASIC and REFERENCE PROCESS MODEL) in the light of its processes. In order to achieve such objective, the authors made the effort to: carry out both the process models with BIM and without BIM and also research the interoperability requirements that could turn into assessment criteria.

In the BASIC process modeling, a process was selected and described, so that it was as close to reality present in companies as possible. To do so, the task sheets were an appropriate mapping tool. In its turn, the REFERENCE process made use of the Delphi methodology, so that the preliminary processes modeled could be refined together with experts. This was necessary given the lack of companies employing BIM in all their processes.

As illustrated in the assessment, the BIM highlight consists of its capacity to gather information from all parties involved in the process and represented by the BIM repository. As a result, the amount of fragmented documentation throughout the lifecycle reduces significantly, which is one of the interoperability issues covered in the scope of this research.

Consequently, a great improvement in the service and information interoperability concerns is observed. Although this result represents great advantage of the BIM in comparison to the traditional process, it was expected.

Processes were modeled according to some restrictions of the NBR 6118 (ABNT, 2014) standard and based on cast-in-place concrete structures for residential buildings molded *in loco*. Except from the demolition standard, which was cancelled, valid Brazilian standards were used in this study. Once no replacement or equivalent standard has been released in the meantime, the cancelled demolition standard was used here, so in case a new standard is released, it can be easily adapted into the methodology of this research.

Additionally, the methodology applied in this study is not strict to cast-in-place concrete structures, so it can be used to evaluate the lifecycle of any AEC component founded on technical standards. Further study is needed to develop processes for other areas in the construction industry, and evaluate the impact of BIM in such systems, which can vary from renewable energy use, plumbing systems, other structural systems and so on. Also, a relevant issue is the information interoperability, which can be supported by semantically annotating the processes with ontology. Finally, processes in the construction industry also need decision support methods.

7.6 ALIGNMENT OF THE CHAPTER IN THE THESIS

In this section, the development of the process models is presented. A comparative of processes using no or low BIM to full BIM is described, and the results provided validation for a BIM based framework, since BIM processes resulted in the most interoperable solution. This is was due to BIM's capacity to gather information from all parties involved in the process and work as an information repository. As a result, the amount of fragmented documentation throughout the lifecycle reduces significantly, improving interoperability.

The same way as the ontologies, this methodology applied in this study is not strict to cast-in-place concrete structures and can be used to evaluate the lifecycle of any AEC field, as the framework proposed. Also, as proposed in the framework, processes were modelled both for the basic stage, and the full-BIM reference stage, providing a foundation for the he next stage of process annotation and decision support.

8 PROCESS ANNOTATION AND DECISION SUPPORT

When systems interoperability solutions are at different levels, they 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 the 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). It is possible to enrich process models with semantic annotations from domain ontologies to formalize of both the structural and information domain in a shared knowledge base (DI FRANCESCOMARINO, 2011; LIAO et al., 2016).

The process model will receive 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 BPMN modelers to enrich the process semantically.

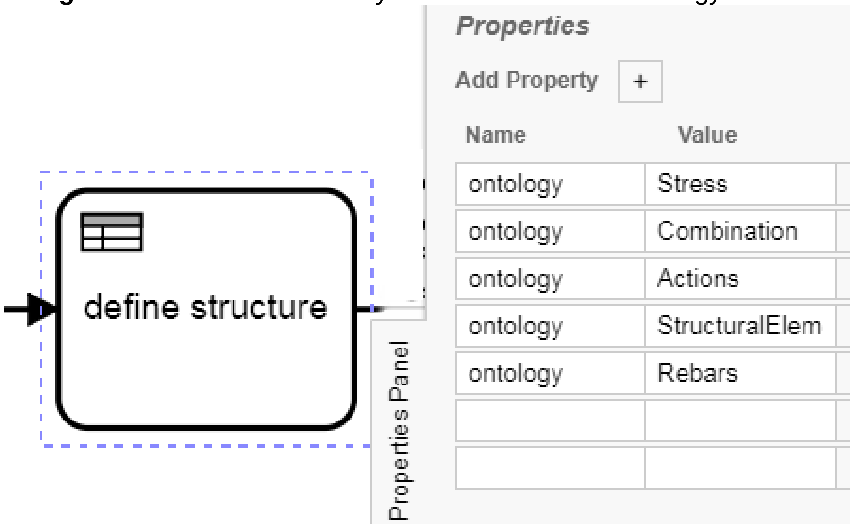
The business layer of the framework represents the standards and certifications used on the field (CHEN, 2008). This information will present decision support factors to influence the process toward more sustainable constructions. In this case, LEED will be used as a reference, since it provides a well-structured scoring system, however any certification or standard can be used. The LEED manual will be structured in a DMN matrix with the ontology and connected to the process in the data layer (TIBAUT et al., 2017).

Based on this matrix, a DMN process can then 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.

8.1 PROCESS ANNOTATION

To develop the semantic annotation of the process, the IAI 2 described in chapter 5 was sent to a company and the data was collected. The information of which ontology classes were used on each task was stored as properties in a small database on each task of the process modeler, thus, annotating the process semantically with the ontology classes, as seen on Figure 68. This organizes the concepts used by class, therefore allowing this data to be consumed in the decision model.

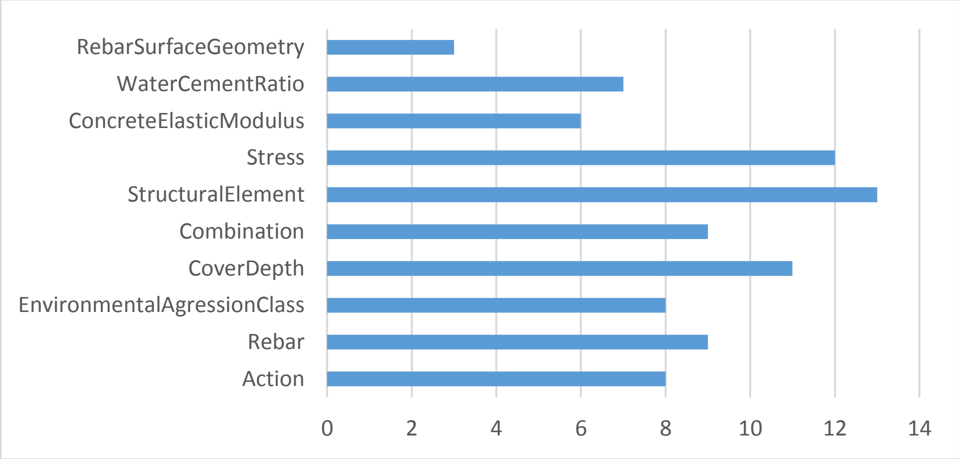
Figure 68 - Task semantically annotated with the ontology classes



Source: Author.

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 69 was developed showing which ontology classes are used more often by the company interviewed. The class StructuralElement appeared in almost all of the tasks of the process. Therefore the information related to it must be carefully treated, ensuring its interoperability integrity throughout the process.

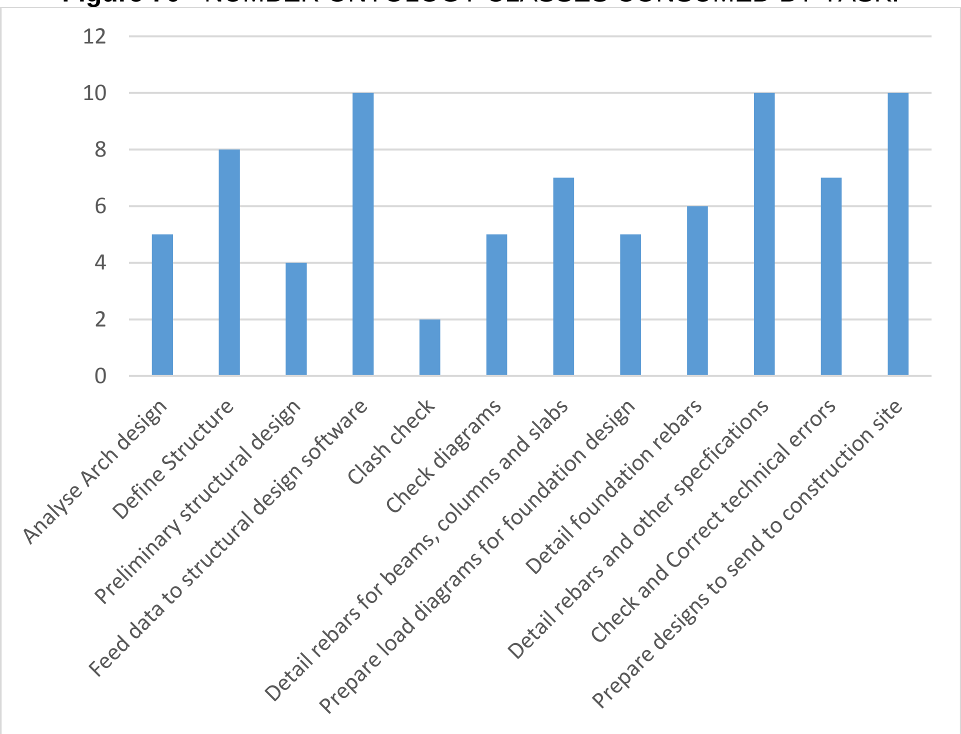
Figure 69 - Number of Times an Ontology Class Was Required in Process



Source: Author.

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 70. 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.

Figure 70 - NUMBER ONTOLOGY CLASSES CONSUMED BY TASK.

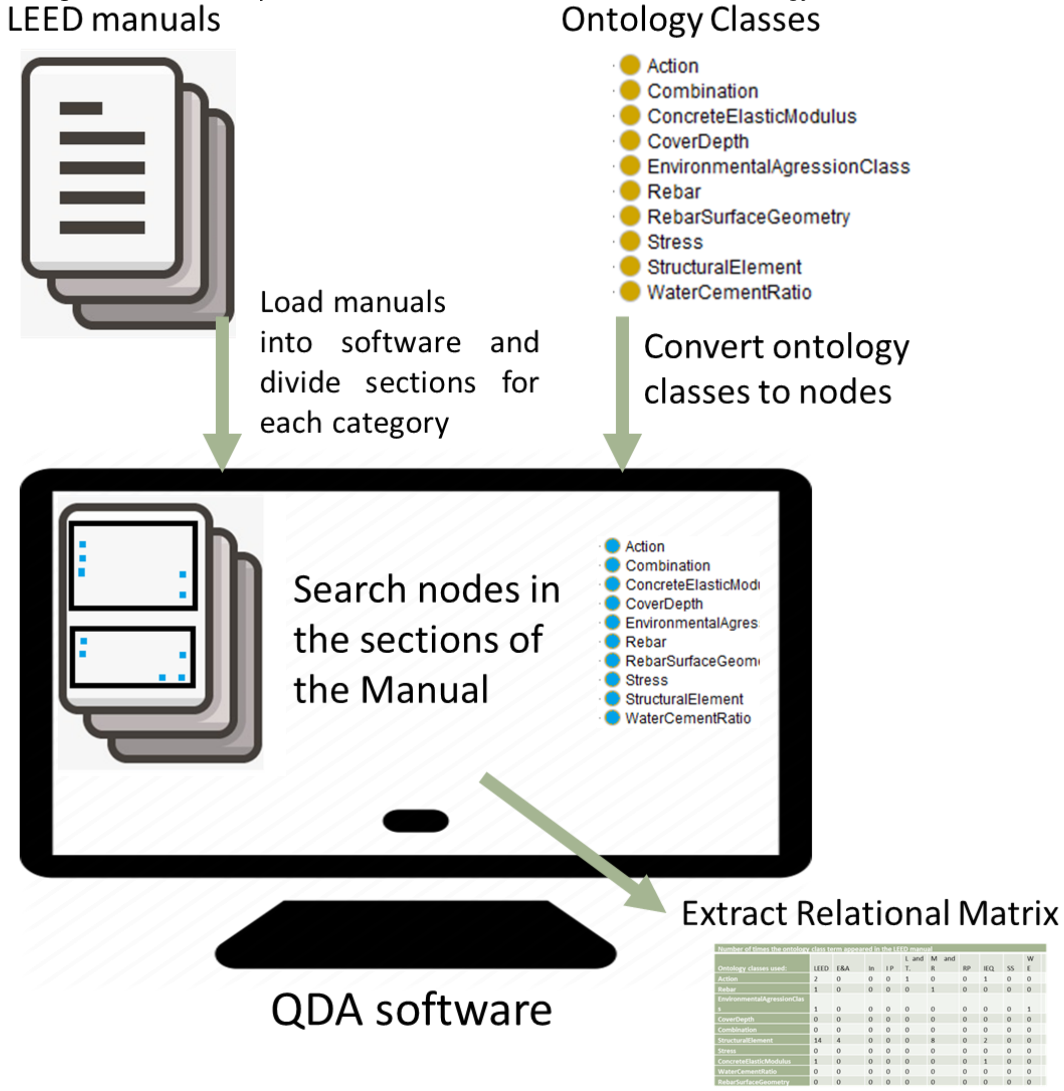


Source: Author

8.2 DMN – SUSTAINABILITY DECISION

Finally, to apply the sustainability concepts to the process, a relational matrix was developed through an word occurrence analysis. The LEED manual was inserted into a QDA 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 is seen on Figure 71. For the developed table, higher number indicates a stronger correlation, and can be seen in Table 24.

Figure 71 - Development of the influence matrix from the ontology and LEED manual.



Source: Author.

Table 24 - Correlation of LEED fields and ontology classes

Number of times the ontology class term appeared in the LEED manual										
Ontology classes used:	LEED	E&A	In	I P	L&T	M&R	RP	IEQ	SS	WE
Action	2	0	0	0	1	0	0	1	0	0
Rebar	1	0	0	0	0	1	0	0	0	0
EnvironmentalAgressionClass	1	0	0	0	0	0	0	0	0	1
CoverDepth	0	0	0	0	0	0	0	0	0	0
Combination	0	0	0	0	0	0	0	0	0	0
StructuralElement	14	4	0	0	0	8	0	2	0	0
Stress	0	0	0	0	0	0	0	0	0	0
ConcreteElasticModulus	1	0	0	0	0	0	0	1	0	0
WaterCementRatio	0	0	0	0	0	0	0	0	0	0
RebarSurfaceGeometry	0	0	0	0	0	0	0	0	0	0

E&A - Energy and Atmosphere; I- Innovation; IP - Integrative Process; L&P - Location and Transport; M&R - Materials and Resources; RP - Regional Priority; IEQ -Indoor Environmental Quality; SS-Sustainable Sites; WE - Water Efficiency.

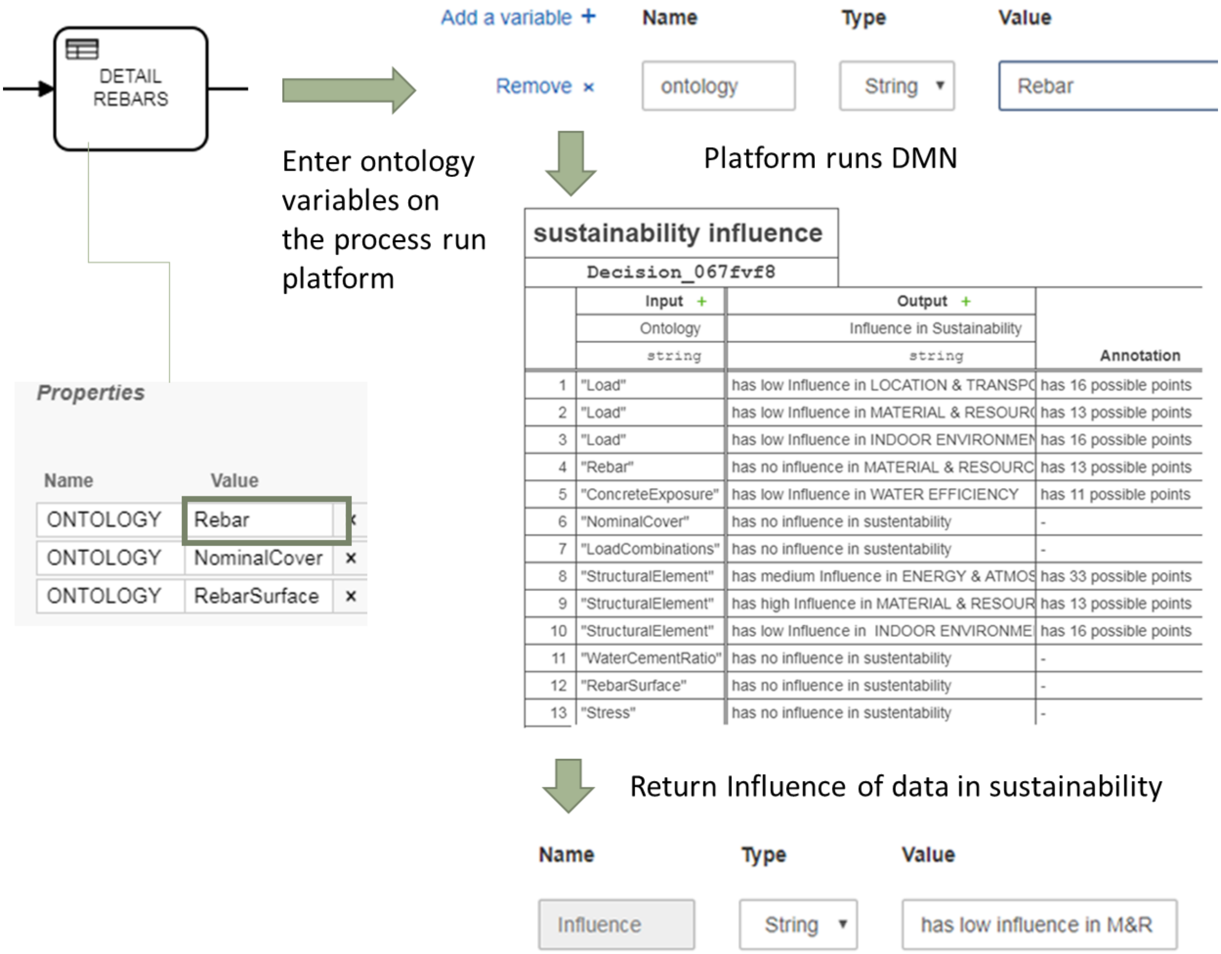
Source: Author.

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 sored 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 72 shows the DMN. Therefore, when the user deploys the process in the BPMN platform he or she will also enter in 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 amount of possible points LEED points for such category, allowing the user to consider a more sustainable option in that task, as shown in Figure 72.

In the example shown in figure, when the structural designer starts the task “Detail Rebars”, he or she will view which ontological concepts are associated with that task. By entering one or more terms in the platform, the system will run the DMN matrix and return LEED influence associated with that concept. In this case “Has low influence in Materials and Resources”, and 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 in 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 72 - DMN table for sustainability in cast-in-place concrete structures and Input/output of ontology in the process task



sustainability influence

Decision_067fvf8

	Input + Ontology string	Output + Influence in Sustainability string	Annotation
1	"Load"	has low Influence in LOCATION & TRANSPO	has 16 possible points
2	"Load"	has low Influence in MATERIAL & RESOUR	has 13 possible points
3	"Load"	has low Influence in INDOOR ENVIRONMEN	has 16 possible points
4	"Rebar"	has no influence in MATERIAL & RESOURC	has 13 possible points
5	"ConcreteExposure"	has low Influence in WATER EFFICIENCY	has 11 possible points
6	"NominalCover"	has no influence in sustentability	-
7	"LoadCombinations"	has no influence in sustentability	-
8	"StructuralElement"	has medium Influence in ENERGY & ATMOS	has 33 possible points
9	"StructuralElement"	has high Influence in MATERIAL & RESOUR	has 13 possible points
10	"StructuralElement"	has low Influence in INDOOR ENVIRONME	has 16 possible points
11	"WaterCementRatio"	has no influence in sustentability	-
12	"RebarSurface"	has no influence in sustentability	-
13	"Stress"	has no influence in sustentability	-

Source: Author.

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 (for example, LEED has specific manuals for the renovation/maintenance stage). This type of decision support can be significant to aid professionals of 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 has on sustainability, reducing the time used to analyze each and every case according to the manual.

These influence factors throughout the process can support decision making considering the most sustainable options for a building. For instance: In the design stage, when the designer is on a task “Define slab type”, he may opt for a plan slab or a waffle slab type. The waffle slab usually creates less residue and also presents a better thermal insulation for a construction, so it would present a higher influence LEED factor, suggesting him to follow the path to the task “select waffle slab type”.

8.3 CONCLUSION OF THE SECTION

From the sustainability point of view, in the case discussed, it was noticed that “StructuralElement” is the term that has the most influence in the sustainability matrix, and also the term that is more often consumed in the processes, 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.

Another important factor was that the tasks “Feed data to structural design software”, “Detail rebars and other specifications” and “Prepare designs to send to construction site” are the ones that consume the most information represented by the ontology classes. Therefore, these tasks should receive special attention in the concern with its interoperability, since there is more data being used and therefore subject to be misplaced or misinterpreted by both systems or users.

Finally, this section demonstrated that it is possible to apply decision models to processes, supported by ontological semantic annotation.

8.4 ALIGNMENT OF THE CHAPTER IN THE THESIS

In this chapter a decision model was structured and implemented, using semantically enriched processes. The processes developed in chapter seven are annotated with the ontology classes presented on chapter six, through an information acquisition instrument. With the semantic data stored in the process tasks, the decision support can easily retrieve this data to direct the processes in the most sustainable direction.

This decision model was developed using DMN, so it could be easily integrated in the BPMN processes. The foundation for the decision mechanism was the relational matrix, developed by performing a word occurrence analysis in a QDA system, by crossing the LEED manual with the ontology developed in the earlier. This analysis showed how processes can be semantically enriched with ontologies to support decision models.

9 DISCUSSION

In this Chapter the main findings and possible applications of the thesis are discussed as well as its limitations and originality value. The contributions are divided according to their focus on interoperability (data, process and services and business).

Also the topics here presented provide an overall view of the results, since more specific discussions are developed on each chapter, providing technical detail on each particular section.

9.1 FINDINGS

Though this thesis is propositional in nature, in its developments and validations, some important findings were noticed. First, the preliminary studies both showed that BIM data interoperability is still not evolved enough to support interoperable processes in the entire lifecycle of the construction industry. The systematic literature review showed that there is little concern with BIM's lifecycle as a whole, and that most studies are concerned with the design stage. The review also showed a lack of concern with services and business interoperability.

The ontology development showed that IFC for structural analysis, especially in the domain of deformation of bodies, still needs some improvement. The processes analysis proved that BIM based processes tend to be much more interoperable than no or low BIM processes. Finally, this research showed that process annotation can improve decision support when allied with DMN. Also, the use of process annotation demonstrated that some process tasks or some data types (ontological classes) should be treated with greater care, since they have more information attached to them or are used more often.

9.2 CONTRIBUTIONS AND POSSIBLE APPLICATIONS

This research was in nature a propositional, therefore, many different applications and uses can be developed from it. First and more noticeably, this framework can be applied to any system in the construction industry. One possible application are other structural systems, since structures represent a big part of the building´s cost and embodied energy. Other fields like electric systems (including but not limited to LED lighting, solar power for residential systems), hydraulic systems and water re-use systems provide interesting possible applications since they tend to have more impact on different stages of the sustainable lifecycle (concrete structures impact a lot on the construction and demolition/deconstruction stages, and these areas tend to have more impact on the operation and maintenance stages). Other possible applications of the framework are masonry and finishing systems and other structural systems such as steel, wood or structural masonry.

Other ways to apply this framework is by using other sustainability certifications such as Green Star, BREEAM or others to create the guidelines for the decision support. Furthermore, not only sustainability certifications can be used, but other objectives can be pursued by applying other guidelines, for example for socioeconomical purposes. This way, the same structure of the framework can be applied not only in environmental sustainability, but in the other two aspects of the triple bottom line, considering the economic and social aspects as well.

Other than this uses for the general structure as a whole, other contributions can be divided in the interoperability concerns themselves.

Data

From programmers and developers’ standpoints, the ontology data structure, its development method and the comparative system to IFC files can be used to implement and improve file formats for BIM, also its import and export capabilities to IFC files, improving interoperability for the data structures in the AEC industry.

Service and process

From the user standpoint (by user meaning professionals and private organizations of the AEC industry) this framework can be used to help these professionals to map and improve process toward more interoperable and sustainable BIM use. Also, by comparing a company´s current processes to the basic and reference models, these professionals may be able to use the proposed assessment methodology to verify how much improvement in interoperability the company can make by improving the processes towards more BIM-based systems.

Also, suppliers and other service providers may benefit from the framework by understanding how to supply information and collaborate, by understanding the information flow in a BIM-based environment.

Business

Developers of certifications and standards may also benefit from the framework, mainly by considering the use of BIM may improve sustainable aspects. Future versions of certifications may specify use of some BIM-based analysis, detail levels to be used in the BIM models for these analysis purposes and provide BIM databases with information related to sustainability (for example the embedded carbon on each material and specifications green materials).

9.3 LIMITATIONS

The ontologies and the processes developed to illustrate the framework were primarily based in Brazilian standards for cast-in-place concrete structures throughout the lifecycle of a building. For the interviews and validation of the processes though the Delphi rounds only professionals from local companies were interviewed, since the interviewees needed to be familiar with the standards.

Finally, to illustrate the application for the decision model and to develop the influence matrix, LEED for new constructions version 4 was used. The justification for the choices and literature support to these decisions are described in the related chapters.

9.4 ORIGINALITY

The originality of this research is seen mainly in its concern for the entire lifecycle of the construction, since the systematic literature review showed there is not a lot of research that comprehends the entire lifecycle, and that some stages such as design and maintenance are rarely studied. The use of BIM allowed this study to cover the entirety of the lifecycle.

Also, the basic structure for the framework presented the semantic notation of processes and its use to guide decision toward more sustainable constructions, which is an original solution in this area. Still in the framework structure, the application of Chen´s (2018) model presented some originality value, since the concern with interoperability as a whole (across data, service, process and business) is not so common in the construction industry.

Finally, the method used for the systematic literature review presented some originality aspects by itself, specially the pairing of the more traditional Ordinatio method with a multicriteria decision method.

10 CONCLUSION

This section presents the conclusions for this research, firstly with key aspects related to the research and objectives, and then with highlights about the contributions in each specific interoperability concern. The limitations and scope are also described in this section. Also applications for this framework will be presented, as well as propositions for future works.

The length of the lifecycle of the construction industry requires special attention when considering sustainability. Since BIM can aid in the management of this lifecycle, the development of a framework to organize the knowledge and processes was the main objective of this research. This framework was based on interoperability concerns (data, process and services and business) in order to ensure that the information flow is well-structured. The core layer for knowledge and data organization is based on ontology from IFC and literature standards. The processes were developed in BPMN through interviews with specialists and the literature. Finally, a relational matrix was developed to influence decision toward more sustainable buildings based on LEED criteria.

The main objective of this thesis was to "Develop a conceptual framework for the decision-making processes for BIM interoperability in a sustainable lifecycle based on an ontological data structure and propose an application for cast-in-place concrete structures", and was achieved, as well as the specific objectives.

The first specific objective as to "Identify weaknesses in the current BIM interoperability for sustainability and cast-in-place concrete structures". Through the interoperability assessment experiments, it was noted that data interoperability is still underdeveloped both for concrete structures and sustainability. However, this raised the concern that there might be other interoperability issues in the AEC industry. Then, a SLR was developed to achieve the second specific objective: "Gather information in the literature to support a framework for the sustainable BIM lifecycle"

From the literature review and some perceptions from the interoperability assessment experiments, a framework was structured to achieve the third specific objective: "Structure and describe the methodology for the development of a framework model for BIM interoperability in a sustainable lifecycle".

In the development of the framework application, the fourth and fifth objectives were achieved: *“*Structure a BIM-based ontology for cast-in-place concrete structures” and “Develop processes for cast-in-place concrete structures”*.* Finally, after the two previous objectives were completed, a DMN decision model was tested, completing the sixth specific objective “Propose a decision model for sustainable constructions by semantically annotating the processes with the ontology”*.* All this was used to validate the framework through application.

10.1 FUTURE WORKS

Two types of future works can emerge from this research. First technical projects can be developed from the foundation here structured. Other possibility are more academic research projects in BIM interoperability.

Technical applications

This framework can be used to guide the development of BIM applications or plugins. The basic structure developed here can be used to develop an application to acquire data for process mining can support the development and improvement of processes. Also, plugins to aid users verify their achieved score and possible points for determined sustainability certification can also be implemented based on this framework structure. Basically, this framework structure can be used to develop BIM systems and platforms that support the processes throughout the lifecycle of a building, ensuring interoperability in all stages and supporting decision models.

Academic research

Considering the framework has a basic and reference models, it can provide some foundation for the development of an interoperability maturity model, to aid BIM users to develop towards more interoperable structures in the lifecycle of a building. In the same BIM direction as the maturity model, an implementation manual for BIM can also be useful for companies that are still in the early stages of BIM adoption, especially since the framework provides reference processes and ontologies.

The methodology used to develop the processes can be used in different fields, providing tools to support process modelling, and to refine the processes into reference models.

Also, the method used to compare the reference ontology to the ontology used in the IFC standard can be used to compare and improve ontologies and machine-formats for other areas of knowledge as well.

Finally, a model to incorporate multicriteria decision models in BIM is perceived to be an interesting topic of research, since BIM provides foundation for collaboration and interoperability.

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APENDIXES

Since the Ontologies and semantically annotated processes cannot be perfectly represented in the printed form, and also aiming to create a lighter and more organized document, the appendixes of this thesis are available at the link:

APPENDIXES

Appendix A Interview Files and printed processes

Appendix B Process model files and processes evaluation

Appendix C Ontology files and comparatives with IFC4

Appendix D Semantically Annotated Processes

Appendix E Published papers

https://drive.google.com/open?id=1hXUzmgxzj419BYQISX283a8waubupgS2P