UNIVERSIDADE FEDERAL DE VIÇOSA

Uma avaliação do esquema de dados *Industry Foundation* Classes aplicado a modelos de pontes no contexto da infraestrutura brasileira

Maria Luisa Ribeiro Antunes
Doctor Scientiae

VIÇOSA - MINAS GERAIS
2025

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Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Civil, para obtenção do título de *Doctor Scientiae*.

Orientador: Jose Carlos Lopes Ribeiro

Coorientadores: Kleos M. L. C. Junior
Jose M. F. de Carvalho
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Maria Luisa Ribeiro Antunes
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Dedico este trabalho ao maior amor da minha vida, meu pai.

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RESUMO

ANTUNES, Maria Luisa Ribeiro, D.Sc., Universidade Federal de Viçosa, março de 2025. **Uma avaliação do esquema de dados *Industry Foundation* Classes aplicado a modelos de pontes no contexto da infraestrutura brasileira**. Orientador: Jose Carlos Lopes Ribeiro. Coorientadores: Kleos Magalhaes Lenz Cesar Junior, Jose Maria Franco de Carvalho e Diogo Silva de Oliveira.

A indústria da construção civil é caracterizada por alto nível de fragmentação. Um único projeto pode demandar inúmeras soluções (modelos Building Information Modeling – BIM), que são desenvolvidas por diversos atores e suas respectivas ferramentas (software). Neste cenário, a eficácia dos processos de colaboração multidisciplinares fica diretamente relacionada à qualidade das trocas de informações realizadas ao longo do ciclo de vida do projeto. Para que esses fluxos ocorram em um alto nível semântico, os software devem aderir a uma estrutura de dados comum, uma vez que não existe um único software capaz de ofertar uma solução completa. O esquema de dados Industry Foundation Classes – IFC foi desenvolvido para viabilizar esta demanda através da interoperabilidade por padrão aberto (OpenBIM), evoluindo exponencialmente e agregando relevante valor a cada nova versão. No entanto, apesar deste avanço, a interoperabilidade neutra ainda representa um desafio significativo para a colaboração eficaz entre gestores e profissionais BIM. Concernente à este obstáculo, o objetivo geral desta pesquisa é identificar as entidades do esquema IFC que respondem à especificação de dados característicos de modelos de pontes, uma vez que estas estruturas refletem uma demanda prioritária, à luz do Decreto Federal 10306 (2020). Constructos foram desenvolvidos e validados através do método Design Science Research – DSR, a partir do estudo profundo do esquema IFC visando solucionar as lacunas identificadas. A implementação prática dos artefatos foi analisada no espectro da verificação automática Information Delivery Specification - IDS, demonstrando que a demanda vivenciada pela governança brasileira pode ser beneficiada também por este recurso. Os artefatos produzidos representam soluções tanto para os gestores de pontes quanto para profissionais BIM, de forma ampla, já que podem ser facilmente replicados.

Palavras-chave: ciclo de vida; interoperabilidade; openbim; industry foundation classes; pontes; information delivery specification

ABSTRACT

ANTUNES, Maria Luisa Ribeiro, D.Sc., Universidade Federal de Viçosa, March, 2025. **An assessment of Industry Foundation Classes data schema applied to bridge models in the context of brazilian infrastructure**. Adviser: Jose Carlos Lopes Ribeiro. Co-advisers: Kleos Magalhaes Lenz Cesar Junior, Jose Maria Franco de Carvalho and Diogo Silva de Oliveira.

The construction industry is characterized by a high level of fragmentation. A single project may require multiple solutions (Building Information Modeling – BIM models) which are developed by various stakeholders using different tools (software). In this context, the effectiveness of multidisciplinary collaboration processes is directly related to the quality of information exchanges throughout the project life cycle. For these workflows to occur at a high semantic level, the software involved must adhere to a common data structure, as no single software can provide a complete solution. The Industry Foundation Classes (IFC) data schema was developed to meet this demand through open-standard Interoperability (OpenBIM), evolving exponentially and adding significant value with each new version. However, despite this progress, neutral interoperability remains a major challenge for effective collaboration between managers and BIM professionals. Regarding this challenge, the general objective of this research is to identify the IFC schema entities that respond to the specification of characteristic data for bridge models, as these structures reflect a priority demand under Federal Decree 10306 (2020). Artifacts were developed and validated using the Design Science Research - DSR method and based on an in-depth study of the IFC schema to address the identified gaps. The practical implementation of these artifacts was analyzed within the scope of automatic verification using the Information Delivery Specification - IDS, demonstrating that the challenges faced by Brazilian governance can also benefit from this resource. The artifacts represent solutions for both bridge managers and BIM professionals in a broad sense, as they can be easily replicated.

Keywords: life cycle; interoperability; openbim; industry foundation classes; bridges; information delivery specification

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LISTA DE SIGLAS E ABREVIATURAS

ABNT – Associação Brasileira de Normas Técnicas

AECO – Arquitetura, Engenharia, Construção e Operação

AIA – American Institute of Architects

AIM – Asset Information Model

BEP – BIM Execution Plan

BIM – Building Information Modeling

bSI – buildingSMART International

bsDD – buildingSMART Dictionary Data

CIC – Computer Integrated Construction

CRS – Coordinate Reference System

DfD – Design for Deconstruction

DNIT – Departamento Nacional de Infraestrutura Terrestre

DPL – Dynamic Project Lifecycle

DSR – Design Science Research

EGM – Earth Gravitacional Model

EIR – Exchange Information Requirements

EPSG – European Petroleum Survey Group

ERT – Electrical Resistivity Tomography

GIS – Geographic Information System

GRS80 – Geodetic Reference System 1980

IAI – Industry Alliance for Interoperability

IDS – Information Delivery Specification

IFC – Industry Foundation Classes

IGNF – Institut Geographique National de France

ITRF – International Terrestrial Reference Frame

ITRS – International Terrestrial Reference System

LITE – Lifecycle Information Transformation and Exchange

MSL – Mean Sea Level

MVD – Model View Definition

NIBS – National Institute of Buildings Sciences

OAE – Obra de Arte Especial

OGC – Open Geospatial Consortium

OIR – Organization Information Requirements

OOP – Object Oriented Programming

PIR – Project Information Requirements

SIRGAS – Sistema de Referência Geocêntrico das Américas

STEP – Standard to Exchange Data Product

SPF – STEP Physical File

TED – Termo de Execução Descentralizado

UFV – Universidade Federal de Viçosa

UTM – Universal Transverse Mercator

WGS84 – World Geodetic System 1984

XML – Xtended Markup Language

SUMÁRIO

CAPÍTULO 1 – INTRODUÇÃO GERAL

Resumo

Neste capítulo apresenta-se a introdução geral ao trabalho, objetivos gerais e específicos. Adicionalmente, a estrutura da tese é narrada, incluindo comentários sobre sua especificidades visando facilitar a leitura e entendimento do conteúdo.

1.1 Introdução

A inovação tecnológica tem agregado relevante valor aos processos de gestão e manutenção de pontes através de bancos de dados eletrônicos, visando o desenvolvimento de modelos que aprimorem técnicas projetuais, construtivas e de manutenção. Ainda que esta abordagem contemple grande parte do ciclo de vida do projeto, a carência de processos eficazes de manutenção e intervenção, característicos da fase "Operação", ainda representam consideráveis desafios para os gestores de pontes. Frangopol, Kong e Gharaibeh (2001) discorrem que as falhas que ocorrem nesta fase representam mais de 60% das ocorrências, enquanto menos de 40% se manifestam durante a fase construtiva, o que pode ser justificado pela duração da fase operacional, significativamente mais duradoura que as demais. Adicionalmente, a modernização de frotas com maior capacidade de carga agrega um fator adicional à demanda das estruturas, enquanto os processos visando mantê-las ou renová-las, não têm acompanhado esta evolução tecnológica ao longo dos anos.

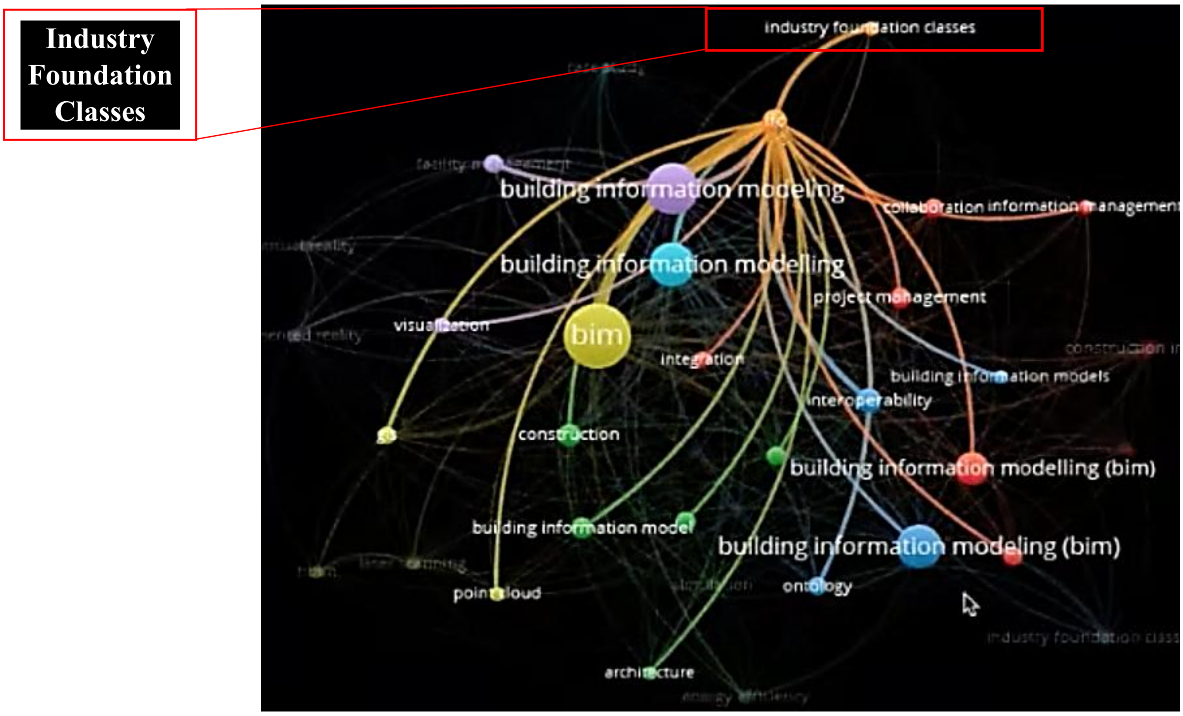
Conforme Zhang *et al.* (2022) as pontes colapsadas possuíam vida útil média variada, como por exemplo: 51,7 anos (Estados Unidos); menos que 25 anos (China). Os países europeus apresentam melhor performance, especialmente em função de programas como *Long Term Bridge Program* e *Sustainable Bridges* (Ge; Xiang, 2011) . Destacam, dentre outras abordagens, que o aumento da vida útil das pontes do ponto de vista da gestão, demanda a elevação do nível de controle e segurança relacionados aos processos de manutenção.

A idade de serviço das estruturas contempla uma expectativa de uso mínima de 50 anos (Associação Brasileira de Normas Técnicas, 2024). No contexto da infraestrutura brasileira, estima-se que aproximadamente 120 mil pontes rodoviárias estejam em plena operação. No entanto, mais de 90% deste universo construído sequer possuem histórico de inspeções (Maciel *et al.,* 2021). Santos *et al.* (2024) discorrem que o quantitativo de pontes rodoviárias é em torno de 113.168 e que apenas 13% delas possuem históricos de inspeções. Esse cenário evidencia a precariedade do controle de dados e de monitoramento das pontes, o que compromete a segurança dos usuários e a sustentabilidade do patrimônio público.

As causas responsáveis pelo término prematuro da vida útil de pontes podem ter origem em diversas fases do ciclo de vida. As denominadas internas, relacionam-se com erros projetuais, falhas construtivas e de manutenção, além de problemas associados aos materiais empregados e as externas, relacionam-se com as sobrecargas, colisões e eventos da natureza (Zhang *et al.,* 2022). Além do contexto qualitativo, o quantitativo de ativos potencializa os desafios enfrentados pelos gestores e, por esta razão, o avanço tecnológico representado por novas ferramentas de trabalho, técnicas de modelagem e análise computacional representam, claramente, um caminho promissor para a Engenharia de Pontes.

O *National Institute of Building Sciences* (NIBS) sustenta que a ausência de protocolos padronizados de intercâmbio de dados, consensuados pela indústria da construção civil, não possibilita uma maneira comum de integrar as informações geradas pelas diversas soluções projetuais e construtivas que possam ser utilizadas durante a fase operacional. A interoperabilidade neutral, denominada *OpenBIM*, é essencial para os processos colaborativos *Building Information Modeling* (BIM), fundamentada pelo esquema de dados *Industry Foundation Classes* (IFC) constitui o cerne desta tese. A demanda de estudos visando a interoperabilidade por padrão aberto foi constatada pelo panorama de pesquisas desenvolvidas entre 1975 a 2020. Apesar de revelar considerável densidade de publicações envolvendo BIM como temática, apenas uma pequena fração tratava da sua essência fundamentadora, o esquema IFC (Fig.1.1).

Fig. 1.1 – Panorama de pesquisa



Fonte: A Autora (2021)

1.2 Objetivos

Visando mitigar a barreira da interoperabilidade neutra, o objetivo geral deste estudo é contemplar uma pesquisa abrangente do *Industry Foundation Classes* (IFC) aplicado às pontes no contexto da infraestrutura brasileira geridas pelo Departamento Nacional Infraestrutura e Transportes (DNIT). Fundamentado no padrão *Standard to Exchange Data Product* (STEP), os artefatos desenvolvidos visam orientar o trabalho de gestores e profisionais envolvidos nos projetos de pontes, à luz do BIM. Como objetivos específicos, o estudo contempla:

i. Identificar e explorar as entidades semanticamente adequadas para especificar dados de projetos de pontes, alinhados à estrutura espacial do IFC [*IfcProject, IfcSite, IfcBridge*].
ii. Desenvolver diagramas de herança das entidades envolvidas.
iii. Desenvolver as respectivas soluções das lacunas identificadas, através do *STEP - File Physical Format* (SPF) e validá-las.
iv. Elaborar o protocolo *Information Delivery Specification* (IDS) visando a verificação automática dos dados abordados no objetivo específico (i).

1.3 Justificativa

Inspirado em iniciativas governamentais internacionais de sucesso, a governança brasileira anunciou mudanças relevantes no cenário da indústria da construção civil nacional através do Decreto 9.377 (Brasil, 2018) Estratégia Nacional de Disseminação do BIM Estratégia BIM BR (revogado à luz do Decreto 11.188 em 2024). Sequencialmente, institucionalizou o sistema BIM na plataforma pública através do Decreto Federal 10.306 (Brasil, 2020) cujo primeiro marco temporal 01/01/2021 determinou, dentre outros quesitos, que as obras de reabilitação estrutural de pontes consideradas de grande relevância, fossem desenvolvidas em BIM.

Evolutivamente e, de forma mais abrangente, os marcos temporais 2024 e 2028 absorveram demais relevâncias do universo de pontes em operação, incluindo a abordagem dos novos empreendimentos, originalmente concebidos em BIM, contemplando assim todo o ciclo de vida do projeto. Visando o atendimento às novas demandas, o DNIT vêm promovendo desde então, várias ações. Esta tese representa uma delas, contemplada pelo Termo de Execução

Descentralizada - TED 00703/2020, firmado entre o DNIT e a Universidade Federal de Viçosa (UFV).

As pontes fazem parte de projetos de infraestrutura, semanticamente abordados pelo esquema de dados IFC a partir da inclusão da entidade *IfcAlignment* no esquema versão 4.1 (*BuildingSMART International*, 2018). As entidades responsáveis pela estruturação de dados geométricos mais complexos, característicos destes projetos, foram apresentadas na versão IFC 4.2 (*BuildingSMART International*, 2019). Já os domínios específicos para infraestrutura terrestre e marítima foram publicados somente no esquema IFC 4x3_ADD2 (*BuildingSMART International*, 2024). Ainda que houvesse uma versão *Model View Definition* (MVD) que suportasse a versão oficial IFC mais atualizada (*BuildingSMART International*, 2025), os fabricantes de software demandariam mais algum considerável tempo para ajustar e certificar suas respectivas aplicações.

Neste cenário, o padrão de interoperabilidade *OpenBIM*, cerne dos processos licitatórios públicos pelo aspecto da isonomia, continua a representar o maior obstáculo para os profissionais. Isso se deve ao fato de que os dados devem esclarecer, de forma inequívoca, os requisitos de informação tanto da organização licitante quanto dos projetos licitados. A crescente adoção do BIM na esfera pública nacional exige a elaboração de planos de execução BIM – PEB (de oferta) o que, por sua vez, demanda um conhecimento mínimo do esquema de dados IFC por parte dos atores envolvidos. Além do aspecto disruptivo das novas práticas, as empresas participantes precisam investir não apenas em hardware e software, mas, sobretudo, na capacitação das equipes BIM, que devem embasar tecnicamente o PEB que fundamentará a produção e a entrega do projeto licitado.

Para que a informação seja devidamente requisitada e, consequentemente atendida, este estudo explora potencialidades do esquema IFC aplicado ao desenvolvimento e interoperabilidade de projetos de pontes. A elaboração da verificação automática dos requisitos de informação, revelados pelos arcabouços explorados na tese, especificados por *IfcProject, IfcSite* e *IfcBridge* visam por fim, especificar a estrutura espacial essencial do IFC aplicado ao modelo de pontes. Para esta finalidade, a ponte Coimbra I foi selecionada como objeto de estudo devido à sua representatividade no contexto da infraestrutura nacional, uma vez que encontra-se em plena operação e é caracterizada por tipologia estrutural em concreto armado.

1.4 Estrutura

Esta tese é estruturada em sete capítulos, sendo o primeiro destinado à introdução geral, cinco na forma de artigos e o final, que aborda as conclusões gerais desta pesquisa. Os capítulos no formato de artigo (2 a 6), exceto o terceiro, são desenvolvidos no idioma inglês e possuem as seguintes seções: *Abstract, Introduction, Background, Method, Results, Analysis, Discussion, Conclusion e References*. O conteúdo é apresentado no padrão dos respectivos periódicos à que foram submetidos e, por esta razão, as referências bibliográficas são apresentadas ao final de cada capítulo. Os capítulos "Introdução Geral" e "Conclusões Gerais" (1 e 7), em português, atendem às formalidades impostas pela ABNT NBR 10520 (Associação Brasileira de Normas Técnicas, 2023).

O primeiro capítulo trata da introdução geral da pesquisa, apresentando uma contextualização da temática, bem como seus objetivos geral e específicos, justificativa e comentários acerca da estrutura da tese.

O segundo capítulo apresenta uma análise do esquema de dados IFC visando explorar as entidades envolvidas na especificação dos arcabouços fundamentais para a representação do Projeto de pontes (*IfcProject*).

O terceiro capítulo explora as publicações BIM no Brasil, através de uma revisão sistêmica à luz do ciclo de vida do projeto e, por esta razão, contempla uma estrutura diferenciada dos demais. Sequencialmente, o quarto capítulo aborda a solução da lacuna de pesquisa identificada através da revisão da literatura desenvolvida. A proposta de representação do novo ciclo de vida foi intitulada *Dynamic Project Lifecycle* (DPL).

No quinto capítulo, o estudo dos arcabouços geográfico e geodésico do projeto discorre com o objetivo de explicitar a inter-relação *IfcProject - IfcSite*. Adicionalmente, dados geotécnicos foram traduzidos, visando explicitar a potencialidade do esquema IFC.

O sexto capítulo contextualiza a especificação de *IfcBridge*, contemplando assim, a estrutura espacial do IFC essencial para os projetos de pontes. Por fim, o estudo demonstra através do desenvolvimento e aplicação da verificação automática de requisitos, *Information Delivery Specification* (IDS), as principais entidades exploradas na pesquisa.

As conclusões gerais da pesquisa discorrem no sétimo capítulo, considerando o conteúdo abordado nos capítulos anteriores, bem como são apresentadas propostas para trabalhos futuros, cuja necessidade e temática foram observadas durante o desenvolvimento da tese.

É importante enfatizar que os temas dos capítulos são complementares, de modo que compartilham algumas referências bibliográficas e podem apresentar elementos de conteúdo semelhantes em suas contextualizaões. Da mesma forma, elementos metodológicos também são compartilhados, assim como resultados e discussões, uma vez que estão expostos ao objetivo geral da tese.

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CAPÍTULO 2 - ANALYSIS OF IFC INTEROPERABILITY DATA SCHEMA FOR PROJECT REPRESENTATION

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Abstract

Collaborative work processes from the perspective of Building Information Modeling demand technical and organizational information requirements from managers. In response, data schema Industry Foundation Classes (IFC) has been making significant entities and domain inclusions with a semantic level capable of supporting OpenBIM interoperability throughout the project lifecycle. This paper applies Design Science Research methodology to explore how the IFC should be specified so that BIM actors can meet the representation context of a project translating data through Inheritance Diagrams, which offer auxiliary contributions. The Protocol developed to address the research problem revealed that some information requirements had not been met, as the universe of optional data in the schema is broad. Therefore, an artifact is created to fully meet the demand and is validated by different software. This reveals that the insertion of data can be performed to meet the desired interoperability and stands a valuable tool for BIM actors.

Keywords: Interoperability. OpenBIM. Industry Foundation Classes. Data schema. Representation context.

2.1 Introduction

A project represents a collection of solutions for a purpose, and historically in the construction industry, it is associated with a context of geometric representation. As a typical product in the architecture, engineering, and construction (AEC) industry, the project can represent either a new or existing enterprise exposed to a wide array of interventions throughout its lifespan. Over time this context of representation has transitioned from two-dimensional (2D) design processes to three-dimensional (3D) object-oriented modeling [1]. This scenario offers more effective conditions for the development of solutions and increases collaborative performance among professionals, as well as the disciplines encompassed by the project process [2].

The Building Information Modeling (BIM) paradigm, throughout parameterization and collaboration, consistently contributes to the optimized resolution of plan, design, construction, and operation projects. The designer's omnipresence has been replaced by the use of software for interconnecting disciplines and contributes to rationalizing decision-making [3].

Behind this scenario, interoperability through open standards, as those supported by the Industry Foundation Classes (IFC) data schema, has been enhanced to facilitate high-level semantic information exchange flows. Additionally, open scripting has become inviting to the realm of algorithms and, in this way, offers solutions for various sectors of the AEC industry. [4].

The IFC evolution is ongoing, especially by following the introduction of the IfcAlignment entity (IFC version 4.1). Additional entities have been added to enhance the semantic specification for mainly linear-based projects. The official IFC 4.3 version incorporates specific domains for specifying land and maritime infrastructures [5]. That data structure has supported research worldwide, aiming to raise the semantic level of infrastructure models. However, the frequency of optional attribute declarations remains significant. While this breadth may be appropriate, given the characteristic diversity in the industry, on the other hand, it may result in absence of relevant information. This dichotomy demands special efforts from the project manager when specifying information requirements that meet the both the organization (Organizational Information Requirements - OIR) and project (Project Information Requirements - PIR). These requirements need to be met even if the BIM software used by the professionals involved in the Project does not specify them (optionally).

The overall objective of this study is to determine the IFC specifier that encompasses the representation context of a project to attend exchange information alignment IFC4.3. To achieve this goal, a bridge model, managed by a government organization was used to meet the specific objectives of the research, as follows:

- Map the schema entities that potentially specify a project representation context;
- Develop entity inheritance diagrams capable of translating the IFC data specification;
- Devise a solution capable of addressing the mapped entities;
- Test the artifact across different software platforms.

In this paper, the problem is represented by certain (technical and organizational) information requirements that BIM managers must specify. To ensure information exchange among different software systems, managers and modelers must meet different project and organization demands, [6] through openBIM standards [7].

The most significant contribution might be driven by the need to address real and tangible challenges, meeting specific needs such as specifying the representation context that a project must entail to meet an IFC interoperability standard (Artifact). Therefore, the software used by various disciplines involved in collaborative workflows must be capable of supporting semantic workflows that meet at least the minimum specifications required by IFC schema [8].

The managers need to dedicate effort so that the project representation context must be specified ensuring that it provides the necessary information to support BIM collaborative efforts effectively at a high semantic level [9].

However, BIM actors must know more than software resources, also pursuing a basic understanding of OOP and the EXPRESS language (as a formal representation of data schema based on OOP) used by the schema to formally describe the data and relationships within BIM models.

In this study, the DSR method (Appendix 2A) was selected to address the research objectives and explore a typical demand in public organizations that promote the management of infrastructure projects. Aiming for replicability, the structure of the study was inspired by five topics: 1. Workflow - An overview of research associated with textual items; 2. Diagrams - The inheritance structure of the entities involved; 3. Information Requirements Mapping - Target data; 4. Protocol - Proposed export configuration; 5. SPF - Developed solution.

The first guideline of methodology presents the relevance of the problem. It sequentially involves mapping the potentially specifying data, aiming at the geometry representation context, the system of units, the geodetic system, alongside the project identification. Evolvingly, the data mapping outlined an in-depth investigation of the entities in the IFC data schema, potentially semantic to the representation context of a project, IfcProject. The main entities involved in IfcProject specification are IfcRoot, IfcObjectDefinition, IfcContext, IfcRepresentation, IfcGeometricRepresentationContext, IfcGeometricRepresentationSubContext, IfcUnitsInAssignment, IfcPropertyDefinition, IfcPropertySet, IfcRelationship, and IfcRelDefinesByProperties, classified in this paper on 3 frameworks: IDENTIFICATION, GEOMETRIC AND UNITS and FINANCIAL.

To mitigate the level of abstraction detected in this approach, entity Inheritance Diagrams were developed to best comprehend the data flow, rules, and relationships applicable to the research problem. They function as data translators, which consist of one auxiliary research contribution to BIM actors.

2.2 Background

2.2.1 Interoperability

The sight of the BIM paradigm, viewed through the project expanded spectrum is related to the phases of lifecycle. This is likely to increase the demand for a type of interoperability that is not restricted to compatibility, but is capable of contemplating the diverse parametric tools used by the different stakeholders involved in collaborative processes [10]. The interoperability demanded by these processes should be characterized by an open data standard that should support file exchange among BIM software as it must utilize the same machine-to-machine language [11].

Interoperability represents a mechanism that enables computer systems to automatically share and exchange data without requiring translation or human intervention. The IFC created to promote interoperability in civil industry, has been widely adopted by large software companies [12]. This adoption is due to the substantial number of attributes that are defined as optional (meaning are not mandatory) [13], consequently meeting the high fragmentation, a typical characteristic of the segment.

ISO 16739 highlights the formal representation bSI uses to formally define the information structure [14]. Due to its wide adherence to ISO 10.303:2016 (Industrial automation systems and integration - Product data representation and exchange) it encompasses a substantial number of documents providing a standardized methodology for the representation and exchange of digital product information across different systems and throughout the lifecycle of a product [15]. Specification data language EXPRESS is specified by ISO 10.303-11 [16].

The case of the IFC is dealt with in ISO 10.3030-21 (Standard for The Exchange of Product Data - STEP) [17]. The overall data exchange and representation standard serves as a widely utilized machine-readable instance file format.

The SPF (STEP Physical File) is a specific format used within STEP to store and transfer standardized data physically. The logic behind STEP is rooted in graph theory, a mathematical model characterized by connections that can represent real-world scenarios, including hierarchical relationships and connections between elements within a defined set [18]. This resource was taken into consideration to illustrate part of the SPF in analysis [19].

2.2.2 IFC 4.3

Ontology is an explicit specification of a conceptualization, models that formally define concepts, relationships, and axioms of a specific domain of knowledge, allowing for a clear and unambiguous representation of the involved semantics [21]. This semantic enables communication between both users and applications in fragmented, heterogeneous multinational business environments [22]. In the context of BIM, ontologies have been used to promote interoperability, allowing different systems and stakeholders to share a common understanding of the concepts and relationships involved in the workflows throughout the project lifecycle [23,24].

The interoperability of the IFC schema draws inspiration from the Object-Oriented Programming (OOP) paradigm, which operates within a framework centered on class hierarchy and the principle of inheritance [25]. This justifies the coherence of the schema fostering enhanced code maintainability and greater flexibility in library creation [26].

In order to deal with such a complex matter, the IFC architecture data was designed in four layers [27] (Fig. 2.1). IFC 4.3 data included the following infrastructure domains: Road; Rail; Ports and Waterways (domain layer). In addition to the interoperability layer applied to infrastructure elements are the Shared Infrastructure Elements.

The IFC data architecture can be compared to a natural tree. At the central layer of the schema is IfcRoot, which represents the root that connects the tree structure to the ground, providing the necessary resources to nourish it. The trunk represents the entities of the Core layer, establishing the link between the root and the entire structure above, supplying these nutrients to the branches (entities of the Interoperability layer), which in turn share them with the leaves or fruits (entities of the Domain layer). In parallel, a data translation mechanism was developed to assist managers with their customized demands. Thus, the entity Inheritance Diagram represents an auxiliary artifact capable of mitigating the level of abstraction in the IFC schema.

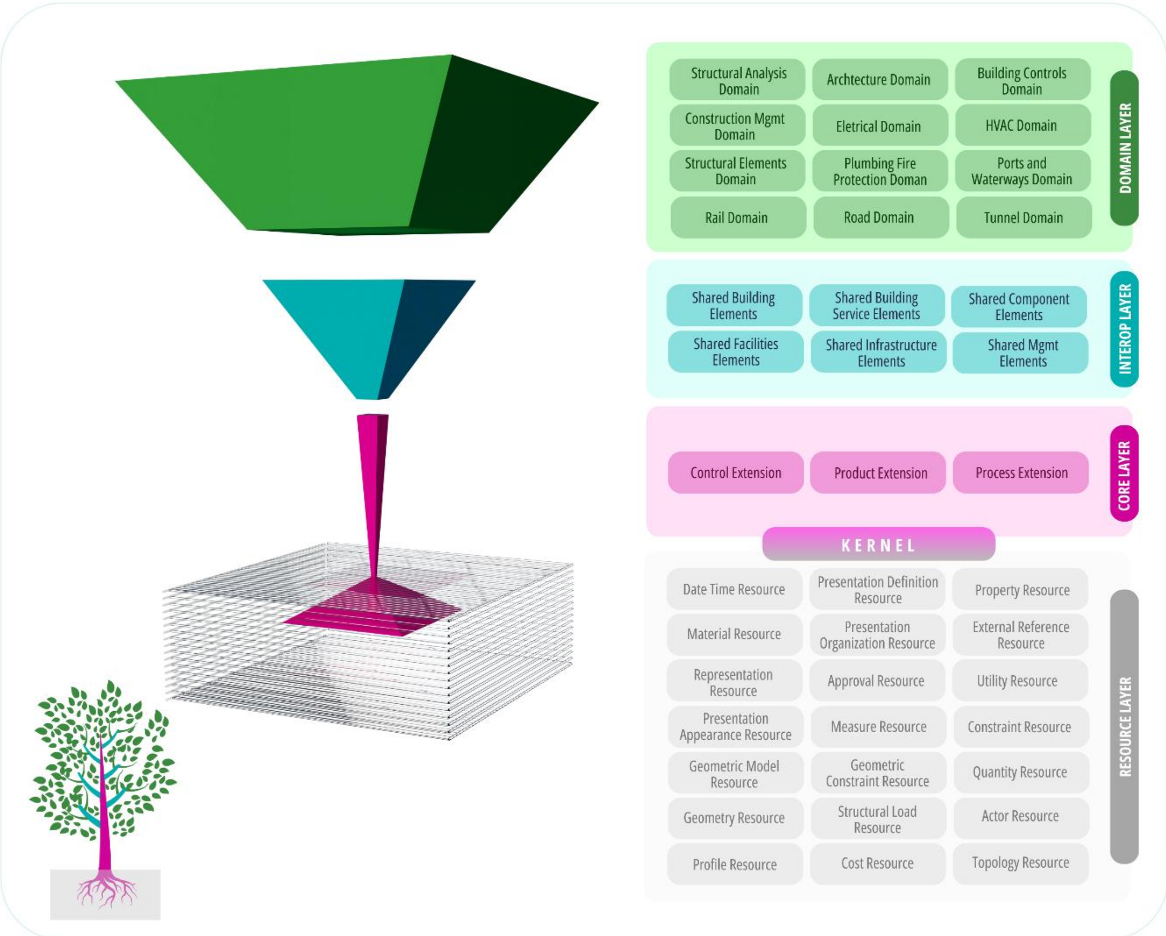

Fig. 2.1 IFC architecture data (3D Tree)
Source: the Author (2024)

2.2.3 Entity Inheritance Diagram

IfcProject originated in the Core layer and has been present in the schema since IFC version 1.0, serving as the general representation context for all other information regarding the various components constituting a construction model. This includes identification, geometric representation contexts, and properties linked to committed resources [28].

The declaration of IfcProject is complex, which motivated the development of its Inheritance Diagram in steps (Figure 2.2, Appendix 2B, and Appendix 2C) and Tables 2.1 and 2.2. The entity Inheritance Diagram shows direct and inverse attributes, cardinalities, rules, sets, and properties according to the bSI documentation. Which aims to meet the overall objective of the paper, relating them to the defined frameworks.

Figure 2.2 presented an entity Inheritance Diagram (applied to IfcProject) utilizing a family tree, a visual symbology capable of clarifying information and relationships among concepts or entities. The data representation employed includes abstract entities (shown with a gray background), instantiable entities (shown with a black background), type (in italics), mandatory attributes (in bold), optional attributes (displayed in regular writing), and inverse attributes (in italics). According to the buildingSMART (bSI) specification, IFC entities are numbered based on the layer number of the architectural data they originate from: 5 (Core); 6 (Interoperability), 7 (Domain), and 8 (Research).

2.2.3.1 IDENTIFICATION Framework

Specifies identification data of a model and declares relevant restrictions; IfcProject.Name must be specified due to imposed formality HasName `[EXISTS(SELF\IfcRoot.Name)]` and formal proposition (one of two schema rules) defines declaratory uniqueness in the schema:

```
RULE IfcSingleProjectInstance FOR (IfcProject);
WHERE WR1: SIZEOF(IfcProject) <= 1;
END_RULE;
```

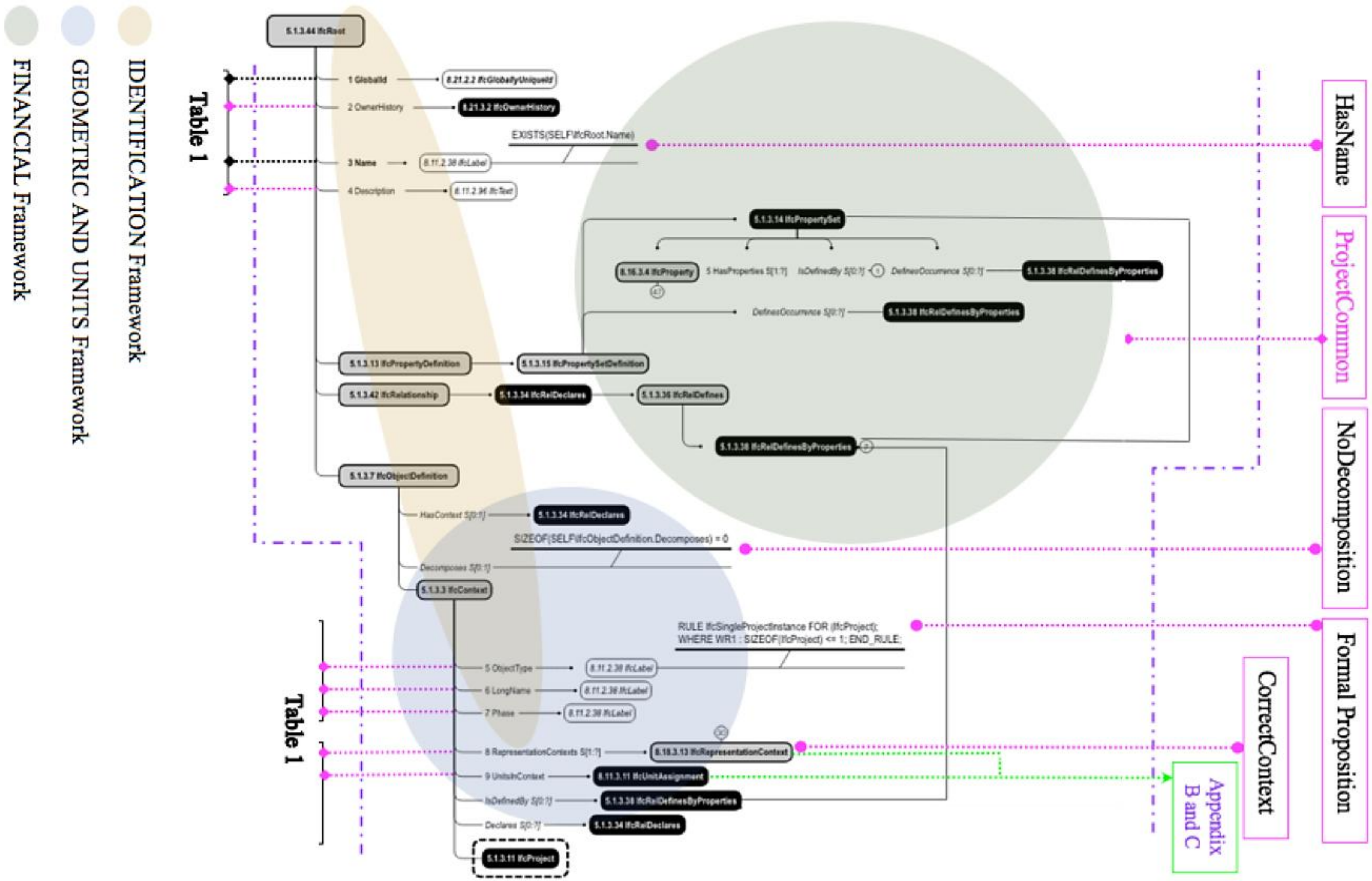

Fig. 2.2 IfcProject Inheritance Diagram
Source: the Author (2024)

Table 2.1. FRAMEWORK DATA

Frame work	Entity.Attribute	State	Extended particular meaning for IfcProject
IDENTIFICATION	IfcRoot.GlobalID	◆ Mandatory	-
	..OwnerHistory	◆ Optional	-
	..Name	◆ Mandatory	-
	..Description	◆ Optional	-
	IfcContext.ObjectType	◆ Optional	No further object
	...LongName	◆ Optional	-
	..Phase	◆ Optional	Current project phase or lifecycle phase of this project (a model)
GEOMETRIC AND UNITS	..RepresentationContexts S[1:?]	◆ Optional	-
	..UnitsInContext	◆ Optional	-
	IfcRepresentationContext.ContextIdentifier	◆ Optional	Identifier of the representation context as used within a project (a model)
	..ContextType	◆ Optional	-
	..RepresentationsInContext S[0:?]	-	-
	IfcGeometricRepresentationContext .CoordinateSpaceDimension	◆ Mandatory	-
	..Precision	◆ Optional	-
	..WorldCoordinateSystem	◆ Mandatory	Establishment of the engineering coordinate system for all representation contexts used by the project (a model)
	..TrueNorth	◆ Optional	The direction of the true north direction of a project
	..HasSubContexts S[0:?] FOR ParentContext	-	-
	..HasCoordinateOperation [0:1] FOR SourceCRS	-	-
	IfcGeometricRepresentationSubContext .ParentContext	◆ Mandatory	-
	..TargetScale	◆ Optional	-
	..TargetView	◆ Mandatory	-
	..UserDefinedTargetView	◆ Optional	-

Source: the Author (2024)

Table 2.2 Framework Data Pset_ProjectCommon

Framework	Property Name	Property Type	Data Type	Description
FINANCIAL	ProjectType	IfcProperty Enumerated Value	PEnum_ProjectType	Additional typing of a project. Project responsible for …
			.MODIFICATION.	… the modification of a facility
			.NEWBUILD.	… the development of a new build facility
			.OPERATION MAINTENANCE.	… operation & maintenance
			.RENOVATION.	… renovation of a facility
			.REPAIR.	… the repair to a facility
	ProjectInvestment Estimative	IfcProperty ReferenceValue	IfcCostValue	Estimate of investment cost
	FundingSource	IfcProperty SingleValue	IfcLabel	Investment funding source
	ROI	IfcProperty SingleValue	IfcRatioMeasure	Return on Investment
	NetEarnedValue	IfcProperty ReferenceValue	IfcCostValue	Net earned value
	PaybackPeriod	IfcProperty SingleValue	IfcDuration	Payback period of investment
	IsDefinedBy S[0:?]	IfcRelDefinesByProperties FOR RelatedObjects		Binds properties set to IfcPropertySet

Source: the Author (2024)

2.2.3.2 GEOMETRIC AND UNIT Framework

Declares many qualitative and quantitative specifications. Hence, the criteria specification of them is essential to guarantee the interoperability required by collaborative processes. An important restriction is present and this `[SIZEOF(SELF\IfcObjectDefinition.Decomposes) = 0]`, the condition shall be IfcProject on the root of the spatial structure tree, and not be used to decompose any other object definition.

GEOMETRIC Framework is specified initially by IfcContext.RepresentationContexts allow it to instantiate multiple representation contexts and subcontexts derived from them [29]. Specified by IfcRepresentationContext, ContextIdentifier defines the identification of a geometric representation, and ContextType the respective type, which can be applied to a model view `[Model]`; plan view `[Plan]`; or not defined `[NotDefined]`. More than one representation context is generally included for the model and, each context may contain derived subcontexts.

In this scenario, IfcGeometricRepresentationSubContext inherits attributes from its supertype, and one special condition is specified: the context instance from which it was derived. So, as a rule, the ParentContext attribute establishes this mandatory link.

HasSubContexts attribute enables geometric representation subsets to be linked to the main context representation and HasCoordinateOperation reports the project geodetic system and, subsequently, establishes a relationship with the project coordinate system.

This coordinate is linked to the WorldCoordinateSystem attribute and represents a relevant reference for disciplines (models) involved throughout the project lifecycle, on 3D coordination. Appendix 2B presents the entity Inherited Diagrams.

UNIT Framework is specified by IfcContext.UnitsInContext, playsing a crucial role in the schema [30], as it defines the set of units used to represent the model through IfcUnitAssignment, which is declared once: `[WR01:IfcCorrectUnitAssignment(Units)].` Local units can be defined differently from those handled globally, and in such instances, they can be declared as long as they do not create redundancy for the same type of unit.

The default measurement units are selected in nature (IfcNamedUnit, IfcMonetaryUnit, and IfcDerivedUnit), and they apply to geometric representation objects, attributes, properties, and quantities. Even though IfcProject is linked to considerable declaratory diversity, demands for local units that are not declared in the general context may occur, such as the monetary unit specified by ISO 4217 [31].

The conversion (IfcConversionBasedUnit and IfcConversionBasedUnitWithOffSet) units declare, through IfcDimensionalExpoents, seven essential magnitudes [Length, Mass, Time, Electric current, Thermodynamic Temperature, Amount of material, Light Intensity]. Appendix 2C illustrates the entity Inheritance Diagrams.

2.2.3.3 FINANCIAL Framework

Financial Framework represents a single set specified by IFC4.3 “ProjectCommon” (Table 2.2) for applying high-level project information [32]. The set links IfcProject to the typing of a project and financial properties in which resources are allocated [33]. The typing is specified by enumerated data PEnum_ProjectType `[.MODIFICATION.,.NEWBUILD.,.OPERATIONMAINTENANCE.,.RENOVATION.,.REPAIR.].` The Property Sets for Contexts concept template describes how a context may be related to a single or multiple property set.

2.3 Method

Design Science serves as the epistemological basis and the Design Science Research (DSR) is the foundation and operationalization for conducting research when the objective to be achieved is an Artifact [34,35,36]. Considering the research-specific objectives, that method has been considered appropriate for this study because its form aims to produce innovative constructions to solve real problems.

The DSR guidelines [37] are detailed in Appendix A. Initially, an in-depth investigation into the IFC data schema was conducted with the aim of semantically translating the identified problem. Gradually, the research was guided by mapping information requirements that may be demanded by organizations in the development of BIM projects. The envisioned structure was based on the three frameworks.

2.3.1 Information Requirements Mapping

The relationship between the potential semantic entities present in the IFC data schema and the demand of the Project representation context were mapped (Figure 2.3) and the engineering choices were explicitly stated, as follows:

A. Identifying the organizational process that leads to the hiring of the project [IfcProject.Name] - Reveals the identity of the organization process;
B. Describing the project being contracted [IfcProject. Description] - Clarifies the BIM use of a model contracted;
C. Indicating the lifecycle phase of the tendered Project [IfcProject.Phase] - Raises the semantic level;
D. Specifying the project coordinate system [IfcGeometricRepresentationContext.WorldCoordinateSystem and .HasCoordinateOperation] - Meets the identification of the project geodesic system and its relation with the engineering coordinate system;
E. True north direction [IfcGeometricRepresentationContext.TrueNorth] - Meets the specification for simulations and anomalies analyses;
F. Defining the level of precision of geometry [IfcGeometricRepresentationContext.Precision] - Mitigates errors in multidisciplinary compatibility processes;
G. Specifying 3D and 2D representation contexts [IfcGeometricRepresentationContext.SpaceCoordinateSystem] - Establishes standards for 3D Coordinate team;

H. Specifying measurement unit system target [IfcProject.UnitsInContext] - Establishes standards for the 3D Coordinate team and informs the current monetary unit target;

I. Revealing the financial markers for development and overall responsibility [Pset_ProjectCommon, declared by IfcProject] - Specifies financial standards required by the organization.

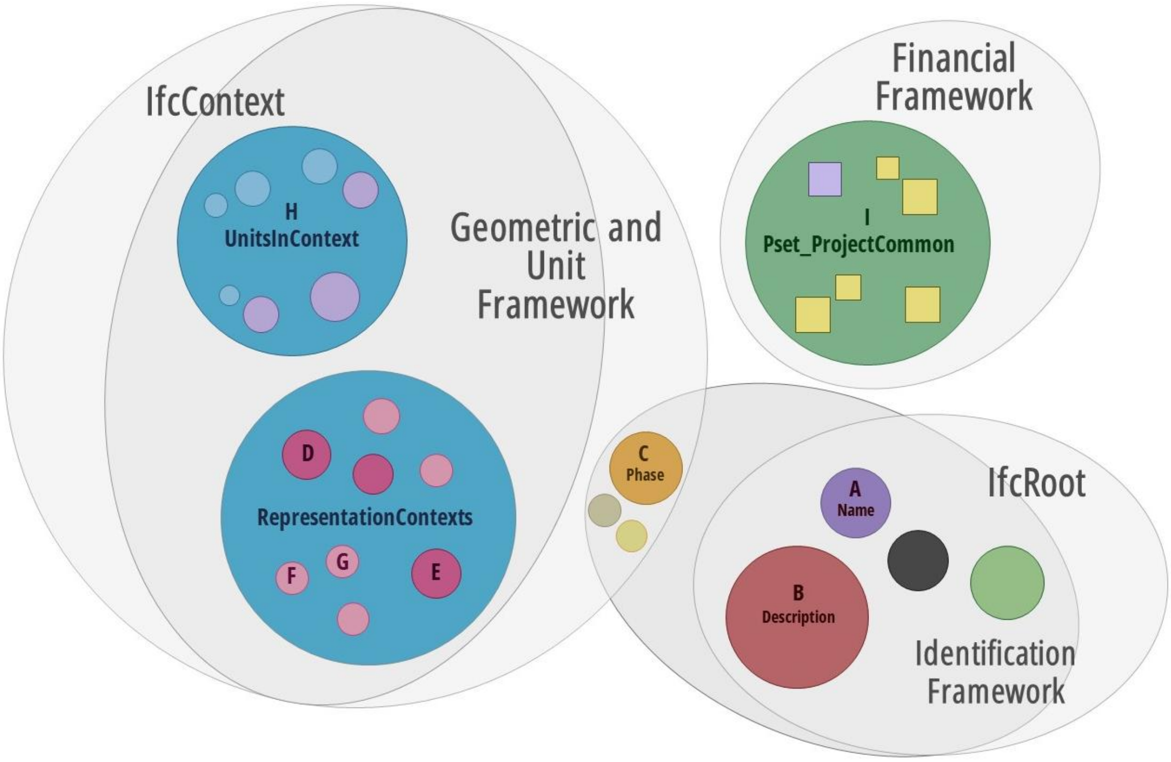

Fig. 2.3 Research Data framework
Source: the Author (2024)

2.3.2 Object of Study (original SPF)

The theoretical application guided by the frameworks was used to explore the resources offered by the working interface. The research scenario was inspired by a real demand experienced by the Brazilian public organization that requires the contracting of a bridge As-is model [38].

The object of study is represented by the SPF generated from the default export process [4x3 Experimental] of the BIM software (Revit). A portion of the generated SPF file is listed (Listing 2.1). and its respective graph is shown (Figure 2.4). Due to limitations in file extension and text, missing entities in the IfcProject instance [#90] are not shown, and the other instantiated entities are referenced at least at the first level.

Listing 2.1

```
ISO-10303-21;
…
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1655308848);
#82=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,#42,#46,#47,
#48,#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,#71,#72,#73,#74,#76,#77
,#78,#79,#80,#81));
#83=IFCAXIS2PLACEMENT3D(#3,$,$);
#84=IFCDIRECTION((6.1230317691118863E-17,1.));
#85=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.001,#83,#84);
#86=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#85,$,.GRAPH_VIEW.,
$);
#87=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,*,#85,$,.MODEL_VIEW.,
$);
#88=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Box','Model',*,*,*,*,#85,$,.MODEL_VIEW.,$
);
#89=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('FootPrint','Model',*,*,*,*,#85,$,.MODEL_V
IEW.,$);
#90=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,' ',$,$,' ',' ',(#85),#82);
…
```

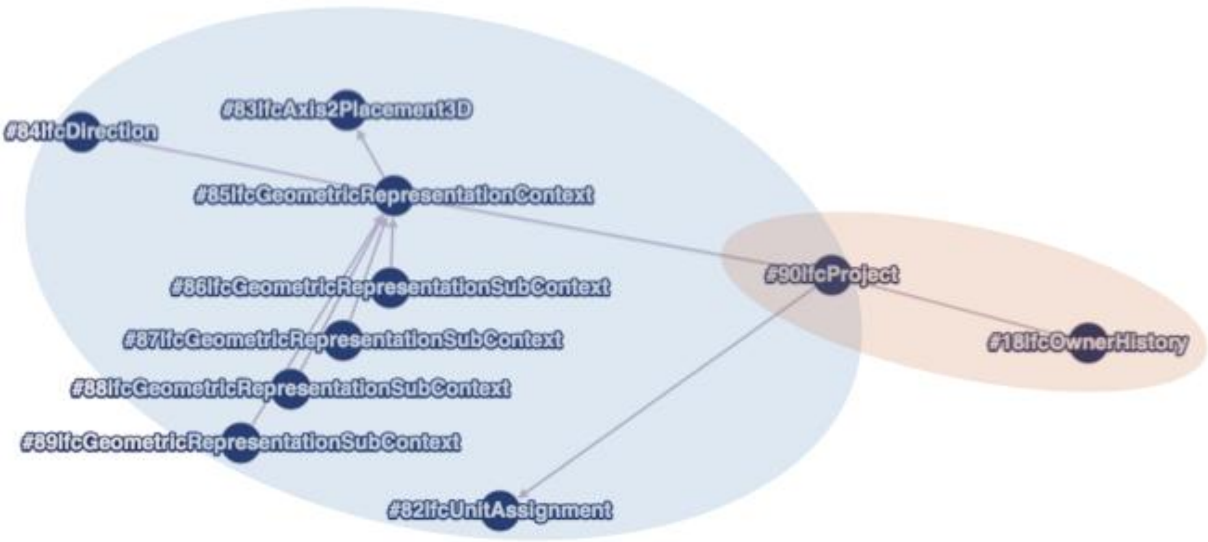

Fig. 2.4 Graph of Listing 2.1
Source: the Author (2024)

Regarding the IDENTIFICATION framework, it was found that GlobalId and OwnerHistory attributes were declared according to the bSI specification. However, Name, LongName, and Phase were revealed in the pattern ['']. Unlike Description and ObjectType, also optional, revealed a pattern of optional values [$].

The demand for the GEOMETRIC AND UNIT framework was not satisfactorily met through the declaration of RepresentationContexts, because the geodesic system was not informed and the true north direction followed the software default pattern [6.1230317691118863E-17,1.]. Despite being clearly specified, the units, IfcUnitAssignment, did not address the declaration of monetary unit.

Regarding the FINANCIAL framework, while the IFC 4.3 schema incorporates Pset_ProjectCommon, the associated properties were not declared.

2.3.3 Developing a Protocol

The main goal of the Protocol developed was to form a dense database, capable of solidly supporting future analyses, however, the results could not fully address the demand. The export configuration was as comprehensive as possible, carried out by a software manual [39].

Drawing upon the study specifics and initial model analyses, the export Protocol was configured from the IFC [4x3 Experimental] by Autodesk Revit version 2024. The options selected are shown in Appendix D, and the explanation provided clarifies the information indicated.

It is worth noting that the Protocol did not achieve 100% performance concerning the mapped demand, and in this regard, the subsequent steps were crucial in addressing the research problem. For this reason, the Protocol ws considered an auxiliary artifact.

2.3.4 Constructing a solution – Artifact

The development of the complete solution was carried out manually, assisted by SPF file post-Protocol. The new data (and information) was insert and IfcProject, IfcGeometricRepresentContext (Appendix 2B), and IfcUnitsInContext (Appendix 2C) Inheritance Diagrams were applied.

i. The IDENTIFICATION framework was cleared and the ObjectType attribute was modified [Not applicable] since inheritance from IfcContext, thus, there was no further PreDefinedType enumeration;
ii. The GEOMETRIC AND UNITS framework had the Precision attribute informed `[1E-5]` to meet the bSI specification and IfcMonetaryUnit `[#69]` informed `[‘BRL’];`
iii. FINANCIAL framework: The Python console of Blender software enabled importing IfcOpenShell [40] to fulfill the GlobalId attribute, highlighted in blue (Fig. 2.5) to insert new

data (IfcRoot subtypes). The other properties of the set were selected and justified in Table 2.3.

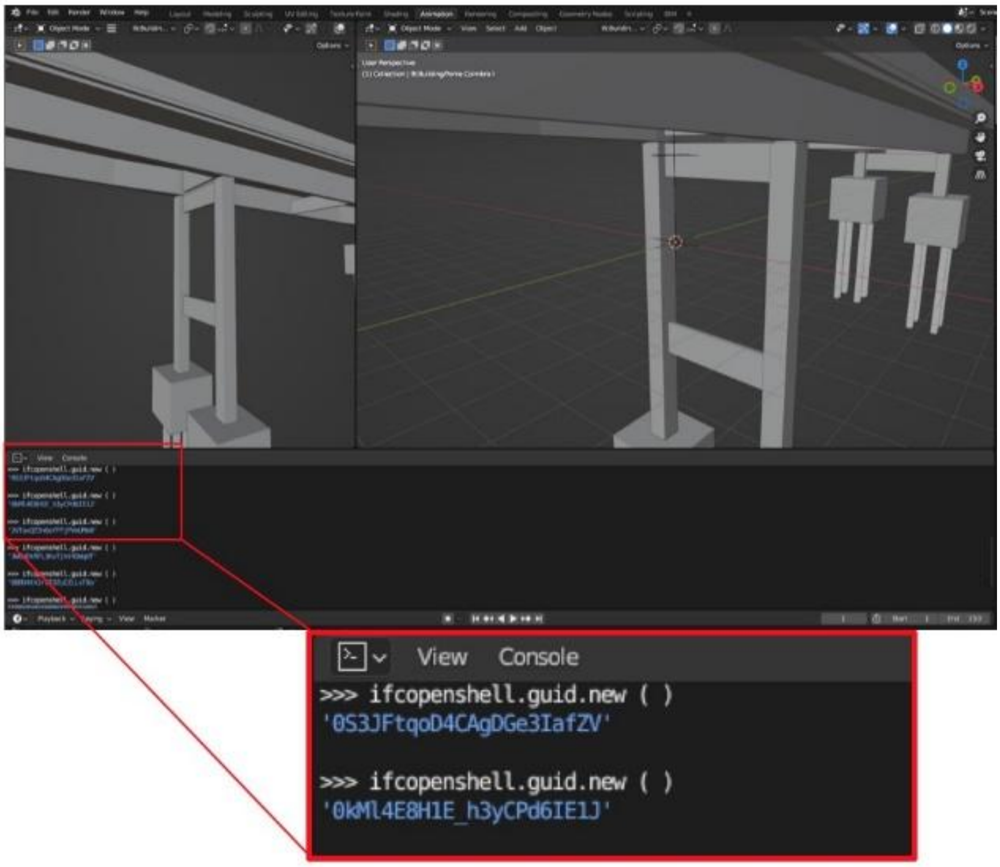

Fig. 2.5 Phython console
Source: BlenderBIM, 2024 (adjusted)

Table 2.3 Pset_ ProjectCommon (5.1.4.2)

# Line of SPF Property Name or Entity GlobalId	Property Type Data Type of property	Description
#80001 ProjectType	IfcPropertyEnumeratedValue (8.16.3.8) PEnum_ProjectType (5.1.8.1)	Typing of a project
#80002 ProjectInvestmentEstimate	IfcProperytReferenceValue (8.16.3.12) IfcCostValue (8.4.3.2)	Statement of the estimated value to be invested
#80003 FundingSource	IfcPropertySingleValue (8.16.3.12) IfcLabel (8.11.2.38)	Declaration of funding source

# Line of SPF Property Name or Entity GlobalId	Property Type Data Type of property	Description
#80004 IfcPropertySet (5.1.3.14) 0S3JFtqoD4CAgDGe3IafZV		Set declaration according to bSI specification
#80005 IfcRelDefinesByProperties (5.1.3.38) FOR RelatedObjects 0kMl4E8H1E_h3yCPd6IE1J		Relationship to connect ProjectCommon and IfcProject
#80001 ProjectType	IfcPropertyEnumeratedValue (8.16.3.8) PEnum_ProjectType (5.1.8.1)	Typing of a project
#80002 ProjectInvestmentEstimate	IfcProperytReferenceValue (8.16.3.12) IfcCostValue (8.4.3.2)	Statement of the estimated value to be invested
#80003 FundingSource	IfcPropertySingleValue (8.16.3.12) IfcLabel (8.11.2.38)	Declaration of funding source
#80004 IfcPropertySet (5.1.3.14) 0S3JFtqoD4CAgDGe3IafZV		Set declaration according to bSI specification
#80005 IfcRelDefinesByProperties (5.1.3.38) FOR RelatedObjects 0kMl4E8H1E_h3yCPd6IE1J		Relationship to connect ProjectCommon and IfcProject

Source: the Author (2024)

2.4 Results

2.4.1 Protocol

The results from the Protocol correspond to the lines highlighted in red in Listing 2.2 and respectively graph (Figure 2.6), both on the next page. The number of lines has increased, consequently, not conform to the same ones instantiated in Listing 2.1.

Listing 2.2

```
ISO-10303-21;
…
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1687808747);
…
#69=IFCMONETARYUNIT('');
…
#83=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,
#42#46,#47,#48,#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,
#71,#72,#73,#74,#75,#77,#78,#79,#80,#81,#82));
#84=IFCAXIS2PLACEMENT3D(#3,#5,#9);
#85=IFCDIRECTION((0.23186335354699686,0.97274836688731603));
```

```
#86=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.001,#84,#85);
#87=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#86,$,
.GRAPH_VIEW.,$);
#88=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,*,#86,$,
.MODEL_VIEW.,$);
#89=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Box','Model',*,*,*,*,#86,$,
.MODEL_VIEW.,$);
#90=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('FootPrint','Model',*,*,*,*,#86,
$,.MODEL_VIEW.,$);
#91=IFCPROJECTEDCRS('EPSG:4674','SIRGAS 2000','SIRGAS 2000 Estacao
8079812',$,$,$,#20);
…
#93=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',2,0.001,#84,#85)
#94=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Annotation','Plan',*,*,*,*,#93,
0.001,.PLAN_VIEW.,$);
#95=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'',$,$,$,'',(#86,#93),#83);
```

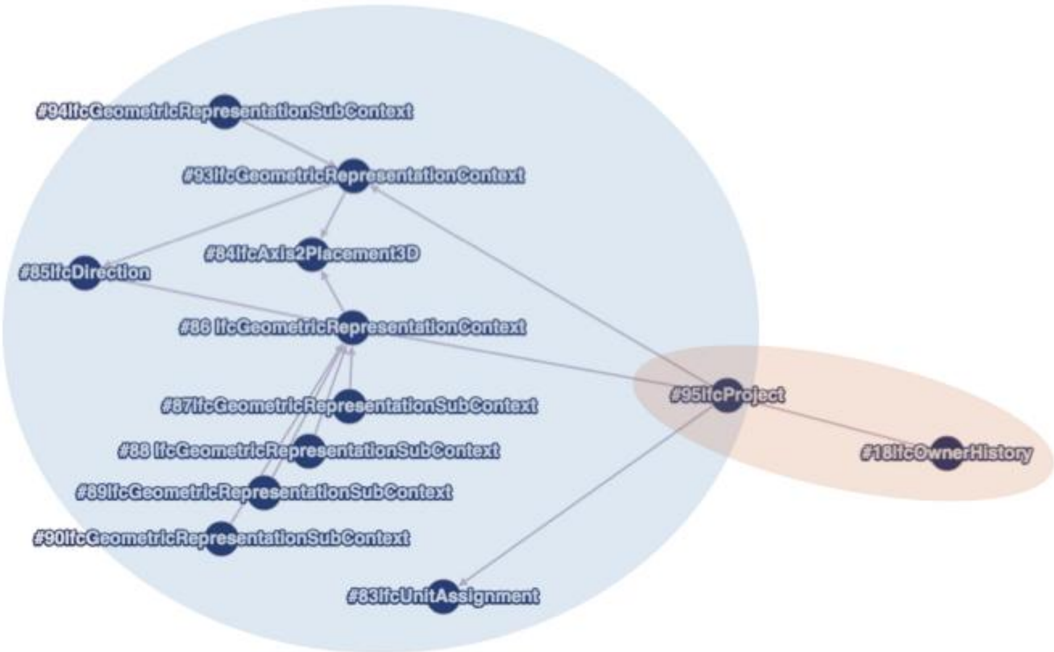

Fig. 2.6 Graph of Listing 2.2
Source: the Author (2024)

2.4.2 Artifact

Protocol information is continuously shown in red and the manually entered inserts are numbered listings as green additions (Listing 2.3). Respectivy graph on next page (Figure 2.7).

Listing 2.3

```
ISO-10303-21;
…
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1687808747);
#69=IFCMONETARYUNIT('BRL');
#83=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,
#42#46,#47,#48,#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,
#71,#72,#73,#74,#75,#77,#78,#79,#80,#81,#82));
#84=IFCAXIS2PLACEMENT3D(#3,#5,#9);
```

```
#85=IFCDIRECTION((0.23186335354699686,0.97274836688731603));
#86=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.00001,#84,#85);
#87=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Axis','Model',*,*,*,*,#86,$,
.GRAPH_VIEW.,$);
#88=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,*,#86,$,
.MODEL_VIEW.,$);
#89=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Box','Model',*,*,*,*,#86,$,
.MODEL_VIEW.,$);
#90=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('FootPrint','Model',*,*,*,*,#86,
$,.MODEL_VIEW.,$);
#91=IFCPROJECTEDCRS('EPSG:4674','SIRGAS 2000','SIRGAS 2000 Estacao 8079812',$,$,$,#20);
…
#93=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',2,0.00001,#84,#85)
#94=IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Annotation','Plan',*,*,*,*,#93,
0.00001,.PLAN_VIEW.,$);
#95=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2023-46','Contratacao de servico para elaboracao do Modelo As-is do viaduto Coimbra I','Nao se aplica',$,'Operacao',(#86,#93),#83);
…
#80001=IFCPROPERTYENUMERATEDVALUE('ProjectType',$,(IFCPROPERTYENUMERATION(.OPERATIONMAINTENAN
CE.)),$);
#80002=IFCPROPERTYREFERENCEVALUE('ProjectInvestimentEstimate',$,'Planilha de composicao de custo preliminar',$);
#80003=IFCPROPERTYSINGLEVALUE('FundingSource',$,IFCLABEL('Recurso do Ministerio dos Transportes'),$);
#80004=IFCPROPERTYSET('0S3JFtqoD4CAgDGe3IafZV',#18,'Pset_ProjectCommon',$,(#80001,#80002,#800
03));
#80005=IFCRELDEFINESBYPROPERTIES('0kMl4E8H1E_h3yCPd6IE1J',#18,$,$,(#95),
#80004);

ENDSEC;
END-ISO-10303-21;
```

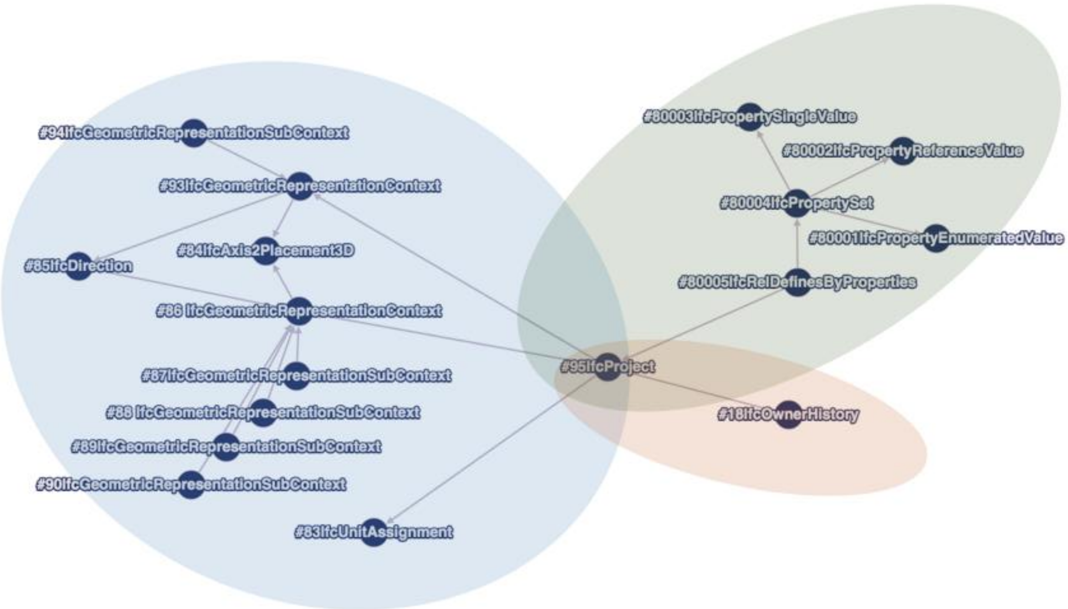

Fig. 2.7 Graph of Listing 2.3
Source: the Author (2024)

In Figure 2.8, the scenario of progression of results obtained in the research is illustrated (shadow of the SPF graphs). The effectiveness of the artifact is evident in the final stage (2.8c), even though the Protocol (2.8b) added considerably more data compared to the initial stage (2.8a). This additionally demonstrates the proper performance of the applied method.

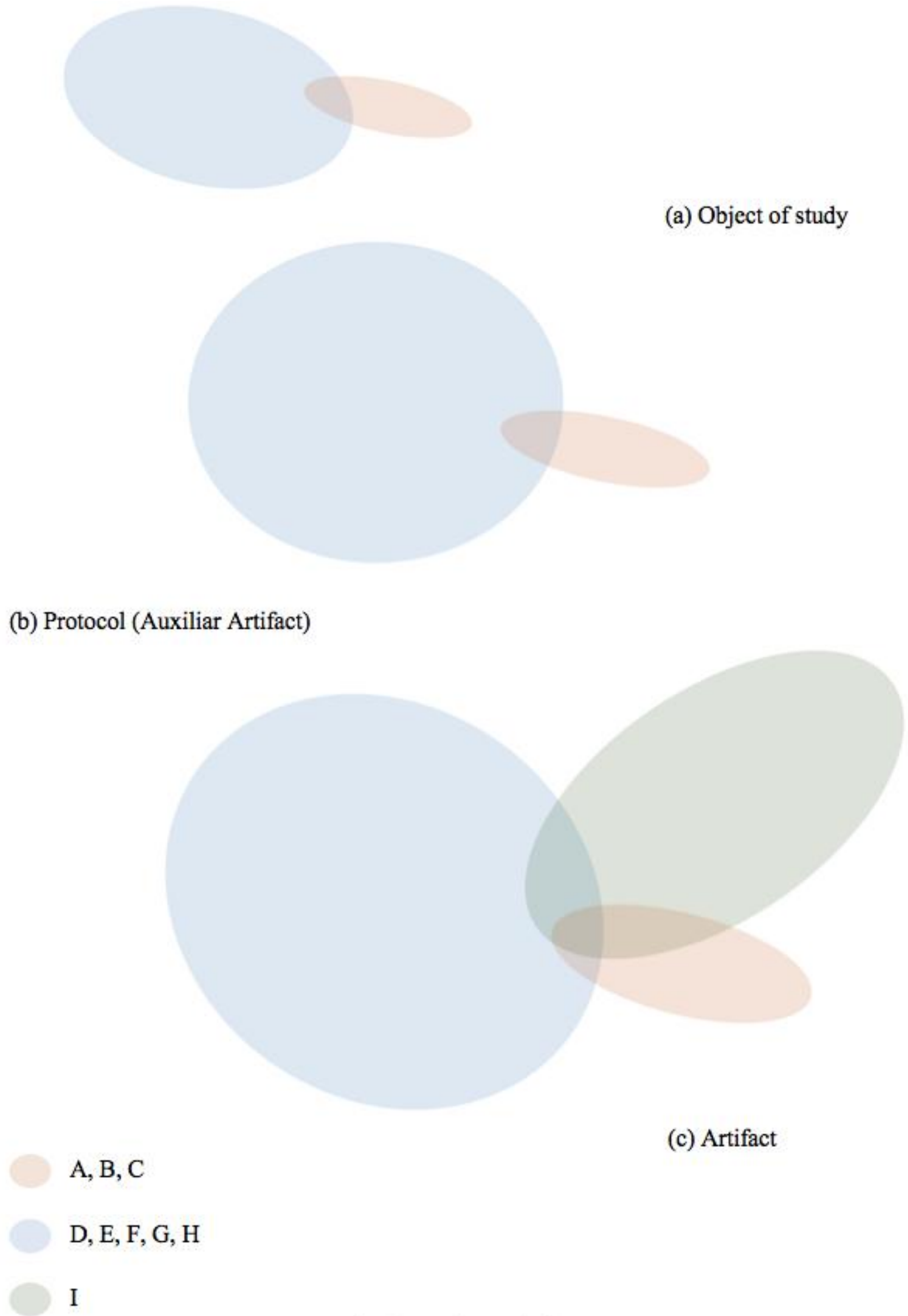

Fig. 2.8 Results Evolution
Source: the Author (2024)

Figure 2.9 illustrates the IfcProject Instance Diagram, which is designed to demonstrate the effectiveness of this representation mechanism and to clearly present all theoretical studies related to the representation context of a project. The instance diagram represents the SPF line `[#95]` from Listing 2.3.

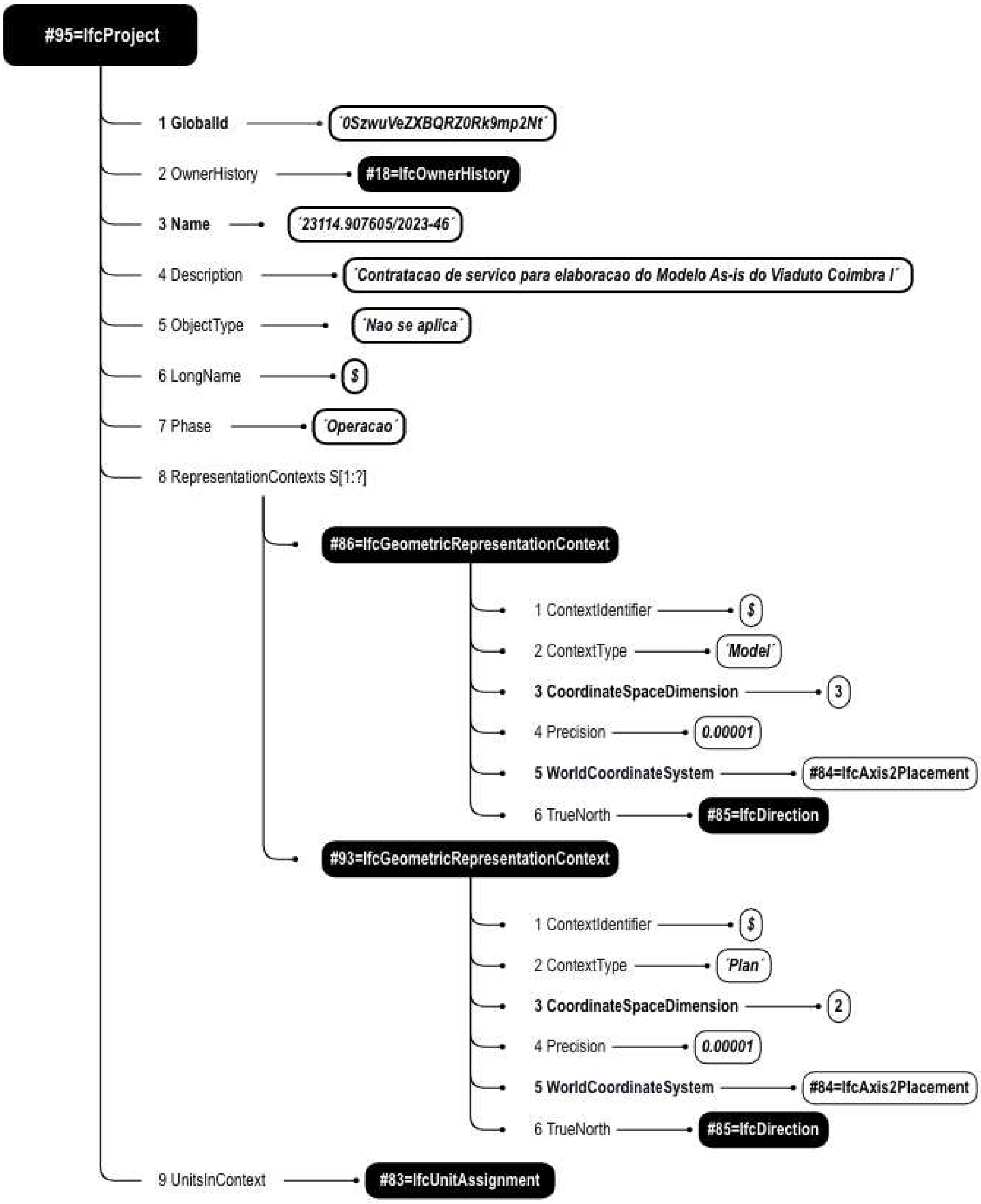

Fig. 2.9 IfcProject Instance Diagram
Source: the Author (2024)

IfcProject.UnitsInContext specified a dense instance [#83]. Just as entity Inheritance Diagrams can be applied to instances of entities, graphs may illustrate instances with a high level of density (Figure 2.10).

Listing 2.4

```
#83=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,#42#46,#47,
#48,#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,#71,#72,#73,#74,#75,
#77,#78,#79,#80,#81,#82));
```

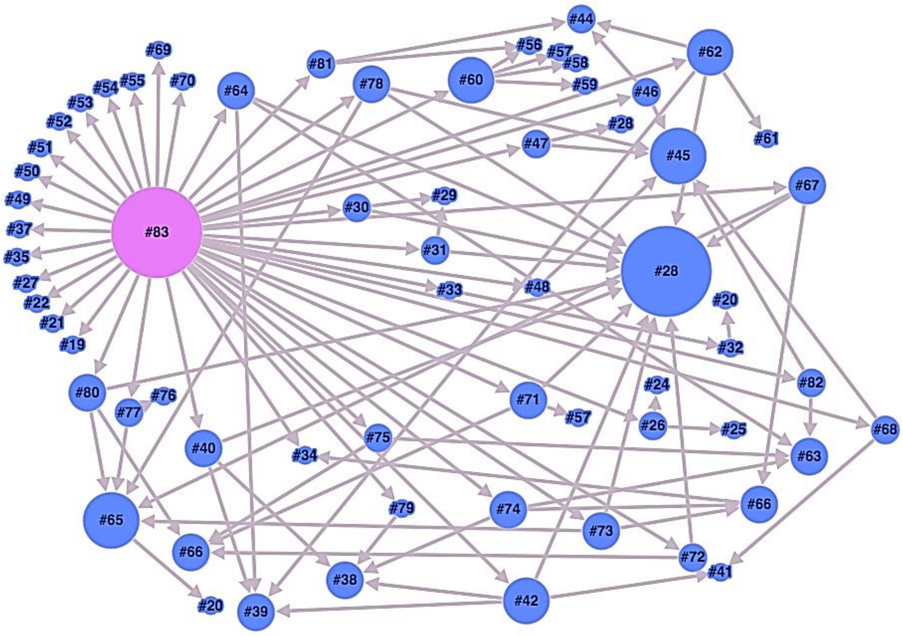

Fig. 2.10 IfcUnitAssignment Graph
Source: the Author (2024)

2.5 Analysis

Even if the modeler revealed the mapped information requirements and applied the developed Protocol, the three requirements mapped would not be met: B, H, and I (Description, Monetary Unit Target, and Financial information).

The framework IDENTIFICATION was not fully met on protocol, since there is no field in the software interface capable of clarifying the model description, unlike Name (Project Number) and Phase (Project Status), possible by Manage, and Project Information source.

In turn, the GEOMETRIC AND UNIT framework was specified: project geodetic system was duly informed in the Geographic Reference Tab on Protocol and reflected new data `[#91]`, while instance `[#85]`, geodesic system reference, and true north direction were informed as due. IfcMonetaryUnit was specified but not informed, so it was reflected in IfcUnitsAssignment with one more unit, 82 entities overall. The software interface does not provide resources for specifying monetary unit. This same issue occurred with the financial data, and consequently, the FINANCIAL framework was not reported after the execution of the Protocol, even though it was configured to export property sets.

The evolutionary pattern of the research was analyzed quantitatively by comparing the entities (E) and attributes (A) existences between the original SPF and the final SPF (Table 2.4).

Table 2.4 Quantitative evaluation

Entity / Attribute	Original SPF	Artifact SPF
MonetaryUnit (E)	**0**	**1**
Currency (A)	**0**	**1**
TrueNorth (A)	**1**	**1**
Precision (A)	**1**	**1**
ProjectedCRS (E)	**0**	**1**
Name (A)	**0**	**1**
Description (A)	**0**	**1**
GeodeticDatum (A)	**0**	**1**
GeometricRepresentationContext [Plan] (E)	**0**	**1**
ContextType (A)	**0**	**1**
CoordinateSpaceDimension (A)	**0**	**1**
Precision (A)	**0**	**1**
GeometricRepresentationSubContext [Plan] (E)	**0**	**1**
ContextIdentifier (A)	**0**	**1**
ContextType (A)	**0**	**1**
TargetView (A)	**0**	**1**
Name (A)	**1**	**1**
Description (A)	**1**	**1**
Phase (A)	**1**	**1**
PropertyEnumeratedValue (E)	**0**	**1**
Name (A)	**0**	**1**
EnumerationValues (A)	**0**	**1**
PropertyReference|Value (E)	**0**	**1**
Name (A)	**0**	**1**
UsageName (A)	**0**	**1**
PropertySingleValue (E)	**0**	**1**
Name (A)	**0**	**1**
NominalValue (A)	**0**	**1**
PropertySet (E)	**0**	**1**
GlobalId (A)	**0**	**1**
Name (A)	**0**	**1**
HasProperties (A)	**0**	**1**
RelDefinesByProperties (E)	**0**	**1**
GlobalId (A)	**0**	**1**
RelatedObjects (A)	**0**	**1**
Total	**5**	**35**

Source: the Author (2024)

Thirty new occurrences were observed: nine specified entities (E), and twenty-one informed attributes (A). The five attributes from the original SPF were adjusted (*). In this scenario, the artifact added a significant increase (600%) fully meeting the information requirements mapped in the initial research stage.

Aiming to analyze the semantic level of the original SPF and the SPF artifact, scores were assigned only twenty-six attributes (twenty-one new and five adjusted) were considered (Table 2.5). The sequence of attributes used in Table 2.4 was preserved on Table 2.5.

0= Absent information ($);

1= Information does not meet the standard value suggested by the bSI documentation;

2= Information meets the bSI standard specification but lacks meaning (´ `);

3= Information meets the bSI standard specification and has meaning.

Table 2.5 Semantic level evaluation

Attribute	Original SPF	Artifact SPF
Currency	**0**	**3**
TrueNorth *	**2**	**3**
Precision *	**1**	**3**
Name	**0**	**3**
Description	**0**	**3**
GeodeticDatum	**0**	**3**
ContextType	**0**	**3**
CoordinateSpaceDimension	**0**	**3**
Precision	**0**	**3**
ContextIdentifier	**0**	**3**
ContextType	**0**	**3**
TargetView	**0**	**3**
Name *	**2**	**3**
Description *	**0**	**3**
Phase *	**2**	**3**
Name	**0**	**3**
EnumerationValues	**0**	**3**
Name	**0**	**3**
UsageName	**0**	**3**
Name	**0**	**3**
NominalValue	**0**	**3**
GlobalId	**0**	**3**
Name	**0**	**3**
HasProperties	**0**	**3**
GlobalId	**0**	**3**
RelatedObjects	**0**	**3**
Total	**7**	**78**

Source: the Author (2024)

In this scenario, analyzed by the semantic spectrum, the level of the final SPF raised from seven to seventy-eight. The semantic analysis reveals a significant 1014,29% increase in the semantic level compared to the original SPF.

This finding demonstrates that the IFC data structure allows software manufacturers to enhance semantic performance and consequently, improve information interoperability between different systems.

2.5.1 Artifact Validation

The artifact was validated using two types of visualization software: Blender Add-on BIM (v. 0.0.230824) [41]; and usBIM.browser (v. 1.6.73) [42]. The findings are illustrated and detailed in a report (Appendix E). The report was designed based on the following frameworks.

The lines analyzed in the SPF file are highlighted at the top of the document, and the visualizations were illustrated according to the respective software interface. The status indicates what each viewer was able to recognize and also demonstrates the results throughout the Artifact.

The skills of Blender BIM and usBIM.browser software complemented each other and enabled the necessary contextualizations by establishing comprehensive comparative standards that consolidated the overall objective of the paper.

2.6 Discussion

It was observed that most of the data described in Tables 2.1 and 2.2 have semantics related to the model, even though the documentation uses the word "project." The inappropriate use of the term in the bSI specification might work against the interoperability of an open standard at a high semantic level, as desired.

The new set included in IFC 4.3 through the ProjectType offers the choice of the project purpose, essentially as a new project `[.NEWBUILD.]`, or facility `[.MODIFICATION., .OPERATIONMAINTENANCE.,.RENOVATION.,.REPAIR.]`. In the case of the object of study, which aims to reflect a facility, the chosen option was `[.OPERATIONMAINTENANCE.]`.

However, the other properties of the set are not explicit if the financial data relation is of a model or a project. Next, details will follow from the perspective of the frameworks.

2.6.1 IDENTIFICATION Framework

IfcProject.Name informed the identity of the organization legal process that gave rise to the contracting the modeling process, .Description detailed it, and, optionally, .LongName (optional) was not cleared.

Due to the model information characteristics, it would be more appropriate for the attribute to be declared of IfcText, as it eventually exceeds the limit of 255 characters. Phase attribute semantically elevates the IfcProject declaration since the same BIM use can occur in different project life cycle phases [37].

Applying this approach to the object of study, the attribute specifies `['Operation']` and, then, semantically adds meaning it is the modeling of a facility and not of a new one. This narrative would justify the mandatory specification rather than an optional one.

2.6.2 GEOMETRIC AND UNITS Framework

IfcGeometricRepresentionContext preliminarily specified Precision and Dimension attributes (F and G information requirement mapped) adequately, but informed neither the identification of the geodetic system of a project (SourceCRS) no the precise direction of true north, even though the modeling of the existing bridge had been developed from the georeferenced point cloud. These findings reflect the importance of configuring the Geographic Location Tab on the Protocol.

IfcUnitAssignment succinctly `[#83]` revealed 74 lines of the SPF file that declared the main units, derivatives, converted, and currency, and together, IfcProject.RepresentationContexts and .UnitsInContex represent dense data.

2.6.3 FINANCIAL Framework

The software usBIM.browser showed exceptional results in the financial data that revealed the set completely. Unlike BlenderBIM, it presented default options for the user to fill in, but the ProjectInvestimentEstimate property was missing.

BlenderBIM indirectly influenced of IfcPropertySet and IfcRelDefinesByProperties entities, as they are subtypes of IfcRoot and IfcGloballyUniqueId specification was possible by the Python console on the software interface.

The research gaps originate from failures during the modeling process due to either the lack of information input (modeler) or the absence of data in the work interface (software) and could be partially resolved by the Protocol, and, completely, by the Artifact.

Table 2.6 presents the list of issues identified to attend to the mapped demand (A until I except F, and G). All of lacks are responsibility from software and / or modeler.

Those issues demonstrated how is relevant BIM actors seek guidance in the bSI documentation to specify the requirements imposed by the execution plans they are obliged to meet, which are optionally not declared by the software they used. In this way, the most significant contribution of this work is the mapping of potentially semantic entities aimed at specifying IFC data responsible for the Project representation specified by IfcProject.

Table 2.6 List of issues found

# of Listing	Issue Nature	Data	Responsibility		Solution by
#90 Listing 3 **A**	Information	IfcProject.Name	Modeler	Not informed	Artifact
#90 Listing 3 **B**	Information	IfcProject.Description	Software	No data on the interface	Artifact
#90 Listing 3 **C**	Information	IfcProject.Phase	Modeler	Not informed	Artifact
#91 Listing 2 **D**	Data	IfcProject.Representation Contexts IfcGeometricRepresentation Context.*HasCoordinate Operation* FOR SourceCRS	Software and Modeler	Modeler used default exportation process	Protocol
#84 Listing 2 **E**	Information	IfcProject.Representation Contexts IfcGeometricRepresentation Context.TrueNorth			
#69 Listing 3 **H**	Information	IfcProject.UnitsInContext IfcUnitAssigment.Units IfcMonetaryUnit	Software	No data on the interface	Artifact
(#80001, #80005) Listing 3 **I**	Data and information	Pset_ProjectCommon	Software	No data on the interface	Artifact

Source: the Author (2024)

One of the benefits offered is revealing to BIM actors which entities can be customized to meet specific requeriments. The investigative scenario supported by the inheritance diagrams strengthens the theoretical foundation and represents a mechanism capable of assisting both in the development of an execution plan and its implementation.

The translation of data by Entity Inheritance Diagrams can help professionals identify the relevant specifications to support choices in their collaborative work plans. This scenario becomes evident especially when compared to the IfcProject diagram provided by the bSI documentation (Fig. 2.11).

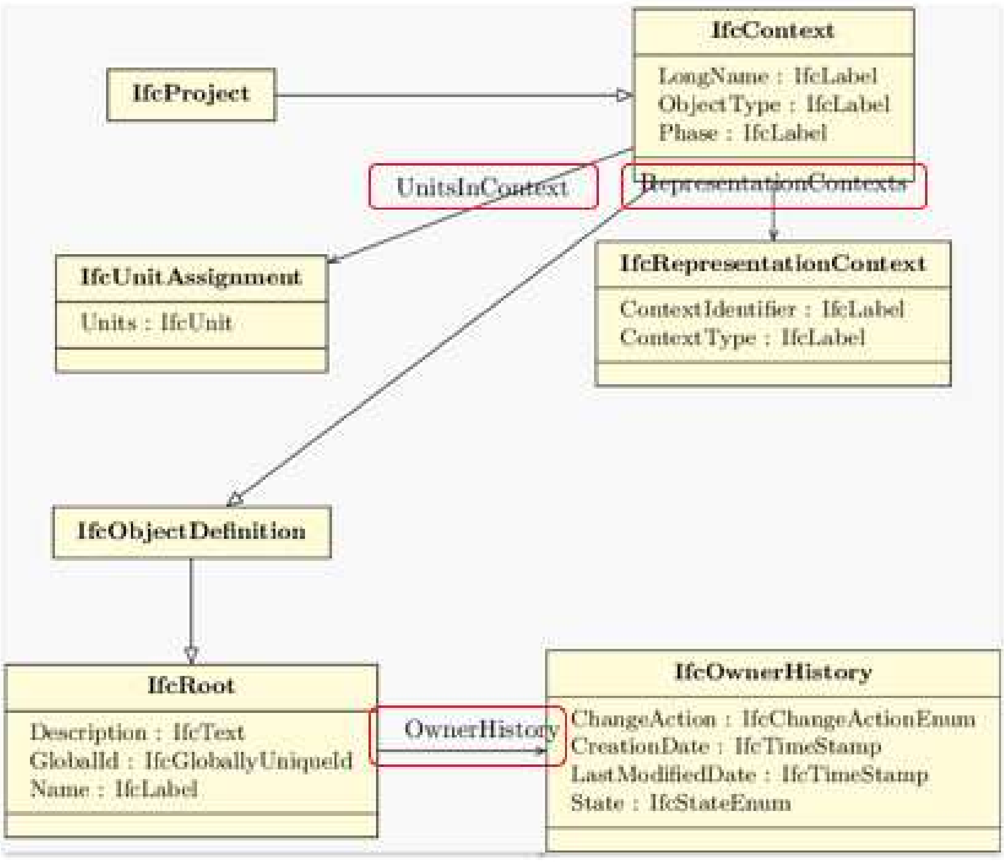

Fig. 2.11 IfcProject Diagram
Source: bSI, 2024 (adjusted)

The diagram presents only the direct attributes of the entity and is limited to the inheritance of IfcObjectDefinition [43]. Some characteristics, such as inverse attributes, inheritance of IfcPropertyDefinition and IfcRelationship, reference number, nature of entities (instantiable or abstract), nature of attributes (optional or mandatory), and cardinality are not presented.

Attributes are represented in different ways as follows: when specified through types they are indicated in the container of the respective specifying entity; when declared as entities they are referenced by arrows (indicating second-order specifications). This logic may be understood by professionals with skills in object-oriented programming, but it can pose a difficulty for users who are not yet familiar with the subject. The absence of inverse attributes and applicable rules for specifying IfcProject reinforces this discussion.

In this way, diagrams present may assist managers and modelers in translating data that aim to clarify information requirements of the organization and the project. Therefore, it represents a relevant research auxiliary contribution.

This theoretical foundation underpinned the development of the Protocol, whose efficacy in specifying the geometric framework is presented, standing as a strong point that it can be used for BIM actors, and organizations in different scenarios and geographic regions.

The Artifact enabled the specification of data that the Protocol did not include. The insertions and changes made possible by the SPF file were manually performed using a simple notepad. In this regard, the process can be replicated from SPF files generated by other BIM software, provided they include versions compatible with the mapped entities.

The validation of the generated file, carried out by two free tools, successfully displayed the data and information insertions with a high level of adequate clarity.

2.7 Conclusion

The study revealed that the IFC 4.3 data schema may be useful for software manufacturers to specify the representation context of an infrastructure project at a high semantic level. The analyses enabled by the developed artifact presented a significant semantic increase, demonstrating that the interoperable performance of the software can be improved.

Although the IFC 4.3 data broadly met the research demand, Revit could not export the required information through the default process [4.3 Experimental]. However, it managed to do so partially through the execution of the developed Protocol. This occurs because this version does not include an official MVD and consequently, the software cannot yet be certified.

Nevertheless, positive feedback was observed, showing that software manufacturers have been anticipating developments, demonstrating continuous evolution in line with IFC schema.

The bSI documentation is constantly evolving and is essential for guiding professionals in the civil industry, as well as software manufacturers. However, still has limitations in the standard used to represent entity inheritance diagrams. They aim to mitigate the level of abstraction of schema and proved to be a potential mechanism capable of assisting collaborative workflows. This gap was addressed with the diagrams developed.

This study was limited to the proprietary modeling software used by the bridge management organization. It would be enriching for other studies to apply the same approach using different BIM software for semantic performance analysis.

Another potential extension would be through the approach of Information Delivery Specification (IDS) using buildingSMART Data Dictionary (bSDD) and BlenderBIM. These capabilities would automate the verification process and, consequently, mitigate potential failures in identifying present and/or missing information requirements as specified by the BIM execution plans.

This possibility is important to the governmental sphere, as the volume of projects is substantial, and the availability of information can positively impact the effectiveness of asset management processes. The accessibility to information can extend the lifespan of built assets and reinforce their sustainability, aligning with the principles of OpenBIM.

Other fields of knowledge are crucial for interacting with infrastructure projects, such as Geographic Information System (GIS) technology. This study focused solely on informing the project geodetic reference system. However, specific studies are needed to enhance the connection between the geometric and geodetic frameworks at a high semantic level.

Aligned with the IFC schema version that includes the entities mapped in this study, the artifact can be replicated in any SPF regardless of the BIM software that generated it. In this direction, the developed construction becomes even more adherent and reinforces the sustainable, neutral, and open aspect that OpenBIM aims to provide to the industry.

Finally, a reflection on the name used by the bSI documentation for the entity "IfcProject" is noteworthy: As a rule, the entity is instantiated once in a model data schema. Therefore, a Project might have several "IfcProject", one for each discipline model. Hence, the denomination of the entity becomes inappropriate, since, traditionally, a Project represents the whole or set of discipline models developed throughout its lifecycle.

However, if the entity were named "IfcModel" (or "IfcDiscipline"), for example, a Project would have several "IfcModel", as many as necessary, thus preserving the meaning and scope of the term "Project" used by the AEC industry over time.

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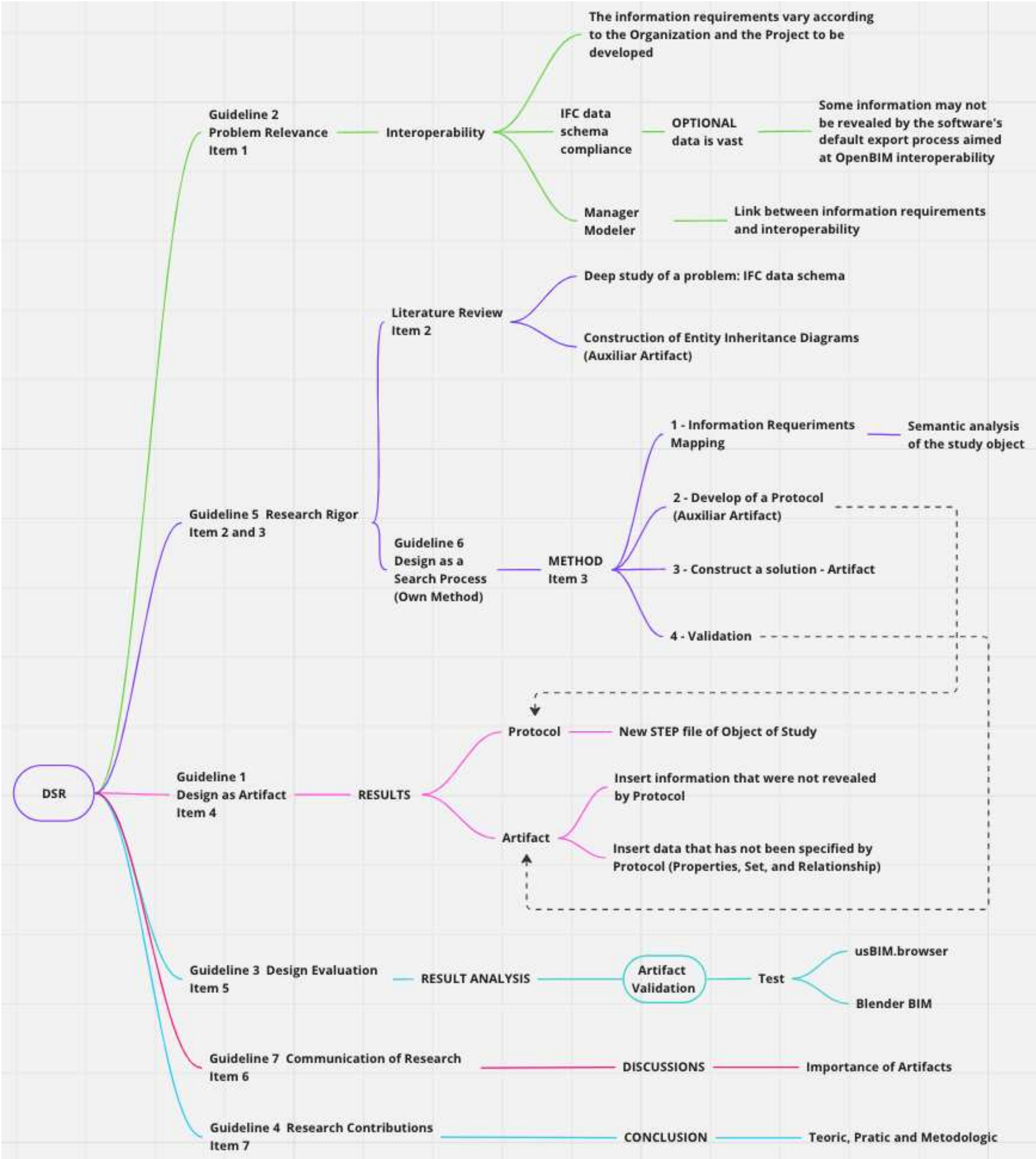
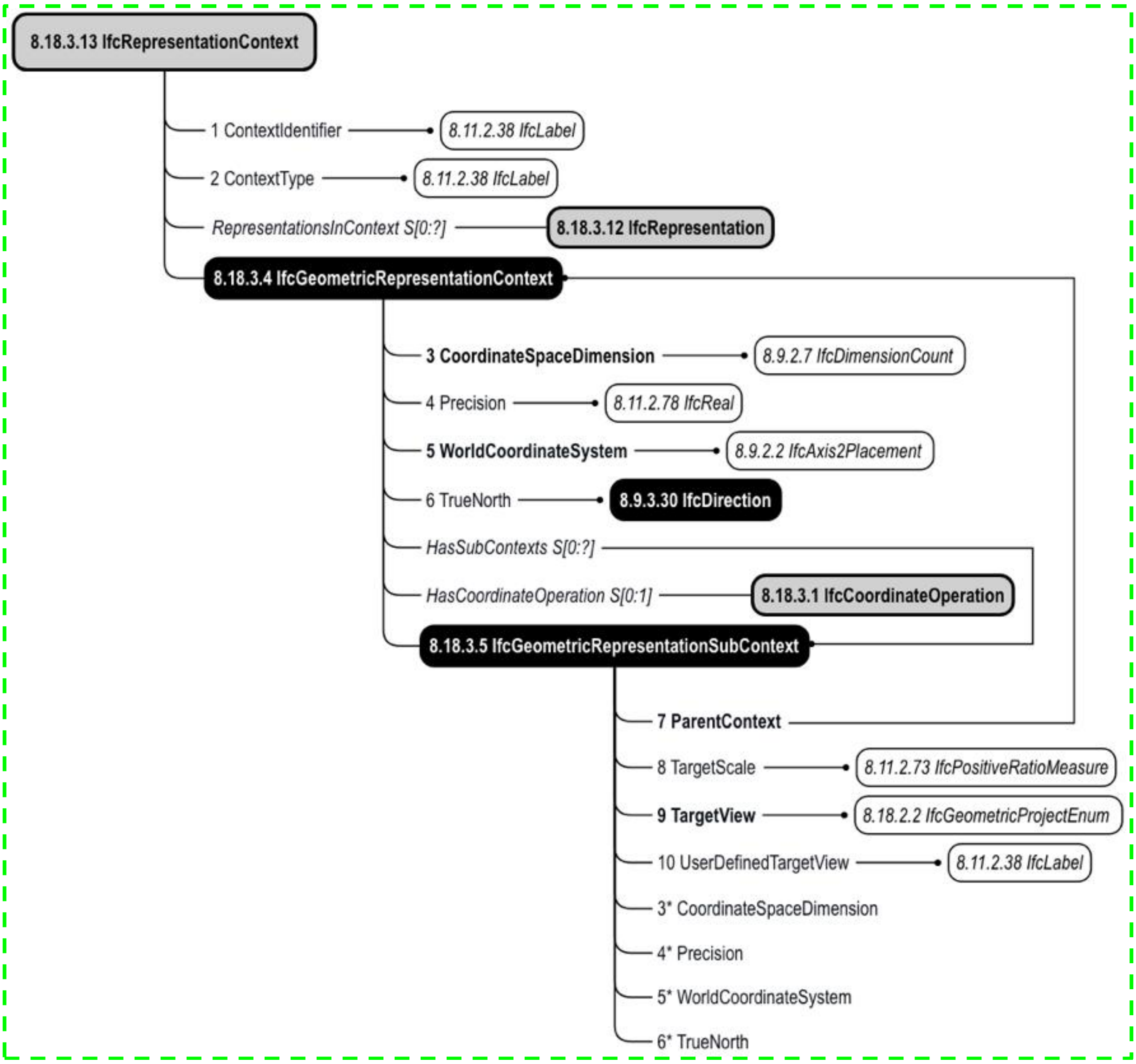
[43] buildingSMART International. IfcProject Diagram. Available online: gramhttps://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/HTML/annex_d/IfcProject.html Accessed in: 27 Jun. 2024

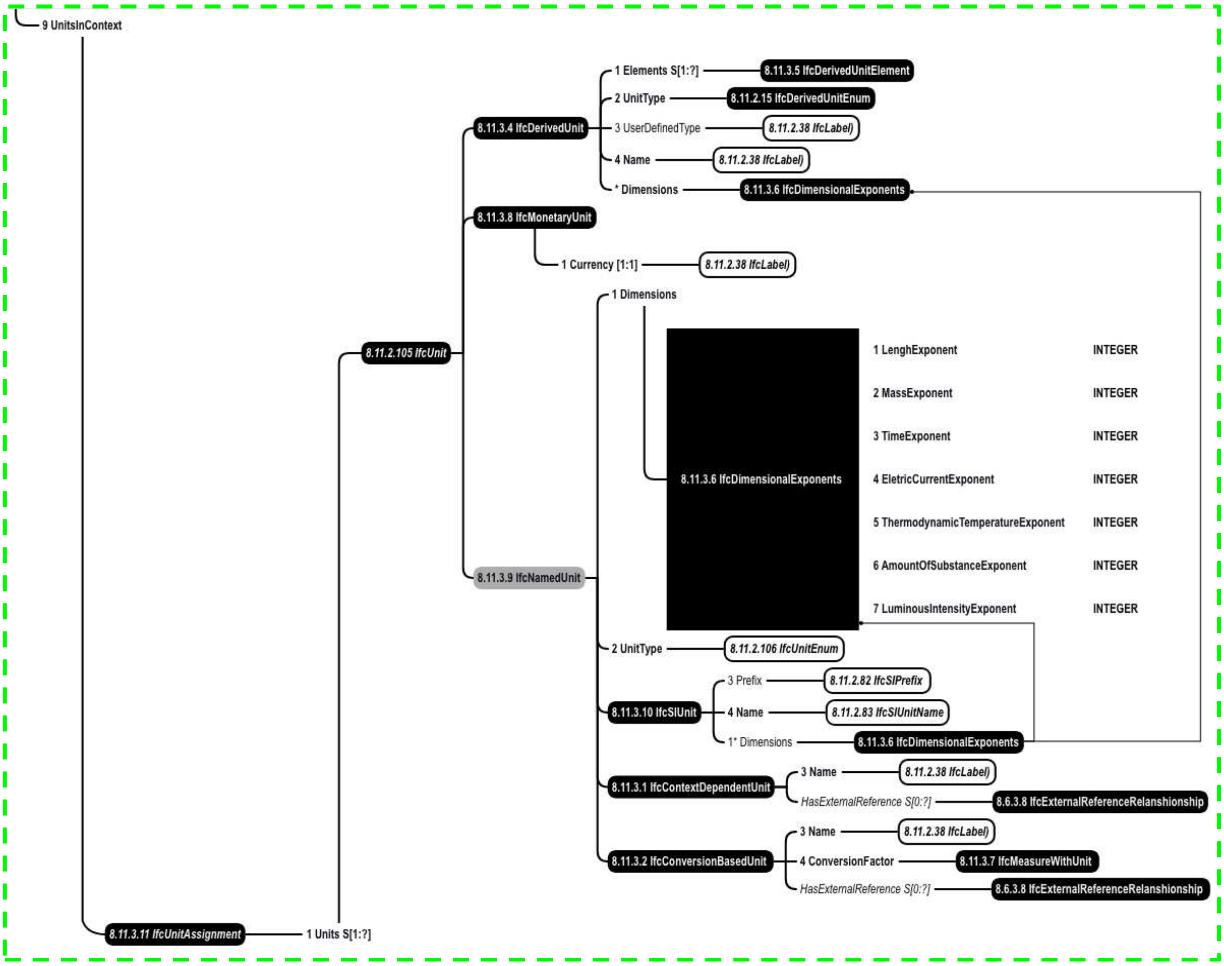
APPENDIX 2A: DSR – Guidelines of Method



APPENDIX 2B: Entity Inherited Diagram
IfcRepresentationContext
IfcGeometricRepresentationContext
IfcGeometricRepresentationSubContext



APPENDIX 2C: Entity Inherited Diagram
IfcUnitAssignment
IfcUnit
IfcDerivatedUnit
IfcMonetaryUnit
IfcNamedUnit



APPENDIX 2D: Protocol

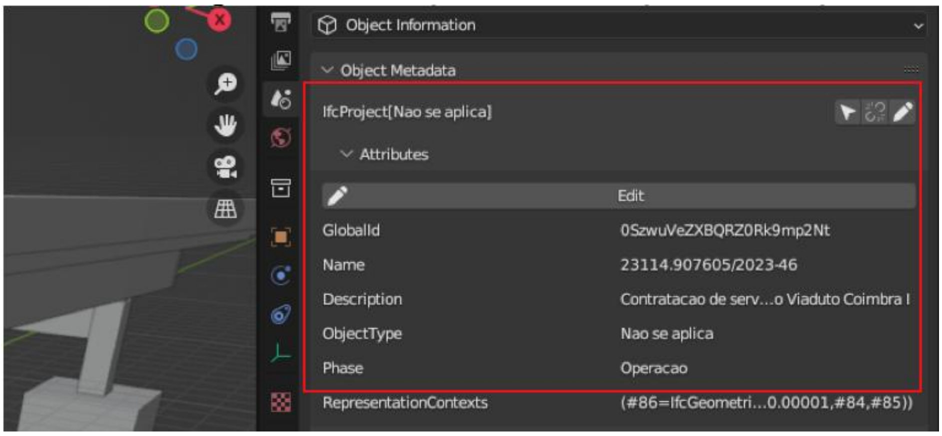
Tab	Data	Information	Justification
Level Detail	Level of detail for some element geometry	High	Highest level
Geographic Reference	Project Location		Project Base Point
	Coordinate Base	Project Base Point	As recommended by the software manufacturer
	Projected Coordinate System Reference	EPSG 4674	ESPG Code
	ESPG (European Petroleum Survey Group) Code	SIRGAS 2000	Geodetic System - Identification
		SIRGAS 2000	Geographic Coordinate System - Description
General	IFC version	4x3 [Exp]	Research Target
	Exchange Requirement	No	Inappropriate. IFC 4
	File type	IFC	The focus of the study
	Phase to export	Existing	The phase of the lifecycle
	Space boundaries	No one	Inappropriate
	Split elements by level	No	Not applicable
Additional Content / Export	Only elements visible in view / Rooms, áreas, and spaces in 3D views	No	Inappropriate/restrictive
	Include steel elements	Yes	Adequate
	2D plan view elements	Yes	Adequate
Property Sets / Export	Revit Property sets	Yes	Adequate
	IFC common property sets	Yes	Adequate
	Base quantities	Yes	Adequate
	Schedules as property sets	Yes	Adequate
	Table as property sets	No	Inappropriate /subjective
	Only schedules containing IFC, Pset, or Common in the title	No	Inappropriate/restrictive
	User-defined property sets	No	Inappropriate/subjective
	Parameter mapping table	No	Inappropriate/subjective
Advanced	Export parts as building elements	No	Not applicable
	Allow use of mixed Solid Model representation	Yes	Suitable for complex geometries
	Use active view when creating geometry	No	Not applicable
	Use family and type name for reference	Yes	Adequate
	Use 2D room boundaries for room volume		Not applicable
	Include IfcSite elevation in the site's local placement origin	Yes	Adequate
	Store the IFC GUID in the element parameter after the export	Yes	Adequate
	Export bounding box	Yes	Adequate
	Keep tessellated geometry as triangulation	No	IFC 4 (inappropriate)
	Use type name only for IFCType name	Yes	Adequate
	Use visible Revit name as the IFCEntity name	Yes	Adequate

APPENDIX 2E: Validation – Report

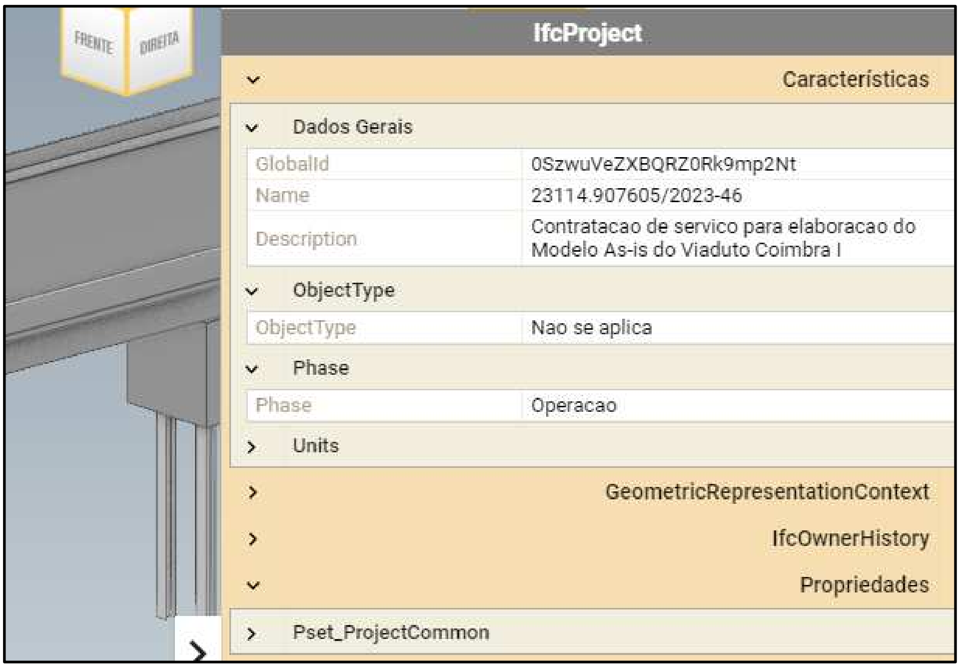
IDENTIFICATION FRAMEWORK

```
#95=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2023-46','Contratacao de servico para elaboracao do Modelo As-is do Viaduto Coimbra I','Nao se aplica',$,'Operacao',(#86,#93),#83);
```

Blender BIM



usBIM.browser



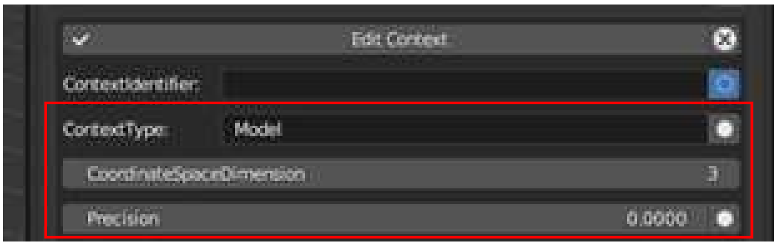
Status:

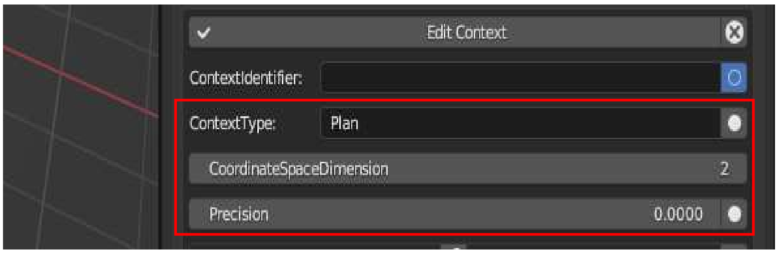
The declared identification attributes were recognized (by both types of visualization software).

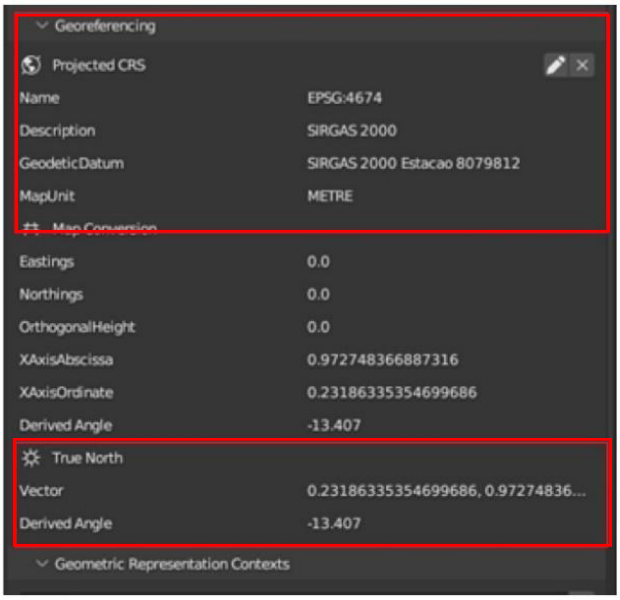
GEOMETRIC AND UNIT FRAMEWORK

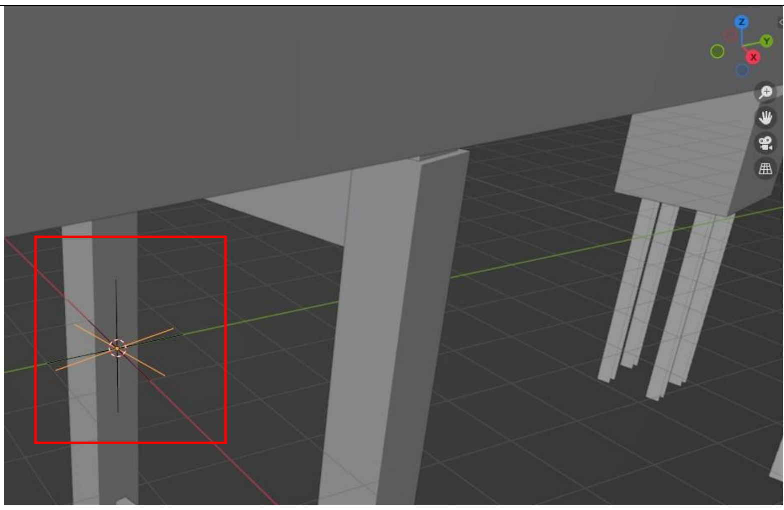
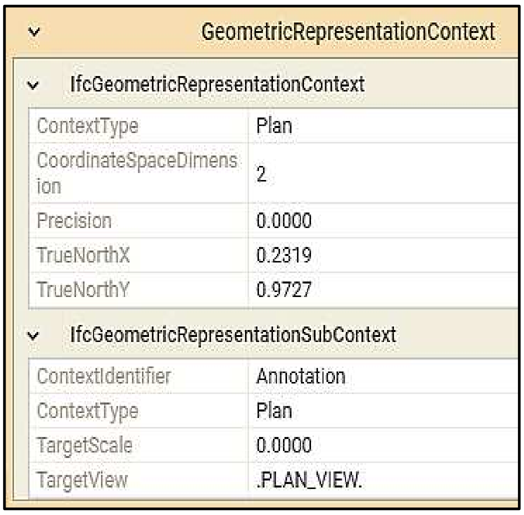
```
#85=IFCDIRECTION((0.23186335354699686,0.97274836688731603));
#86=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.00001,#84,#85);
#91=IFCPROJECTEDCRS('EPSG:4674','SIRGAS 2000','SIRGAS 2000 Estacao
8079812',$,$,$,#20);
#93=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',2,0.00001,#84,#85);
```

Blender BIM

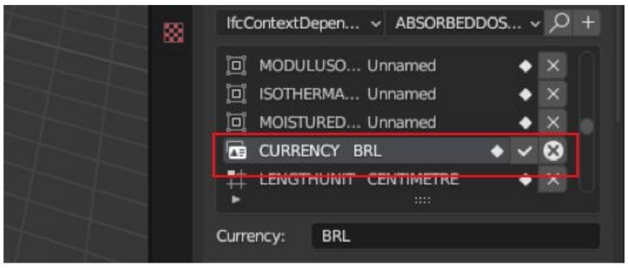




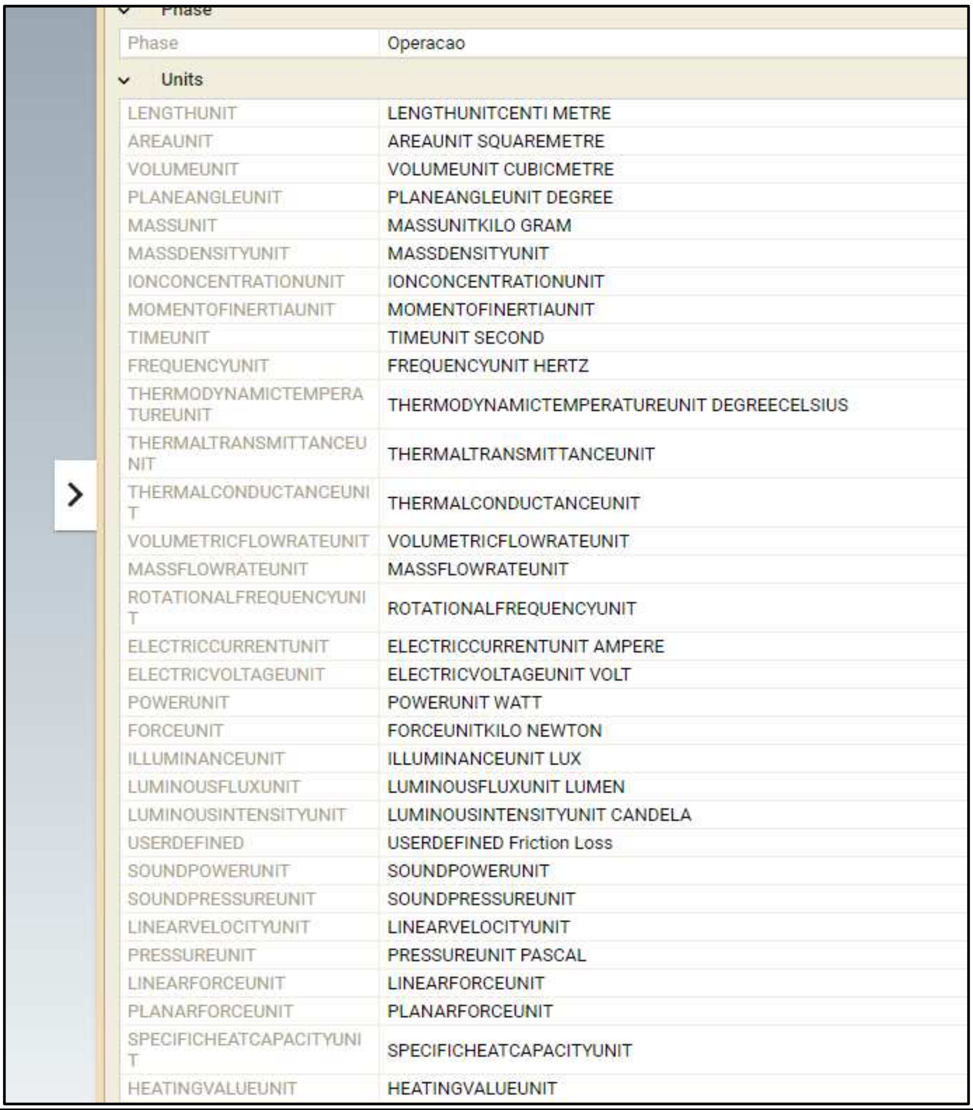


<table>
<tr><td></td><td></td></tr>
<tr><td></td><td>Status: The Geometric framework was fully recognized and, additionally, the geodetic data including the true north direction.</td></tr>
<tr><td rowspan="2">usBIM.browser</td><td>
</td></tr>
<tr><td>Status: The Geometric framework with only one instance of specified [Plan]. Geodetic data was not identified.</td></tr>
<tr><td colspan="2">

```
#69=IFCMONETARYUNIT('BRL');
#83=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,#42,#46,#47,#48,#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,#71,#72,#73,#74,#75,#77,#78,#79,#80,#81,#82));
```

</td></tr>
<tr><td rowspan="2">Blender BIM</td><td>
</td></tr>
<tr><td>Status: The unit system was completely identified.</td></tr>
</table>

usBIM.browser

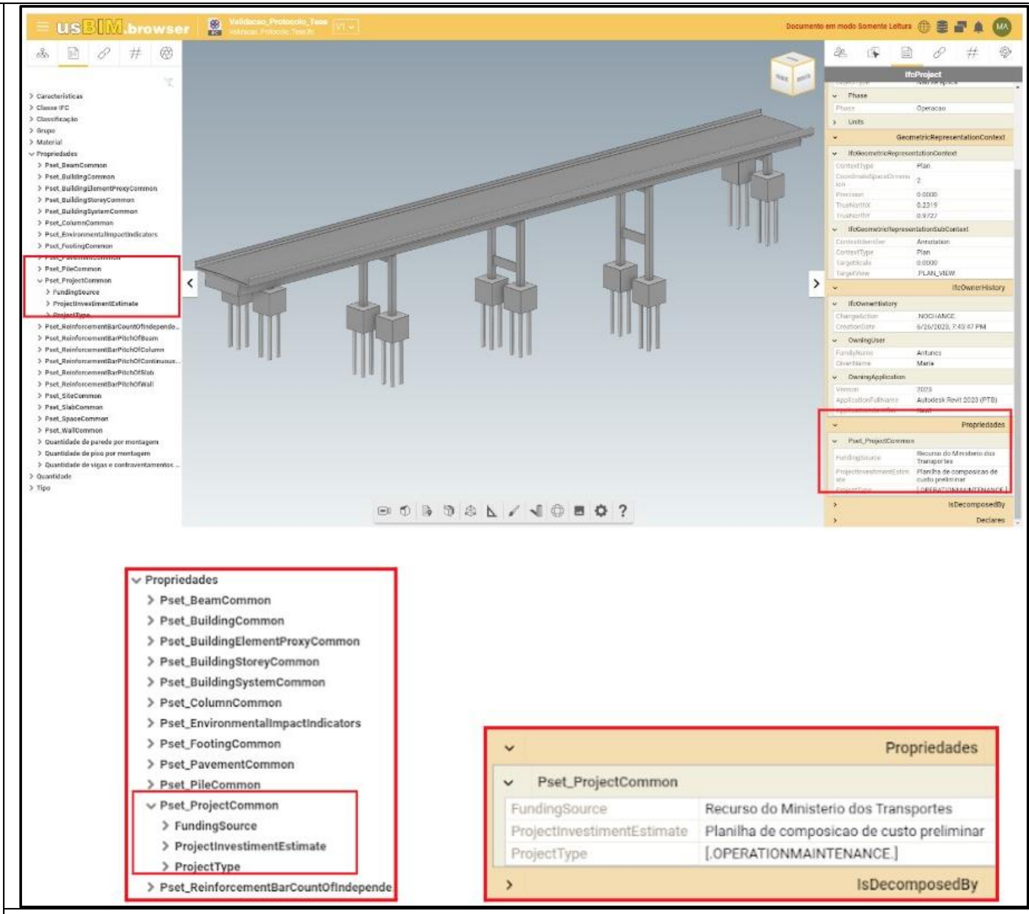


Phase	
Phase	Operacao
Units	
LENGTHUNIT	LENGTHUNITCENTI METRE
AREAUNIT	AREAUNIT SQUAREMETRE
VOLUMEUNIT	VOLUMEUNIT CUBICMETRE
PLANEANGLEUNIT	PLANEANGLEUNIT DEGREE
MASSUNIT	MASSUNITKILO GRAM
MASSDENSITYUNIT	MASSDENSITYUNIT
IONCONCENTRATIONUNIT	IONCONCENTRATIONUNIT
MOMENTOFINERTIAUNIT	MOMENTOFINERTIAUNIT
TIMEUNIT	TIMEUNIT SECOND
FREQUENCYUNIT	FREQUENCYUNIT HERTZ
THERMODYNAMICTEMPERATUREUNIT	THERMODYNAMICTEMPERATUREUNIT DEGREECELSIUS
THERMALTRANSMITTANCEUNIT	THERMALTRANSMITTANCEUNIT
THERMALCONDUCTANCEUNIT	THERMALCONDUCTANCEUNIT
VOLUMETRICFLOWRATEUNIT	VOLUMETRICFLOWRATEUNIT
MASSFLOWRATEUNIT	MASSFLOWRATEUNIT
ROTATIONALFREQUENCYUNIT	ROTATIONALFREQUENCYUNIT
ELECTRICCURRENTUNIT	ELECTRICCURRENTUNIT AMPERE
ELECTRICVOLTAGEUNIT	ELECTRICVOLTAGEUNIT VOLT
POWERUNIT	POWERUNIT WATT
FORCEUNIT	FORCEUNITKILO NEWTON
ILLUMINANCEUNIT	ILLUMINANCEUNIT LUX
LUMINOUSFLUXUNIT	LUMINOUSFLUXUNIT LUMEN
LUMINOUSINTENSITYUNIT	LUMINOUSINTENSITYUNIT CANDELA
USERDEFINED	USERDEFINED Friction Loss
SOUNDPOWERUNIT	SOUNDPOWERUNIT
SOUNDPRESSUREUNIT	SOUNDPRESSUREUNIT
LINEARVELOCITYUNIT	LINEARVELOCITYUNIT
PRESSUREUNIT	PRESSUREUNIT PASCAL
LINEARFORCEUNIT	LINEARFORCEUNIT
PLANARFORCEUNIT	PLANARFORCEUNIT
SPECIFICHEATCAPACITYUNIT	SPECIFICHEATCAPACITYUNIT
HEATINGVALUEUNIT	HEATINGVALUEUNIT

Status: 38 units were listed in total.
The monetary unit [#69] was not recognized.

FINANCIAL FRAMEWORK

```
#80001=IFCPROPERTYENUMERATEDVALUE('ProjectType',$,(IFCPROPERTYENUMERATIO
N(.OPERATIONMAINTENANCE.)),$);
#80002=IFCPROPERTYREFERENCEVALUE('ProjectInvestimentEstimate',$,'Planilh
a de composicao de custo preliminar',$);
#80003=IFCPROPERTYSINGLEVALUE('FundingSource',$,IFCLABEL('Recurso do
Ministerio dos Transportes'),$);
#80004=IFCPROPERTYSET('0S3JFtqoD4CAgDGe3IafZV',#18,'Pset_ProjectCommon',
$,(#80001,#80002,#80003));
#80005=IFCRELDEFINESBYPROPERTIES('0kMl4E8H1E_h3yCPd6IE1J',#18,$,$,(#95),
#80004);
```

usBIM.browser	 Status: All specified properties of the framework have been identified.
Blender BIM	 Status: The framework was identified partially: ProjectType (default with enumeration for user select); ProjectInvestimentEstimate property has not been identified; FundingSource was identified.

CAPÍTULO 3 - CICLO DE VIDA DA CONSTRUÇÃO CIVIL: UMA ANÁLISE SISTÊMICA À LUZ DAS PUBLICAÇÕES BIM NO BRASIL

Este capítulo foi submetido em 27/08/2024 para análise na revista científica: Antunes, M. L. R.; Ribeiro, J. C. L César Júnior, K. M. L.; Rocha, M. S. S. Ciclo de vida da construção civil: Uma análise sistêmica à luz das publicações BIM no Brasil. ***Design & Tecnologia*** *(2024).*
Atualmente encontra-se em processo de revisão.

Resumo

A linha temporal das publicações com temática em Building Information Modeling (BIM), no cenário nacional, iniciou, em 2010 e está em plena evolução, em resposta ao arcabouço legislatório proposto pela governança através dos Decretos Federais e pelos profissionais da cadeia produtiva, por meio da consolidação de normas técnicas. Um reconhecimento da comunidade internacional da maturidade BIM brasileira foi endossada com a inclusão do capítulo do país na BuildingSMART, em 2023. Este panorama constitui o cenário de pesquisa que visa o levantamento sistêmico da literatura (Cadernos, Guias, Coletâneas e Manuais) publicada no Brasil sob a ótica dos Usos do BIM e suas ocorrências ao longo do ciclo de vida do projeto. Consideraram-se os conteúdos desenvolvidos por entidades governamentais e não governamentais de diversos setores da indústria da construção civil elaborados por equipes multidisciplinares. A análise sistêmica revelou que considerável percentil das amostras relaciona os Usos BIM com as fases do ciclo de vida. Esta dinâmica dominante é inspirada no modelo apresentado pelo BIM Execution Plan Guide (BEP) proposto pela Penn State University, originalmente em 2009. Desde então, novas versões atualizaram o guia quantitativa e qualitativamente. No entanto, a diversidade de aplicações BIM demandadas pelo setor Arquitetura, Engenharia, Construção e Operação (AECO) suscitou a necessidade de analisar semanticamente o conteúdo que vem sendo replicado, ou simplesmente traduzido pela literatura brasileira e, consequentemente, adotado pelas empresas e profissionais. Sob a revisão sistêmica, esta discussão é pautada à luz da gestão da informação da construção explicitando que o modelo amplamente referenciado na literatura não é amplo o suficiente para abordar as demandas da indústria.

Palavras-chave: Ciclo de vida. Construção Civil. Usos BIM. Fases

3.1 Introdução

3.1.1 Generalidades

A linha do tempo das publicações de conteúdo BIM no Brasil inicia-se na década de 2010. Dentre as iniciativas de entidades governamentais, o Ministério do Desenvolvimento, Indústria e Comércio Exterior (MDIC) desempenhou um papel inovador especialmente quando disponibilizou uma biblioteca de objetos paramétricos e constituiu a comissão de estudos (CE) voltada para a elaboração do contexto normativo brasileiro (CAREZATO, 2018). Sequencialmente, a Comissão de Estudos Especiais (CEE) iniciou a tradução da norma ISO 12006 “Construção de edificação - Organização de informação da construção” Partes 1 e 2, publicadas em 2010 e 2012, respectivamente. A partir destes marcos, a ABNT NBR 15965 (BRASIL, 20XX) “Sistema de Classificação da Informação da Construção” e suas sete partes foram desenvolvidas ao longo de onze anos.

Durante este intervalo, as governanças dos estados de Santa Catarina e Paraná atuaram com expressivas contribuições (Cadernos BIM) revelando o pioneirismo da região sul do país. Paralelamente, fora do espectro governamental, vale destacar a Associação de Escritórios de Arquitetura (AsBEA, 2013) que atuou como precursora com a publicação do Guia de Boas Práticas.

Em nível federal, a estratégia BIM BR, endossada pelo Decreto Federal 10.306 (BRASIL, 2020) fundamentou os marcos temporais pautados em uma base tecnicamente capaz de sustentar a interoperabilidade ao longo do ciclo de vida do projeto, abordando basicamente: Gestão de Projetos (2021), Gestão de Obras (2024) e Gestão de Operação (2028).

Iniciativas relacionadas ao arcabouço legislatório e a gestão de projetos foram permeadas com inovação, como ocorreu com a publicação da 2ª Edição do Caderno de Edificações do Governo do Estado do Paraná customizado à ISO 19650 “Organização da informação da construção - Gestão da informação usando modelagem da informação da construção. Outras normas iniciaram abordagens à temática BIM, como a ABNT NBR 9452:2024 Inspeção de Pontes, viadutos e passarelas de concreto armado, revelando a granularidade do universo de aplicações possíveis.

Paralelamente, a candidatura do Brasil foi aceita pela BuildingSmart (bSI), entidade não governamental sem fins lucrativos que concentra esforços de vários setores da indústria da construção civil a nível mundial visando desenvolver a interoperabilidade por padrão aberto OpenBIM. A organização é composta por representantes da governança e da indústria, profissionais, fabricantes de softwares e acadêmicos que desenvolvem a estrutura de dados IFC (*Industry Foundation Classes*). Dessa forma, a criação do capítulo brasileiro representou o reconhecimento internacional da maturidade BIM no Brasil. Na Figura 3.1 ilustra-se a linha temporal das publicações BIM que ocorreram no Brasil no intervalo de 2010 e 2023.

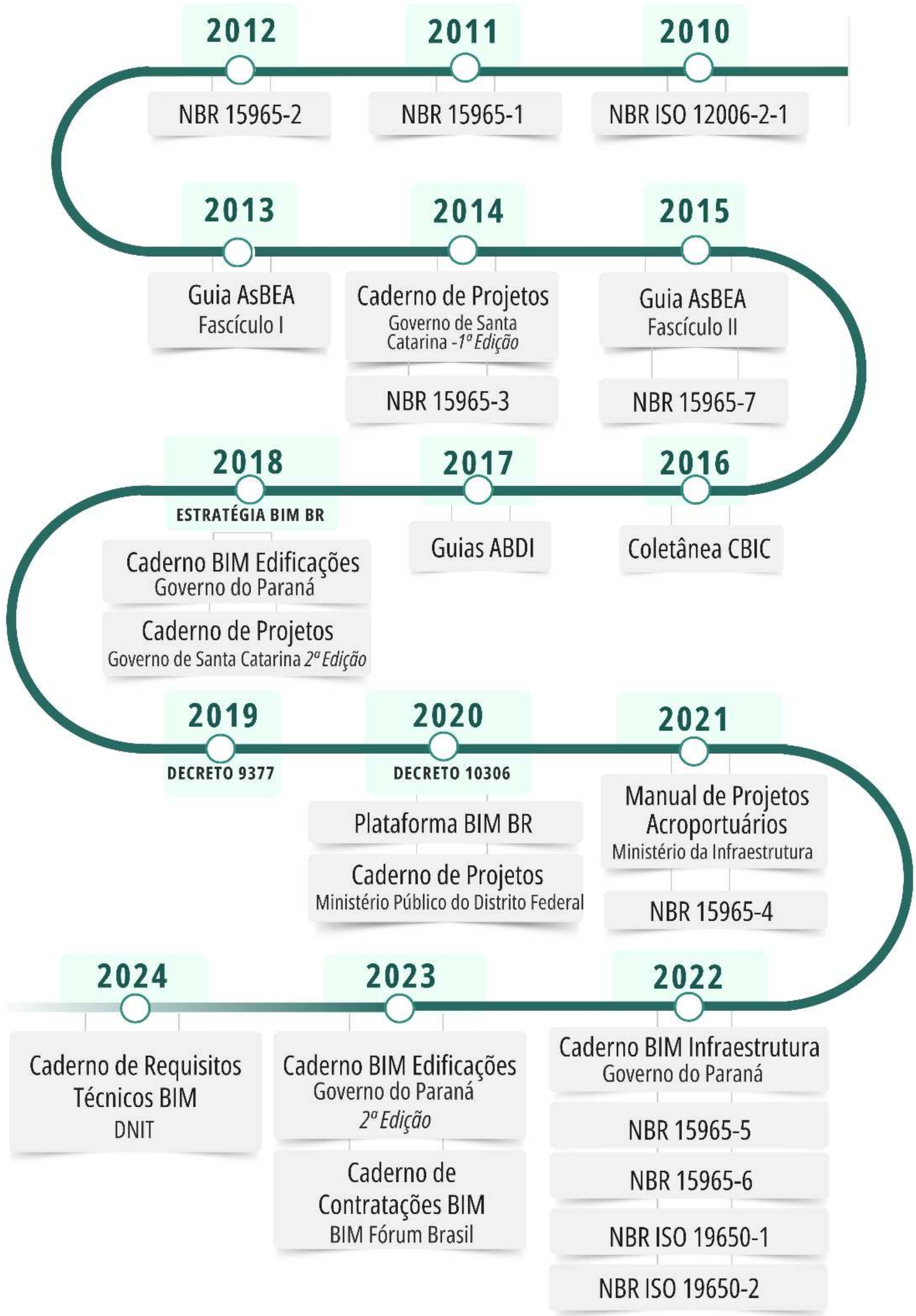


Fig. 3.1 Publicações BIM
Fonte: A Autora (2024)

A base bibliográfica embasou análises sob a ótica sistêmica com foco na representação do ciclo de vida e, adicionalmente as aplicações possíveis do BIM (Usos) indicados e mapeados ao longo das fases que o compõe. Constatou-se que relevante percentil das publicações nacionais referencia os casos de Usos BIM, através das fases do ciclo de vida do projeto, representado no padrão evolutivo linear, proposto por uma única fonte. Ainda que a minoria das publicações utilize padrões diferenciados de representação de ciclo, nenhum modelo é aderente à dinâmica apresentada pela ABNT ISO 19650-2 (2023). Neste cenário, o estudo visou à revisão sistemática da literatura à luz dos modelos de ciclos de vida referenciados pelas publicações. Os resultados revelaram uma considerável lacuna na forma de representar o ciclo de vida.

3.1.2 Building Information Modeling (BIM)

De acordo com a *National Institute of Building Sciences* (2007), o BIM pode ser compreendido como o ato de criar um ou mais modelos de um projeto com o objetivo de contemplar ações como: visualizar; analisar; compatibilizar; controlar; estimar custos e prazos; simular, construir; gerir, além de outros propósitos.

Neste cenário, os modelos BIM correspondem a subconjuntos de um conjunto principal (o projeto ou empreendimento) e, portanto, estabelece uma forte afinidade com a teoria dos sistemas, desenvolvida no início do século XX por Ludwig Von Bertalanffy e reforçada por Bossel (2007). De acordo com os autores, um sistema é constituído de elementos conectados em uma estrutura característica e única. Esta conformação única executa funções específicas no ambiente onde o sistema existe. Estas servem a um propósito particular do sistema (ROCHA, 2018).

Neste contexto, um sistema pode ser formado por "*n*" subsistemas e que, cada um deles possui certa autonomia, o que os capacita a interagir com os demais. De acordo com Gallopin (1996) sistemas podem ser abstrações definidos por um observador de um subsistema ou do sistema como um todo, que se deseja analisar. De acordo com o autor, o ponto de vista e os interesses de exploração definem o escopo, o número e tipo de atributos do subsistema ou do sistema. Apesar de hipoteticamente não corresponder exatamente à realidade, esses modelos podem fornecer um padrão esquemático que facilita compreendê-los e, assim, trabalhar a realidade (BOSSEL, 1999).

Eastman *et al.* (2008) afirmam que o BIM permite a inclusão e a manipulação contínua de dados digitais por todo o ciclo de vida de um projeto desde a sua concepção, construção, até sua operação e, eventualmente, fim. Este padrão pode ser aplicado ao sistema do corpo humano: concepção; nascimento; crescimento; envelhecimento; morte.

A esta sucessão de estágios ao longo de um intervalo de tempo, Rocha (2018) denomina "fases" que podem ser equivalentes às fases do ciclo de vida de um empreendimento, de um objeto ou de qualquer outro sistema.

Alinhado às definições de Succar (2009), o conceito de BIM relaciona-se com a tríade: Tecnologias, Processos e Políticas que, quando integrados, sustentam as melhores práticas entre os *stakeholders* envolvidos no projeto. Como reforçam Ruschel e Andrade (2009) afirmando que os fundamentos do BIM não se restringem à parametrização, mas também à interoperabilidade demandada pelo intercâmbio de informações nos fluxos colaborativos. Da mesma forma, Manzione (2013) afirma que o uso de diferentes ferramentas paramétricas possibilita que os profissionais pratiquem processos de trabalho baseados em um padrão neutro e aberto, permitindo a representação do projeto em um ou mais modelos digitais, por meio da especificação de uma estrutura de dados.

3.1.3 Usos do BIM x Ciclo de Vida

De acordo com o *National Institute of Building Sciences* (2007) BIM Use ou Model Use é um método, ou estratégia, para atingir um ou mais objetivos específicos que demandam uma linguagem com nível semântico suficientemente capaz de descrevê-los. The Uses of BIM (v. 0.9, 2013) publicado pelo *Computer Integrated Construction* (CIC) *of Penn State*, define a semântica dos casos como um método de aplicar BIM durante o ciclo de vida de uma instalação para alcançar um ou mais objetivos específicos. O documento discorre que os Usos do BIM podem ser classificados com base na finalidade de implementar BIM ao longo do ciclo de vida de um ativo.

Além da finalidade em si, várias outras características podem ser definidas para identificar e comunicar adequadamente um Uso BIM. Essas finalidades e características foram definidas em níveis variados que dependem das especificidades das aplicações a que se destinam, classificadas em primárias [***Gather; Generate; Analyze; Communicate; Realize****] e secundárias [Qualify; Monitor; Capture; Quantity; Prescribe; Size; Arrange; Coordinate; Forecast; Validate; Visualize; Draw; Transform; Document; Fabricate; Control; Assemble; Regulate*] de forma a atender o caráter fragmentado da indústria da construção civil (Fig. 3.2).

Succar *et al.* (2020) apresentam um mecanismo que, através de uma classificação de parâmetros alinhados semanticamente, fundamenta combinações capazes de estabelecer um universo imensurável de Usos BIM. Na mesma direção, Ngwepe *et al.* (2015) discutem sobre as fases do ciclo de vida destacando as questões relacionadas com a gestão dos resíduos sólidos derivados dos processos de demolição e reuso, propondo que estes parâmetros devem representar fases específicas do ciclo, pós fase operacional.

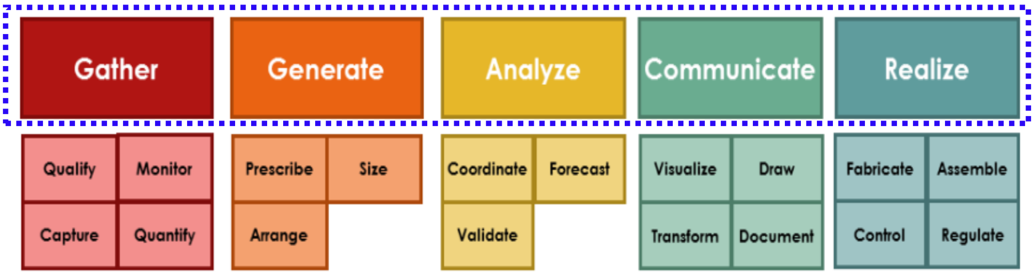
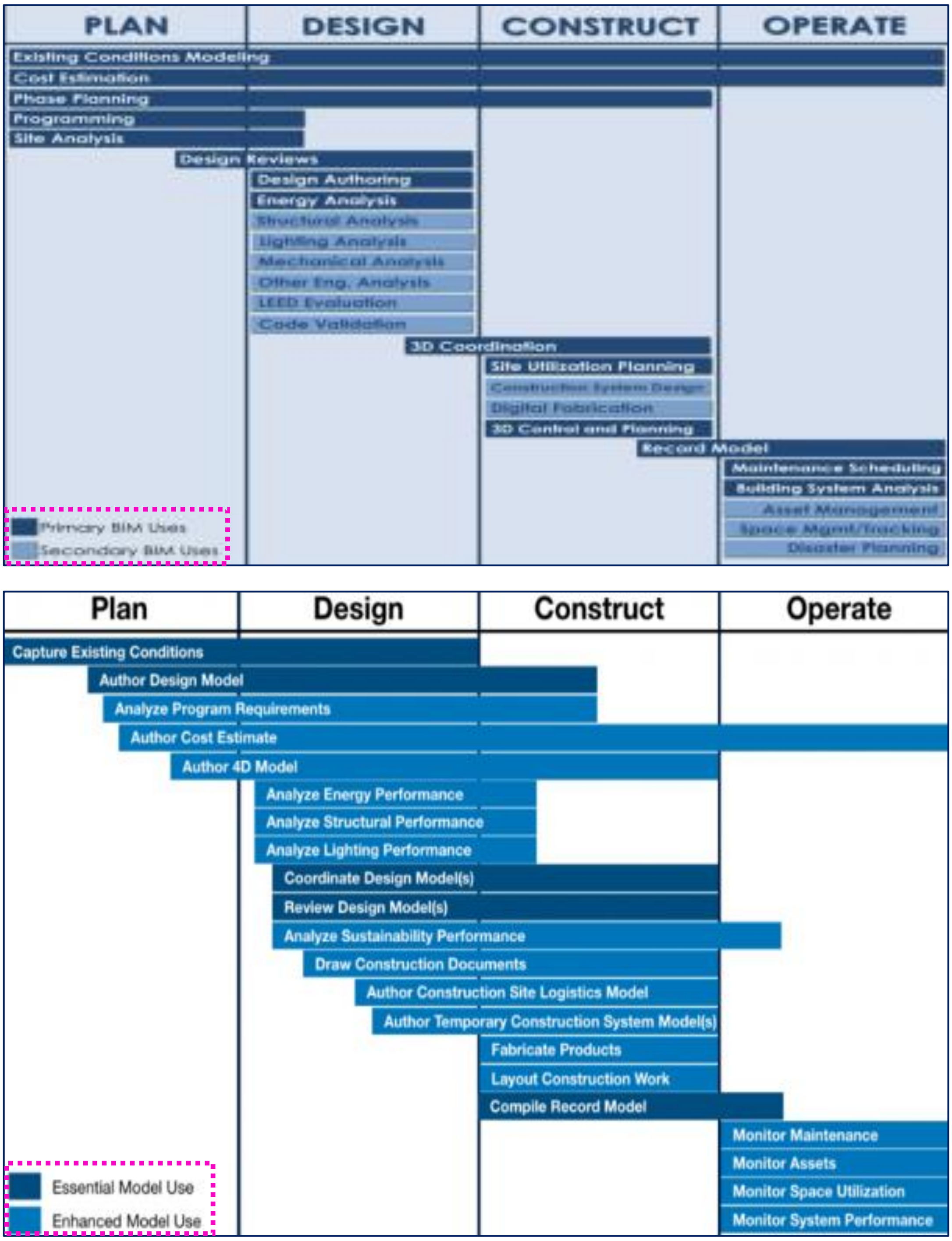


Fig. 3.2 Características dos Usos BIM
Fonte: CIC, 2013 (modificado)

O BIM *Execution Plan Guide* – BEP (2009), originalmente, apresentou 25 Usos BIM primários e secundários ao longo das fases do ciclo de vida, organizados na ordem cronológica no padrão evolutivo linear (Fig. 3(a)). Desde então, o BEP Guide passou por atualizações e alguns Usos BIM foram acrescidos e/ou retirados.

Os Usos BIM foram organizados por fase do projeto, identificados e refinados através de entrevistas, análise de estudos de caso e revisão da literatura. A versão mais recente do documento destaca que podem existir outras aplicações BIM especialmente considerando o cenário tecnológico disponível (v. draft, 2023), ilustrado na Figura 3.3(b). O mesmo Uso (ou aplicação BIM) pode ocorrer em uma fase, mais de uma e em todas, alinhando-se neste cenário, a um gradiente qualitativo.

A revisão sistemática da literatura internacional desenvolvida por Mirniazmandan *et al.* (2020) revelou que dentre os 19 guias publicados em 9 países entre 2012 e 2021, os Usos BIM são citados por 12. Deste universo, seis foram qualificados como altamente detalhados: *New York City BIM Guidelines; BIM Standart and Guide; BIM Guidelines for Design and Construction; NATSPEC National BIM Guides; National BIM Guides for Owners* e *Rail Baltica BIM Manual*.



(a)

(b)

Fig. 3.3 Usos BIM ao longo do ciclo de vida do projeto: (a) Versão 0.9; (b) Versão 3.0
Fonte: a. BIM Guide, 2009 (modificado); b. BIM Guide, 2023 (modificado)

Os Usos BIM foram explorados pela organização BIMe *Initiative* (CHANGE AGENT AEC, 2019) v1.26, como parte de linguagem modular visando a conexão de requisitos. A proposta identificou e reuniu requisitos de informação de modelos digitais 3D organizados em três categorias: I - General Model Uses que codifica os modelos de Usos BIM generalizados descrevendo-os através de sinônimos; II - *Domain Model Uses* que organiza e codifica modelos de Usos BIM através de sete grupos *Capturing and Representing; Planning and Designing; Simulating and Quantifying; Constructing and Fabricating; Operating and Maintaining; Monitoring and Controlling; Linking and Extending*; III - *Custom Model Uses* que combina as categorias I e II a fim de que um Uso BIM atenda variadas demandas de requisitos de informação de organização e do Projeto. Neste cenário, o universo de aplicações BIM ao longo das fases do ciclo de vida torna-se imensurável.

Estes requisitos estabelecem fluxos de informação demandados entre as fases do ciclo de vida. Succar e Poirier (2020) exploram estes fluxos através do LITE (*Lifecycle Information Transformation and Exchange*). Os autores discorrem que para viabilizar a entrega e operação de ativos, as informações capturadas nas fases anteriores do ciclo precisam ser transformadas em "ativos digitais". Durante as fases iniciais, os ativos digitais podem ser definidos através de Usos da Informação (Usos de Modelos, Usos de Documentos e Usos de Dados), que mais tarde são transformados (Modelos, Documentos e Conjuntos de Dados) e, ao serem executados através da construção, fabricação e montagem, transformam-se em ativos físicos. Ao longo do tempo, esta dinâmica pode reincidir durante a vigência da fase operacional visando à sustentabilidade do ativo.

3.2 Método

3.2.1 Parâmetros de pesquisa

O método selecionado para o estudo contemplou uma revisão sistemática da literatura visando esclarecer: Como o ciclo de vida da construção civil tem sido representado, no que concernem as fases e atividades típicas do setor, nos Manuais, Guias, Cadernos e Coletâneas BIM publicados no Brasil?

Para responder à pergunta de pesquisa, selecionaram-se as publicações BIM propostas por entidades governamentais e não governamentais brasileiras, elaboradas a partir de esforços de equipes multidisciplinares. A análise sistêmica visou à abordagem dos Usos BIM, bem como a representação do ciclo de vida utilizado como referência. Os parâmetros de pesquisa e as justificativas que embasaram suas escolhas, foram previamente estabelecidos (Tabela 3.1).

Tabela 3.1 Parâmetros estruturantes

Parâmetro	Descrição	Justificativa
1.Temporal	A partir de 2010	Abordar amplamente as publicações BIM no cenário nacional
2.Multidisciplinidade	Mínimo de 10 profissionais e/ou entidades envolvidas	Analisar conteúdos produzidos através do esforço plural evitando teses, dissertações, artigos e/ou publicações elaboradas por número restrito de autores
3. Densidade	Mínimo de 40 páginas	Analisar publicações com alto nível de conteúdo

Fonte: A Autora (2024)

3.2.2 Protocolo

A primeira etapa do processo de trabalho, denominada Pré-teste, fundamentou-se na técnica PICO - Problema, Intervenção, Comparação e Resultados (SACKETT *et al*., 2000) para delimitar a amostragem de pesquisa. O string: [("ciclo de vida") AND ("representação") AND ("fases") AND ("Coletânea BIM" OR "Caderno BIM" OR "Guia BIM" OR "Manual BIM")] foi gerado utilizando-se o software Parsifal.

A partir da estratégia de busca avançada selecionada na base de dados plataforma *Google*, estabeleceu-se o intervalo temporal entre 2010 e 2023, no idioma Português e localidade Brasil. A plataforma de busca escolhida não se configura como uma base de dados exclusivamente acadêmica, dado que a revisão aqui executada não é uma revisão cienciométrica. Portanto, nesta se visam encontrar publicações disponíveis em sítios distintos da rede mundial de computadores, que só um instrumento como o buscador *Google* seria capaz de recuperar.

O resultado obtido (489 ocorrências) foi exposto aos parâmetros 2 e 3 (Tabela 3.1), extraindo-se: normas; repositórios de universidades; sites de empresas privadas; sites patrocinados; editais; decretos; boletins; licitações; cartilhas; congressos e eventos. A amostragem foi reduzida para 184 publicações, porém considerada quantitativamente inadequada (apenas oito organizações atenderam os requisitos). Neste cenário, o *string* foi reformulado [“Caderno BIM" OR "Coletânea BIM" OR "Guia BIM" OR "Manual BIM"], mantendo-se o mesmo padrão de busca. Como resultado, 1530 publicações foram submetidas aos mesmos parâmetros iniciais e, sequencialmente à triagem representada pelos filtros (Tabela 3.2), obteve-se uma amostragem de 12 publicações alvo (Tabela 3.3).

Tabela 3.2 Filtros

Requisito	Descrição
Filtro 1	Temática BIM elaboradas por entidades / organizações vinculadas à cadeia produtiva do segmento civil, exceto as caracterizadas pela iniciativa privada
Filtro 2	Temática BIM desenvolvida por equipe de profissionais e/ou entidades
Filtro 3	Temática BIM com mínimo de 40 páginas

Fonte: A Autora (2024)

Tabela 3.3 Amostragem

Publicação / Amostra	Versão / Ano	Entidade
1. Caderno de Especificações Técnicas para contratação de projetos em BIM (p.131)	2018	Governo Estadual do Paraná
2. Caderno de Especificações Técnicas p contratação de Projetos em BIM(p.125)	2ª Ed./ 2023	Governo Estadual do Paraná
3. Caderno de Infraestrutura BIM (p.117)	2022	Governo Estadual do Paraná
4. Caderno de Contratações BIM (p.48)	2023	BIM Fórum Brasil
5. Caderno de Apresentação Projetos BIM (p.95)	2015	Governo Estadual de SC
6. Caderno Especificações Projetos BIM(p.91)	V.2 / 2018	Governo Estadual de SC
7. Manual BIM da INFRA (p.205)	2023	Ministério dos Transportes
8. Coletânea Implementação do BIM para construtoras e incorporadoras -V. 1 (p.119)	2016	Câmara Brasileira da Indústria da Construção
9. Coletânea Guias ABDI – MDIC - Guia 01(p.76)	2017	Ministério Ind., Com. Exterior e Serviços
10. Manual BIM para desenvolvimento de Projetos (p.171)	2022	Secretaria de Estado de Obras e Infraestrutura do DF
11. Caderno de Projetos e de Gestão Edificações em BIM (p.315)	2020	Ministério Público DF e Territórios
12. Manual de Projetos Aeroportuários	2021	Ministério da Infraestrutura (p.378)

Fonte: A Autora (2024)

Visando a abordagem do contexto das publicações das entidades governamentais a nível federal, não contempladas pelas etapas anteriores, uma pesquisa complementar foi realizada utilizando-se como busca, os sites oficiais do governo brasileiro. A nova seleção atendeu os mesmos critérios aplicados nas etapas anteriores e integralizou uma nova publicação, elevando para 14 o número de publicações (Tabela 3.4).

Tabela 3.4 Amostragem complementar

13. Requisitos para desenvolvimento de Projetos em BIM	2022	Departamento Nacional de Infraestrutura Transportes - DNIT (p. 67)
14. Caderno de Requisitos Técnicos BIM	2024	DNIT (p. 82)

Fonte: A Autora (2024)

A leitura das publicações (textos completos) foi realizada no intuito de se verificar os critérios de pesquisa e, consequentemente, a validação qualitativa da amostragem final. Durante esta apuração, eliminaram-se as amostras 1, 5 e 13 visando evitar duplicidades, uma vez que as entidades governamentais (governos do estado de Santa Catarina, Paraná e DNIT) publicaram versões mais atualizadas. A amostra 10 foi eliminada em função de não citar Usos BIM e não representar o ciclo de vida, logo não correspondia ao propósito sistêmico, reduzindo a amostragem para 10 publicações. O diagrama de fluxo PRISMA (MOHER *et al.*, 2009) foi utilizado para detalhar o Protocolo desenvolvido, a partir da reformulação do *string* (Tabela 3.5).

Tabela 3.5 Diagrama PRISMA

Registros identificados através de busca nas bases de dados (n = 1530)

↓

Registros adicionais identificados através de outras fontes (n = 2)

↓

Registros após remoção de duplicatas (n = 739)

↓

Registros triados (n = 793)

↓

Registros excluídos [após aplicação dos filtros] (n = 780)

↓

Textos completos avaliados para elegibilidade (n = 14)

↓

Textos completos excluídos, com razões (n = 4)

↓

Estudos incluídos na síntese qualitativa (n = 10)

↓

Estudos incluídos na síntese quantitativa (meta-análise) (n = 10)

Fonte: A Autora (2024)

3.3 Resultados e Análise

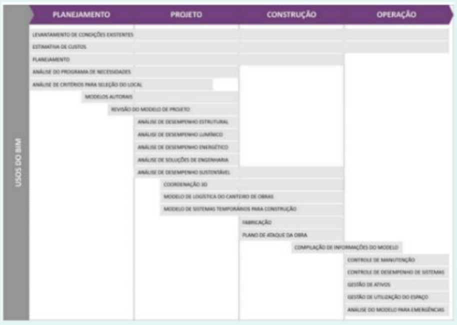
Na Figura 3.4 apresenta-se o mapeamento das ocorrências sob o espectro de dois requisitos sistêmicos: Usos BIM e da representação do ciclo de vida (eixos X e Y). Sequencialmente, o detalhamento das ocorrências é revelado por amostra (Fig. 3.5) conforme numeração especificada no protocolo (apresentada no item 3.2.2).

Fig. 3.4 Mapeamento dos resultados
Fonte: A Autora (2024)

AMOSTRA 2

Replica Usos BIM BEP Guide

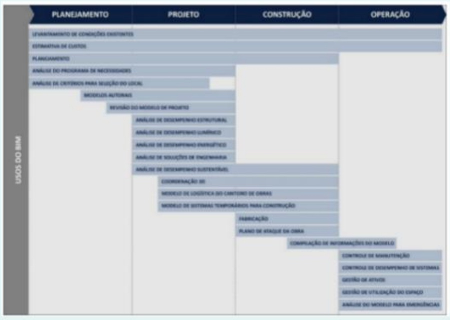
Replica Ciclo de Vida BEP Guide



AMOSTRA 3

Replica Usos BIM BEP Guide

Replica Ciclo de Vida BEP Guide



AMOSTRA 4

Replica Usos BIM BEP Guide

Replica Ciclo de Vida BEP Guide

AMOSTRA 6

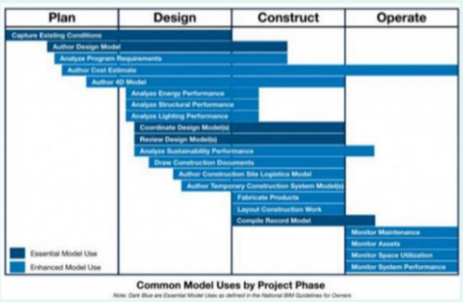
Usos BIM Customizados

Fonte: AutoDesk

AMOSTRA 7

Replica Usos BIM BEP Guide

Replica Ciclo de Vida BEP Guide



AMOSTRA 8

Replica Usos BIM BEP Guide

Replica Ciclo de Vida BEP Guide

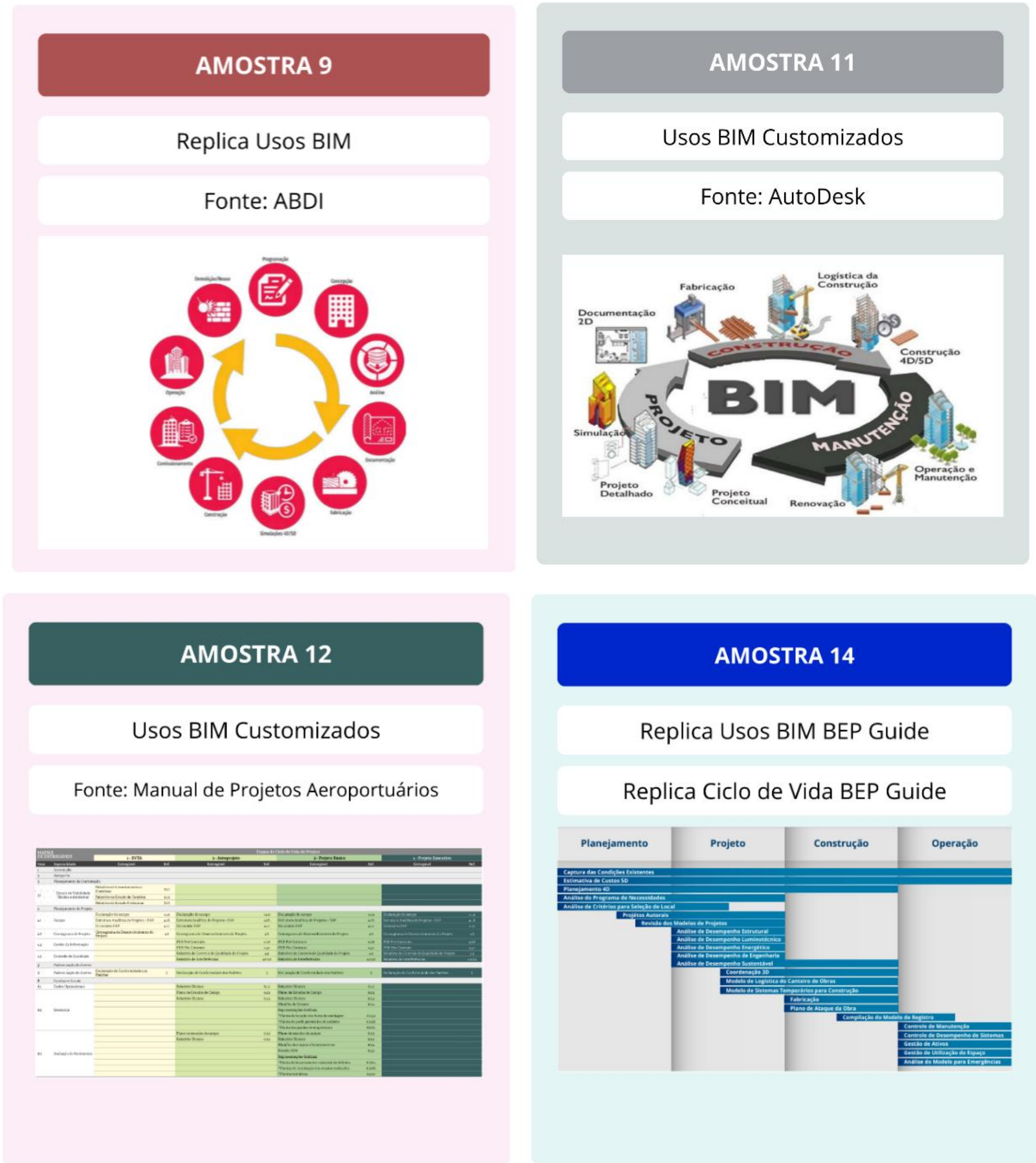


Fig. 3.5 Detalhamento das amostras
Fonte: A Autora (2024)

A análise sistêmica visou ainda esclarecer a conexão das possíveis aplicações do BIM e as fases do ciclo de vida com outras formas de representação do ciclo de vida, referenciados pelas amostras (Tabela 3.6). Baseando-se na arguição: "*A amostra replicou os Usos BIM e/ou o modelo de ciclo de vida referenciados pelo BEP Guide?*"

a) Se sim, plenamente, todas as colunas são preenchidas (cor rosa)
b) Se replica parcialmente ou não replica:

b1) Quanto aos Usos BIM: Se replica, a coluna [Replica BEP Guide] é preenchida (cor rosa);

b2) Quanto à representação do ciclo de vida: Se Não replica: parâmetros adicionais (i.,ii.,iii.) são esclarecidos:

i. Forma de representação do ciclo [Linear ou Circular];
ii. Fase final do ciclo [Identificação];
iii. Fonte [Identificação].

Neste cenário, constatou-se que 60% (sessenta por cento) das amostras replicam os Usos BIM e o ciclo de vida (BEP Guide) em plenitude, traduzindo para o português e/ou customizando as demandas da organização; 20% (vinte por cento - composto pelas amostras 9 e 11) replicam apenas os Usos BIM (BEP Guide) e representam o ciclo de vida em outro padrão; 20% (vinte por cento) constituído pelas amostras 6 e 12 não replicam os Usos BIM nem o modelo de representação de ciclo de vida proposto pelo BEP Guide.

Tabela 3.6 Resultados

Amostra	Replica BEP	Representação	Fase final	Fonte
2				
3				
4				
6		Circular	Manutenção	Autodesk
7				
8				
9		Circular	Demolição /Reuso	Própria
11		Circular	Manutenção	Autodesk
12		Linear	Projeto Executivo	Própria
14				

Fonte: A Autora (2024)

As amostras que não replicam o BEP Guide (amostras 6 e 12) exploram as aplicações BIM no contexto processual clássico (Estudo Preliminar/ Anteprojeto / Projeto Básico e Projeto Executivo) e, consequentemente, não exploram os Usos BIM sob o espectro do ciclo de vida ampliado. A amostra 6 apresenta um modelo de representação de ciclo de vida incluindo a fase [Manutenção] referenciada em fonte estadunidense. A amostra 12 representa o ciclo de vida customizado e, portanto, até o fim da fase projetual.

As amostras 9 e 11 replicam os Usos BIM do BEP Guide, porém representam o ciclo de vida no padrão (circular) e utilizam diferentes fontes. A amostra 9, em especial, agrega diferenciado valor em sua narrativa quando apresenta as ações típicas do setor civil relacionando-as às fases [Projeto; Aquisição; Montagem; Operação], em consonância com a National BIM Standard – NBS (Fig. 3.6). De acordo com a NBS, citada pelo Guia ABDI (2017), a fase [Operação] aborda ações relacionadas a Alterações [Análise; Recuperação; Renovação; Demolição] estabelecendo assim conexão com as fases antecessoras.

PROJETO	AQUISIÇÃO	MONTAGEM	OPERAÇÃO
REQUISITOS	FORNECESORES	QUALIDADE	COMISSIONAMENTOS
Programa	Qualificação	Testagem	Ponto de início
Cronograma	Disponibilidade	Validação	Testagem
Qualidade	Estabilidade	Inspeção	Equilíbrio
Custo	Capacidade	Aceitação	Treinamento
LOCAL	MATERIAIS	SEGURANÇA	OCUPAÇÃO
Zoneamento	Especificação	Requisitos	Processos de venda
Características Físicas	Seleção	Logística	Administração da edificação
Abastecimento de serviços (água, luz, gás, etc)	Compra	Treinamento	Segurança
Características ambientais	Certificação	Inspeção	Serviços aos moradores
FORMA	CONTRATAÇÃO	CRONOGRAMA	ALTERAÇÕES
Arquitetura	Solicitação de orçamento	Fabricação	Análise
Estrutura	Solicitação de propostas	Entregas	Recuperação
Envelope (fachada, coberturas)	Seleção	Recursos	Renovação
Sistemas	Contrato	Instalação	Demolição
ESTIMATIVA	PREÇO	CUSTO	MANUTENÇÃO
Quantidade	Quantidade	Produtividade	Prevenção
Preço dos sistemas	Preço unitário	Solicitação	Agendamento de manutenção
Comparação	Mão-de-obra	Orçamento	Garantias
Reajuste	Equipamento	Seleção	Contratada

Fig. 3.6 Inter-relacionamentos
Fonte: ABDI, 2017 (modificado)

Neste contexto, as atividades características das fases iniciais do ciclo de vida ocorrem também durante a fase operacional, retroalimentando um fluxo contínuo visando prolongar a vida útil do ativo. Vale ressaltar que ainda que a amostra 8 se caracterize como parte do universo percentil mais representativo das publicações que replicam o BEP Guide plenamente, discorre adicionalmente sobre ações clássicas do setor AECO, a partir de dois modelos de ciclo: padrão evolutivo linear e padrão circular. Ambos denominam as etapas: Pré-obra, Obra e Pós-obra, porém o exemplo que utiliza o padrão circular (Fig. 3.7) indica Início e Descarte após as atividades [Descomissionamento; Reforma].

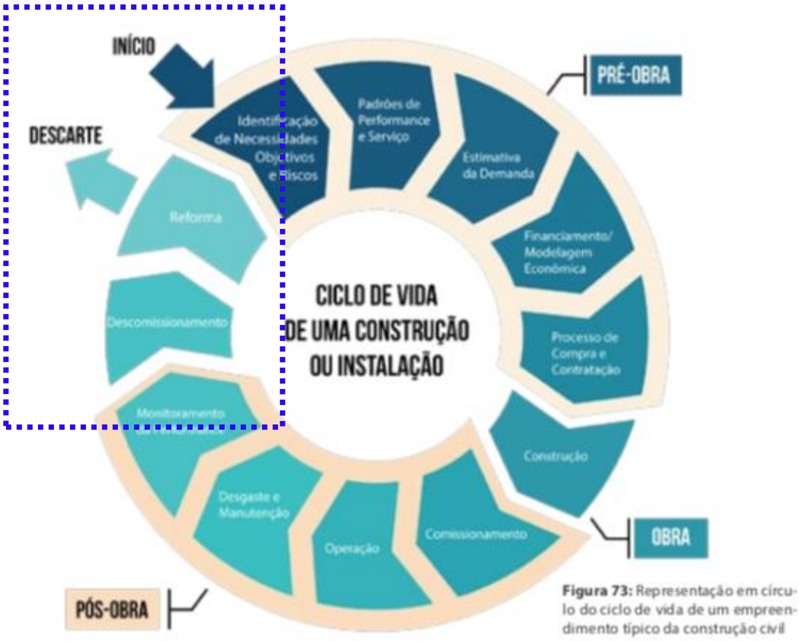


Fig. 3.7 Representação do ciclo em círculo
Fonte: CBIC, 2016 (modificado)

3.4 Considerações finais

Um projeto pode demandar ao longo das fases do ciclo de vida inúmeros modelos BIM, onde cada um representa uma aplicação ou Uso BIM desenvolvido para atender uma demanda específica. Neste cenário, alinhado à teoria dos sistemas, uma definição simples de BIM seria: “Um sistema (projeto) formado por vários subsistemas (modelos BIM) sustentado pelos pilares: Parametrização, Colaboração e Interoperabilidade”.

A influência da literatura estadunidense nas publicações BIM brasileiras, de maior relevância, é notória sobretudo a plena replicação do conteúdo desenvolvido pela Penn State University em 60% das amostras analisadas. Considerando o panorama legislatório vigente. Especialmente em conformidade com a ISO 19650:2023, uma lacuna de pesquisa é delineada uma vez que a gestão da informação demanda o relacionamento da fase “Operação” às antecessoras. Neste contexto, estudos futuros precisam explorar a dinâmica do fluxo contínuo alinhada à forma de representação do ciclo de vida, de forma a permeá-lo.

Ainda que algumas publicações apresentem o ciclo de vida do projeto no padrão mais aderente à dinâmica cíclica, que os ciclos ideologicamente deveriam representar, nenhuma amostra explorou semanticamente as fases, ou estágios do ciclo. A fase operacional demanda maior atenção em função de absorver atividades mantenedoras e interventivas que visam prolongar a vida útil do projeto. E, por esta razão, contempla não somente ações típicas deste estágio do ciclo, mas também atividades que ocorrem nas fases iniciais, durante a sua vigência.

Os processos de reformas, duplicações de pistas de infraestruturas e/ou reabilitações estruturais, são alguns exemplos que os ciclos de vida representados pelo padrão evolutivo sequencial, não conseguem representar com clareza o aspecto síncrono de suas ocorrências visando a sustentabilidade do ativo.

Quando o contexto processual que visa o prolongamento da vida útil termina, uma nova fase é demandada para agregar significado à dinâmica cíclica, porém no sentido semântico contrário. Ações como "Descomissionamento" e "Desocupação" total do espaço são semanticamente adequadas para a fase que visa o fim do ciclo.

Da mesma forma que a fase operacional demanda ações já vivenciadas nas fases anteriores, esta fase final também necessitaria. No entanto existe uma diferença fundamental entre as fases: as ações interventivas durante a fase operacional podem ocorrer quantas vezes forem necessárias enquanto que na fase final ocorrem uma única vez. Isto se dá, porque o contexto processual final visa que o *site* (terreno) retorne ao seu estado de origem cedendo espaço para que um novo projeto, um novo ciclo, possa ser iniciado.

Neste cenário, o padrão de representação do ciclo de vida do projeto, amplamente referenciado na literatura brasileira torna-se inadequado. Desta forma, definir semanticamente as ações que caracterizam os Usos BIM e as fases do ciclo de vida do projeto torna-se fundamental.

Estas constatações configuram a necessidade de realização de estudos específicos que explorem outro tipo de representação para o ciclo de vida, além da semântica das fases que o compõem motivada pelo fato de que um mesmo Uso BIM pode ocorrer em mais de uma fase do ciclo e, até mesmo, em todas.

Por fim, vale destacar que o alinhamento semântico é uma discussão pautada nos tópicos introdutórios de normas internacionais quando traduzidas para o português. De fato, alguns termos técnicos quando traduzidos, podem associar equívocos de significado. Citam-se, como exemplos, os termos: "*Project*" traduzido para projeto (substantivo) pode ser confundido com a ação de projetar e, não com o contexto do projeto como produto da indústria civil (o empreendimento como um todo); "*Design*" traduzido como projetar (verbo) pode ser associado ao entendimento de desenvolvimento de uma solução, uma disciplina (parte do todo) e, neste contexto, ser confundido com a amplitude do termo "*Project*".

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CAPÍTULO 4 - DYNAMIC PROJECT LIFECYCLE - DPL: A PROPOSAL FOCUSED ON INFORMATION MANAGEMENT AND IFC DATA INTEROPERABILITY

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Abstract

Given the evolution of the Industry Foundation Classes (IFC) data schema and the regulatory framework addressing information management, professionals in the civil industry must specify the requirements for information and interoperability. However, the sector diversity and constant technological advancement make specifying data for disciplinary models developed throughout the Project lifecycle a dynamic task. According to ISO 12006-2 and 19650-1, the Project process context and information management have a strong connection. In this scenario, this study aims to develop a Lifecycle in compliance with the normative framework, semantically aligned with OpenBIM standard interoperability. This demand was outlined by the information feedback, especially in the operational phase of the project, also addressing the semantically opposite phase, which aims to conclude the end of life. The artifact developed through the Design Science Research (DSR) method also proposes a Pset_ProjectLifecycle, as the analyses revealed the specification through IfcProject.Phase and ProjectType are still semantically limited.

Keywords: IFC Data Schema. Interoperability. Project Lifecycle. Information Lifecycle. Information Management. Industry Foundation Classes.

4.1 Introduction

Building Information Model (BIM) protocols, guides, or standards prescribe how the civil industry should use models to deliver high value and mandate the application of those protocols. Government agencies create regulatory frameworks, necessary for promoting and supporting BIM adoption through national standards. In response, owner organizations have published several documents, including standards, collaboration guidelines, and/or BIM Execution Plan (BEP). Those documents define how information will be used in collaborative practice, as well as the phases of the design and construction process [1].

The construction process utilizes resources to achieve results through organized classes of objects under the spectrum of the main types of construction processes: Pre-Conception Process; Conception Process; Production Process (construction); Maintenance Process, thus referring to the lifecycle phases or stages [2]. The standard discusses the organization of information proposed in classes aiming at the syntax required by the IFC object-oriented data specification, which is managed by buildingSMART International in the construction industry [3].

The IFC data schema addresses the highly fragmented nature of the sector and, consequently, OpenBIM interoperability standard [4,5,6,7]. In this context, software applications need to meet the proposed data specification to respond to the universe of applications (BIM Uses), represented by disciplines (models) that may occur in one, several, or all phases of the lifecycle, depending on the specifics of each project. The systematic literature review identified the key parameters to clarify questions such as 'What are the deliverables in each phase of the project lifecycle?' and 'What are the major phases of the project?' [8]. Results showed that 60% of documents reviewed break down the project implementation into different stages, fostering the exploration of increased accuracy and detail in the schematic design phase.

Since the advent of BIM, contracting processes have required the use of classification systems that are semantically aligned with the information exchange standards demanded throughout the project timeline. During the procedural evolution described, the various stakeholders involved collaborate in a multidisciplinary manner through their tools. However, for information exchange flows to occur across different systems, interoperability must be achieved through a neutral and open standard, rather than by compatibility.

The IFC has consistently evolved over the years, with significant additions to the data schema architecture layers (Domain, Interoperability, Core, and Resource) aimed at raising the semantic level of the OpenBIM standard. This way, it has provided consistent responses to the civil sector to meet the demands involved in building and infrastructure projects [9].

The different types of information provided by IFC include geometric, functional, technical, cost, and maintenance data, which may be required throughout the project timeline, from briefing (program requirements), design, documentation, construction, operation, maintenance, to demolition. ISO 12006-2 presents these stages incorporate processes of a semantic nature outlined [2], showed in Table 4.1.

Table 4.1 ISO 12006-2 References

Process of construction	**Definition**
(3.3.4) Pre-Conception	Construction properties before design development
(3.3.5) Conception (Design)	Construction properties for the built environment before it is physically produced
(3.3.6) Production (Construction)	Results in the built environment, potentially including demolition and recycling
(3.3.7) Maintenance	Operation of the built environment and preservation of its functions

Source: the Author (2024)

In a scenario characterized by constant evolution and technological innovation, Lifecycle Information Transformation and Exchange (LITE) framework [11] explored the civil industry terminologies used [Information; Asset; Information Requirements; Information transformation; Demand Organization; Design, Construction, and Operation; Information address to digital assets; Document; Model; Data]. Sequentially, it presented a model of parameter combinations. The authors encourage the scientific community to test the possibilities of BIM applications through LITE, noting that these possibilities tend to be immeasurable.

This finding raises the need for a semantic analysis of actions typical to the sector, representing a research gap to be explored in this study. These actions encompass a wide range of activities within the civil engineering segment [12], aimed at generating specific types of information. Additionally, such actions can be organized accordingly to the processual context structured by the lifecycle stage [2]. Therefore, the general objective of the paper is to introduce the development of a new project lifecycle representation model that encompasses the breadth identified in the literature and is semantically aligned with current BIM standard.

Information supports decision-making throughout the entire project lifecycle, including, when applicable, the intention to build, modify, expand, or decommission (general asset management system). The design intent should be implemented during the operational phase, where trigger events may require an information management response, resulting in one or more information exchanges [13]. Trigger events encompass anything that occurs (either planned or unplanned) and changes an asset or its state over time, leading to information exchange.

4.2 Background

4.2.1 ISO 19650-1

Information management governed by ISO 19650-1 establishes that the lifecycle be understood in phases as follows: the Delivery Phase, corresponding to the part of the cycle in which the asset is designed, constructed, and commissioned, as well as the operational phase, occurring during the time the asset is in use, operated, and maintained. The connection between these phases is marked by the continuous flow of information generated by trigger events, indicating that the information management process can occur throughout the entire lifecycle [14].

It should be initiated each time a contract is made for any phase (delivery or operation). Thus, the asset may be modified or have its state altered through these events, resulting in information exchanges. In this way, the verification of design intent should be carried throughout the review of asset's performance during full operation.

Construction processes unfold over periods composed of one or more stages. Each stage is a high-level characterization of the main parts of a project. Task sequencing can be organized according to these stages, thus representing a subordinate level.

The Asset Information Model (AIM), generated after the completion of the project's construction phase, can be considered a deliverable - the construction product. Together with the Project Information Model (PIM), these information models form a set of structured (and unstructured) information produced throughout the information lifecycle (delivery phase and operational phase) to support decision-making processes. According to the standard, a structured information set is referred to as a "container" only when it meets a previously agreed convention and is retrievable via file or system (or an application's storage hierarchy) for the duration required for enterprise management.

Regarding the Organizational Information Requirements (OIR), it is legislated that they relate to the information needed to support decision-making, while the Project Information Requirements (PIR) respond to the specific demands, both from project management processes and asset management processes. To address this, Information Exchange Requirements (EIR) are required to detail the production methods to be implemented. The Asset Information Requirements (AIR), on the other hand, establish the commercial, managerial, and technical aspects of asset information production.

4.2.2 IFC Data

The IFC schema is a data specification developed by the construction industry aimed at interoperability through an open standard. This standard must meet, at a high semantic level, the collaborative workflows established between the various disciplines required by a project. OpenBIM aligns with the principle of equality, present in public bidding processes, and for this reason, adds significant value to governance worldwide [5]. In Brazil, the neutral and interoperable standard must be adhered to according to Federal Decree [15].

According to the IFC data schema, IfcProject is the entity that encompasses the three basic frameworks of a model: Identification, Geometric and Units, and Financial [4]. The specification of the Identification framework must clarify, among other attributes, the current phase of the project lifecycle [IfcProject.Phase]. This is because the same model use can occur in multiple lifecycle phases, or even in all phases. For example, the Use “Existing Conditions Modeling” may be required for a new project [Feasibility phase] or an existing one, originally not BIM conceived [Operation phase].

Other entities in the IFC schema, such as the property ProjectType, specify the type of project associated through an enumeration `[.MODIFICATION., .NEWBUILD.,.OPERATIONMAINTENANCE.,.RENOVATION.,.REPAIR.]` which refers to the current phase of the model lifecycle. However, to ensure a high semantic level, the

BuildingSmart Dictionary Data (bSDD) establishes the meanings of other properties to further specify the objects [16]. For example, the whole lifecycle or only a given phase from which data valid could be: Aquisition; Creadletosite; Deconstruction; Disposal; Disposal Transport; Growth; Installation; Maintenance; Manufacture; Occupancy; Operation; Procurement; Production;production Transport; Recovery; Refurbishment; Repair; Replacement; Transport; Usage; Waste; Whole lifecycle.

The options demonstrate a typological diversity of actions that can be organized by nature [17]: Maintenance, Occupancy, Operation, and Usage are classified as "Stages of Use" and can be associated with the idea of a new or existing project. However, other activities within the same stage, such as Growth, Repair, Recovery, Replacement, and Refurbishment, are limited to the context of an existing projects.

Others activities, such as Procurement and Aquisition, could be organized across all stages of the lifecycle, unlike: Waste, Disposal, Deconstruction, Disposal Transport, which can be addressed during the construction stage as well as the post-construction stage, including the end of life stage.

4.2.3 BIM Uses and Lifecycle Phases

The Uses of BIM are explored by various guides around the world to guide professionals in the civil industry in the development of BIM execution plans. In the Americas, the BIM Execution Plan Guide has been used as inspiration by the governance of several countries (Attachment 4.1). Originally published in 2009 [18], the guide identified twenty-five BIM Uses, organized by the project phase of development. Those were identified through numerous interviews with industry experts, analysis of implementation case studies, and a literature review.

The semantic matrix titled "Model Uses" is based on five primary actions [Gather; Generate; Analyze; Communicate; Realize] and eighteen secondary actions [Qualify; Monitor; Capture; Quantify]; [Prescribe; Size; Arrange]; [Coordinate; Forecast; Validate]; [Visualize, Draw, Transform; Document]; [Fabricate; Assemble; Control; Regulate], respectively [19].

The publication has undergone updates and adjustments (both quantitative and qualitative) over time. There have been changes in the naming and semantics of the Uses (some were excluded and/or added), as well as variations in their occurrences throughout the phases of the lifecycle, represented in the linear temporal evolutionary pattern [20]. To demonstrate these changes, two BIM Use cases were selected for this study, such as shown in Table 4.2.

Table 4.2 Extract from changes in BIM Uses

	Phase of Lifecycle	
BIM Uses	BEP v. 0.9 (2009)	BEP v. 3.0 (2023)
1. Cost Estimation (Changed to: Author Cost Estimate)	Plan, Design, Construct Primary	Plan, Design, Construct, Operate Enhanced
2. Design Authoring (Changed to: Author Design Model)	Design Primary	Plan, Design, Construct Essential

Source: the Author (2024)

Although the project operational phase [Operate] is characterized by the demand for information triggers [2], it is currently represented in the BEP by a single occurrence of a primary Use [Compile Record Model], initiated in the construction phase [Construct]. The other mapped Uses are characterized by secondary classes, such as "Analyze Sustainability Performance", "Author Cost Estimate", and those related to monitoring, both originating from the preceding phases of the lifecycle.

From another perspective, the Uses were expanded [21] in a broader and more flexible way, not linking them to specific phases of the lifecycle but instead to 7 modes of model use: [Capturing and Representing; Planning and Designing; Simulating and Quantifying; Constructing and Fabricating; Operating and Maintaining; Monitoring and Controlling; Linking and Extending]. A reflection between the two publications is presented in Table 4.3, using the Model Uses [A. Demolition Planning; B. As-constructed and their respective Model Uses Series] and their correlation with the lifecycle phases referenced by the BEP guide.

Table 4.3 Reflection between Model Use and Lifecycle Phase

Mode Uses Series (Succar et al., 2016)	**Model Use** (Succar et al., 2016)	**Lifecycle Phase** (BEP v.3.0, 2023)
Planning and Design	A. Demolition Planning	Plan
Capturing and Representing	B. As-constructed representation	Construct

Source: the Author (2024)

Model Use A and B could be developed for both a new project context and an existing project. In the BEP guide, Model Use A would be identified in the Plan phase, as there is no mention of the Use in the Operation phase. Model Use B would be linked to the As-built Record option, resulting from the construction stage.

In light of ISO 12006-2 and ISO 19650-1, the phases of the lifecycle presented in the standard outlined by the BEP guide do not address the operation phase concerning the demand for triggers. In the case of the BEP Guide, the AIM would be limited to the Use "Compile Record Model". This occurs because the conceptual and representational standard of the proposed lifecycle was designed based on the context of a new development.

The need to explore the context of projects originally not conceived in BIM is justified by the vast universe of existing assets. In this scenario, the models resulting from the construction phase (As-is Model) would represent the information container, used as the base to develop the Asset Information Model (AIM) [22].

Strictly speaking, the As-built and As-is information containers could reflect different phases of the project lifecycle, although as AIM databases, they serve the same purposes. Ideologically, they should correspond to the actual reality, as conceived (and constructed), and in this direction, they can additionally be considered As-constructed models [21].

The other Uses mapped in the operational phase of the lifecycle, as proposed by the guide, are characterized by their nature: Enhanced Model Use [Analyse Sustainability Performance; Author Cost Estimate] and Monitor [Maintenance; Assets; Space Utilization; System Performance], both originated from the preceding phases of the lifecycle. It is evident, therefore, that there is a gap in the representation standard of the operational phase, aligned with the information triggers related to the activities that are characteristic of the previous phases [Plan, Design, Construct], classified as "Essential." Additionally, it is key to implement the inclusion of a phase that addresses the opposite semantic sense of operation, that is, the end of the useful life and, consequently, the end of the lifecycle.

4.3 Method

4.3.1 Design Science Research (DSR)

The development of a new lifecycle model is guided by design science. Through design science, the aim is to create an artifact to achieve a practical objective, focusing on the proposition of how things should be [23]. It is fundamentally a problem-solving paradigm to improve an organization's effectiveness and efficiency by creating innovations [24].

Design Science Research (DSR), as a methodology for the development of artifact creation science, consists essentially of two activities: building and evaluating, typified four possible research outputs: (i) Constructs, which form the basic language of concepts used to characterize a phenomenon; (ii) Model, a set of propositions or statements expressing the relationships between constructs; (iii) Methods, which are the means of performing activities toward an objective, based on constructs and models; (iv) Instantiation, the physical implementation of the artifact in its environment, operationalizing constructs, models, and methods [25].

Constructs can be formalized as in data modeling, with structures such as entities, attributes, relationships, identifiers, and constraints, aiming for precise structuring [26]. In this direction, the study proposes an artifact capable of representing a lifecycle model of a typical project in the construction industry, semantically aligned with the new demands in the sector and normative framework compliance.

The discussion regarding the representation form of the artifact involves understanding the language and symbolism to be used and the correlations to be established between them. In this way, it represents a response to the screening developed through similar constructs and the lifecycle stages that address possible applications (BIM Uses). Concerning the lifecycle stages, part of the results achieved from the previous systematic literature review research reveal the influence of BIM Uses [27]. Considering the current normative framework, particularly following ISO 19650-1, a research gap has been highlighted, as it addresses information management requirements between the operations phase and its predecessors. In this context, future studies need to explore the dynamics of this continuous flow and its relationship with the form of lifecycle representation to integrate it effectively.

Based on the studies conducted, it was observed that the lifecycle should address two distinct concepts involved in the development process of a project. While the former concerns the dynamics associated with the cyclical and iterative nature of the project, which is executed and revisited periodically, the latter relates to the form of its representation.

Regarding the form, there is a greater representation of the linear evolutionary pattern than the circular one that cycles typically suggest [28,29,30]. The circular or circumference geometric shape is adopted by Circular Economy theory, characterized as restorative and regenerative within a feedback loop concept, where the output of one process serves as the input for the next [31].

In the civil sector, this information flow indicates the possibility of a new service life period for a subsystem (part) of the project, or even the entire system [29]. Consequently, this flow requires the recurrence of actions characteristic of the initial lifecycle stages during the operational phase of the asset. The circular form serves as the development field for demolition or deconstruction practices as strategies for the circular economy [32]. However, the circular nature and dynamic movement were not jointly represented in any of the lifecycle models identified.

Based on these observations, the development of the artifact was carried out through a retrospective and prospective reflective learning process, referencing the retrodictive methodological [12], as well as the abductive and deductive approaches for conducting DSR [33], as illustrated in Figure 4.1.

The identification of the problem and the establishment of a knowledge base were previously conducted through a literature review, which identified the available representations of the project lifecycle. Subsequently, the initial development stage focused on the semantic aspects of the lifecycle phases, with a second emphasis on the behavioral aspect, which links the construction industry with BIM Uses. The initial development stage discusses the description of typical actions in the civil sector that occur throughout the phases of a project's lifecycle. In this way, the artifact was developed and described through a process of retroduction, conceptual grouping, and reflective learning [12]. The abductive method, like the retrodictive method, is suitable for the creative reasoning stage in the construction of the semantic lifecycle, named Dynamic Project Lifecycle (DPL), as it proposes a theory to explain the facts and organize the information (deduction), which is then empirically tested (induction).

Retroduction follows an approach divided into three stages, beginning in the domain of the real empirical, observing and experimenting with connections between phenomena to explain events activated in the real domain. In the second stage, a hypothetical model is proposed, involving structures and mechanisms located in the real domain that, if they existed and acted in the proposed manner, would provide a causal explanation of the phenomena in question. The final stage involves subjecting the proposed explanation to empirical scrutiny [33,12].

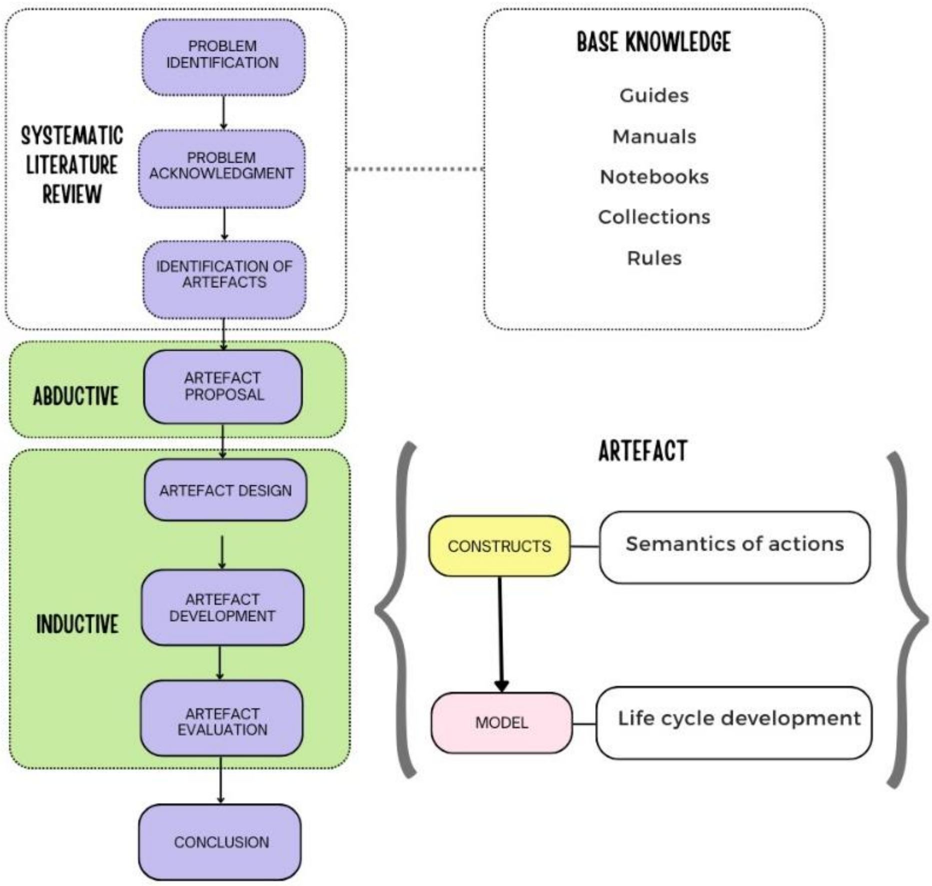


Fig. 4.1 DSR steps developed
Source: the Author (2024)

4.3.2 Lifecycle of a project

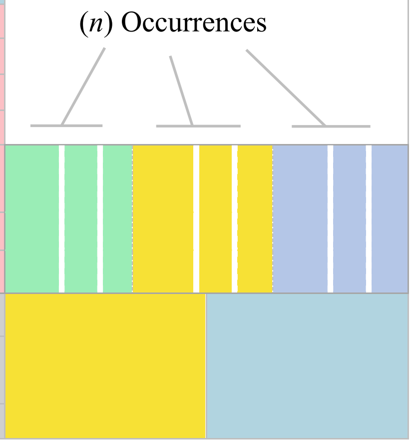
The typical actions of the Architecture, Engineering, Construction, and Operation (AECO) sector, represented by BIM Uses models, are widely disseminated and based on a primary classification. This organization of classical concepts underpins the procedural context of the project. Through an amplified spectrum of activities, more specific aspects populate the lifecycle phases, thus representing secondary actions [19].

4.3.2.1 Semantic of actions

Typical actions in the civil construction sector can occur in a single phase, in multiple phases, or throughout the entire lifecycle, depending on the context of their applications. However, some actions occur regularly throughout the cycle, regardless of the processual contexts, which in this study are called "Constant Actions" [Manage; Plan; Coordinate; Represent and Simulate; Verify].

The actions exposed to the context of the construction process [14] were considered "Primary Actions"; the "Secondary Actions" inherit the context of the primary ones and add specificities [19,35,36,37]. The primary actions analyzed under the processual context [2] structure the typical lifecycle of the civil industry through phases or stages (Table 4.4).

Table 4.4 Actions and Context

Constant Actions **Manage; Plan; Coordinate; Represent and Simulate; Verify**			
Primary Actions	**Processual Context**	**Secondary Actions**	**Tertiary Actions** Primarily recurring
1. Incept **2. Pre-conceive**	**START of a lifecycle** Project Process **[Feasibility]**	1.1 Prospect	
		2.1 Study	
		2.2 Estimate	
		2.3 Capture	
3. Conceive	Project Process **[Conception]**	3.1 Dimension	
		3.2 Specify	
		3.3 Validate	
		3.4 Quantify	
		3.5 Budget	
4. Execute	Production Process **[Execution]**	4.1 Build	
		4.2 Control	
5. Operate **6. Maintain** **7. Modify**	Maintenance Process **[Operation]**	5.1 Comission	
		5.2 Monitor	
		5.3 Inspect	
		6.1 Renovate	
		7.1 Deconstruct or Demolish*	
		7.2 Reform	
		7.3 Rehabilitate	
8. Finalize	Finalization Process **[Closure]** **END of a lifecycle**	8.1 Decommission	
		8.2 Deconstruct or Demolish*	
		8.3 Vacate	

Source: the Author (2024)

The processual context at the beginning of the cycle addresses the primary actions [Incept and Pre-conceive], aligning with the semantics of the first phase of the lifecycle. In this study, called [Feasibility], it is characterized by its investigative and generalist nature, based on two basic actions:

[Incept] - represents the beginning of the Project creation process. For this reason, the secondary action [Prospect] was selected as semantically appropriate;

[Pre-conceive] - addresses the other parts of the project process aligned with the nature of the initial processual context and, therefore, is semantically related to the secondary actions [Study; Estimate; Capture].

The following processual context addresses the project process [2] in this study named [Conception]. In this way, the primary action [Conceive] is semantically related to the secondary actions [Dimension; Specify; Validate; Quantify; Budget], adding the evolutionary condition of the project until the validation of the involved disciplinary solutions is consolidated, studied, and estimated in the previous stage.

From these milestones, the represented idea underpins its materialization through the processual context of Project Production, in this study named [Execution]. The production or construction process denotes the primary action [Execute] in response to the solutions that will be materialized and, therefore, aligns with the secondary actions [Build; Control], semantically appropriate for the construction stage, which aims to transform the project into a "Product" of the construction Industry [2]. This milestone marks the beginning of the project's service life, turning it into a built asset.

The following stage is based on the Maintenance Process and addresses the greatest number of primary actions. Due to the density of the primary actions, the context was named [Operation].

The processual context of the lifecycle aims, in addition to operating, to prolong the service life and consequently the sustainability of the project. Thus, the primary actions [Operate; Maintain; Modify] are related to the temporal aspect with no expected end, as is the case with the other contexts:

[Operate; Maintain] – related to the secondary actions [Comission; Monitor; Inspect; Renovate]. Maintenance nature with the preservation of the original project scope;

[Modify] - related to the secondary actions [Deconstruct or Demolish; Reform; Rehabilitate]. Interventive nature, in response to changes in the project scope that may arise from the dynamics of space usage: qualitative typological (change in the type of space use); quantitative (change in horizontal and/or vertical projections).

The primary action [Modify] adds significant complexity to the operational context of the cycle, as it requires the information trigger [2]. In this scenario, primary actions from other processual contexts may be required synchronously, in light of the full operational capacity of the asset. This condition is not addressed by the lifecycle models represented in the linear evolutionary standard, nor is it sufficiently explored by the models represented by the circular standard. To address this dynamic, the recurring primary actions were termed "Tertiary Actions" (Table 4.5).

Table 4.5 Recurring and resulting actions

Secondary Actions	**Processual Context**	**Tertiary Actions** (Primarily Recurring)		
7.1 Deconstruct or Demolish 7.2 Reform 7.3 Rehabilitate	Maintenance Process **[Operation]**	Incept Pre-conceive	Conceive	Execute
8.1 Decomission 8.2 Deconstruct or Demolish 8.3 Vacate	Finalization Process **[Closure]** END of a lifecycle	Conceive		Execute

Source: the Author (2024)

Although the standard does not present a specific process for the completion of the cycle, the analysis under the semantic spectrum of primarily and secondary actions highlighted the need to explore the processual context of a phase between [Operation] and the end of the cycle. Aligned with the processual context [Operation] which aims to extend the service life, the semantically opposite demand, aiming to conclude it, was named [Closure]. In this scenario, the primary action [Finalize] aims to achieve the opposite of the previous phase and, therefore, it denotes the secondary actions [Decommission; Deconstruct or Demolish; Vacate]. The actions [Reform; Rehabilitate] relate to recurring primary actions from the preceding processual contexts [Feasibility; Conception; Execution].

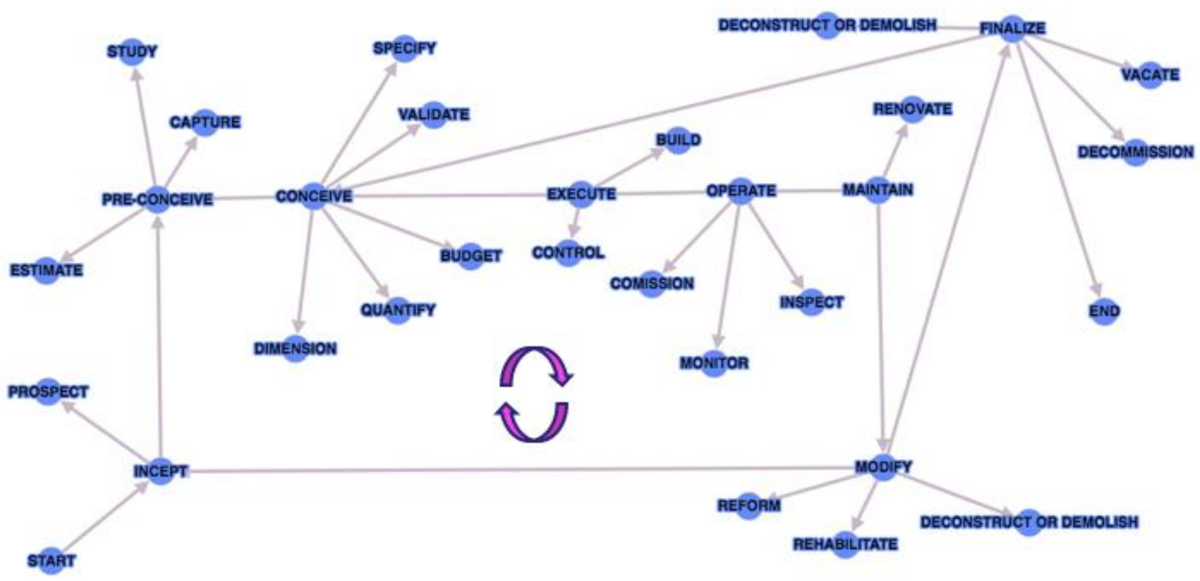
These recurrences correspond to the triggers [2] and occur after the occupation of the constructed asset, which may require (n) occurrences and, consequently, the incidence of actions [Incept, Pre-Conceive, Conceive; Execute] will correspond to a smaller cycle (mini-cycle) with a synchronous dynamic to the operational current phase. In this scenario, the actions [Deconstruct or Demolish] are applied according to the specificity of each project.

The finalization process also requires the occurrence of primary actions, but they only occur once and are restricted to the contexts [Conception and Execution], as the project ceases to be viable. This happens because they are characterized by the primary action [Finalize] in light of the [Closure] context, which aims at the end of the project's service life. In this case, the actions [Deconstruct or Demolish] are fully applied to return the site to its original condition.

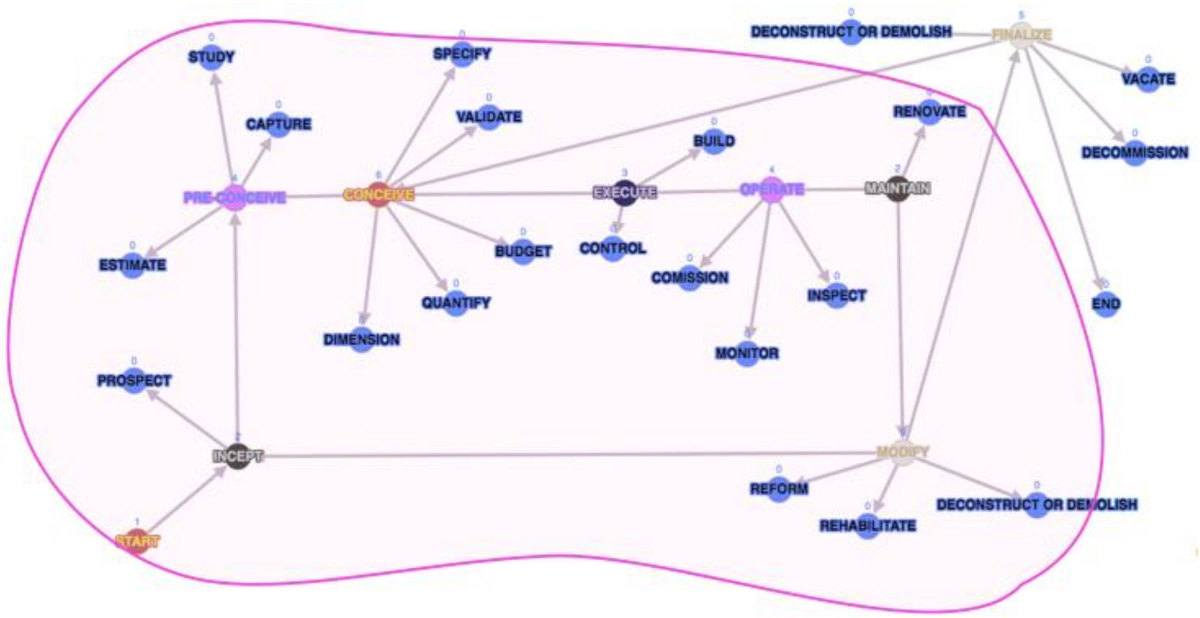
The mini-cycles represent important mechanisms (triggers) that occur as many times as necessary to ensure project sustainability. It is worth noting that the secondary action [Deconstruct], aligned with the primary action [Modify], is related to design decisions and, therefore, [Incept, Pre-Conceive, Conceive], to enable the recovery and reuse of the project through Design for Deconstruction (DfD). Deconstruction is an alternative to the action [Demolish] aimed at minimizing waste sent to landfills, through activities such as dismantling buildings and renovating construction elements, presenting itself as a more environmentally suitable option [38].

The incidence of mini-cycles aligns with the information cycle between the operations phase and the delivery phase [2]. In this way, when maintaining the asset service life is no longer the objective of the [Operation] process context, a new phase [Closure] will occur, and the actions [Deconstruct or Demolish] will aim to maximize and facilitate the recovery of materials and construction components. In the final stage, deconstruction practices might as a strategy for the circular economy [32].

To illustrate the connections established between the primary and secondary actions, graphs were created [39,40] (Fig. 4.2(a) and 4.2(b)). Fig. 4.2(a) establishes the relationships between the primary and secondary actions and indicates a trigger event. In this way, the loop represents the (n) mini-cycle possible occurrences, aimed at extending the project service life.



(a)



(b)

Fig. 4.2 Project lifecycle graphs: 4.2(a) Main context; 4.2(b) Semantic targets
Source: the Author (2024)

Fig. 4.2(b) details the quantity of outputs per vertex (from 0 to 6) and highlights the semantic way of project expanding service life (pink background). Closure phase has not the same context, because the semantic target has opposite way (finish service life), and address the end of asset lifecycle.

4.3.2.2 Artifact – Lifecycle representation

The development of the lifecycle representation of a project involved two key aspects: form [circular] and dynamic [cyclical]. The cyclical movement reflects the project´s dynamic and interactive nature, recurring periodically. The circular form (circle geometry) was inspired by the theory of the Circular Economy where the output of one process becomes the input of the next one.

The semantic analysis of the primary actions supported the classification of the stages (or phases) of the cycle under the spectrum of the procedural context. The artifact called Dynamic Project Lifecycle (DPL), was developed and illustrated in parts (Fig. 4.3 and Fig. 4.4) drawing inspiration from the graphs presented. In line with the cyclical nature that life cycles intuitively suggest, a circular representation was used to organize the procedural context (outer circumference). The evident actions are illustrated through the color gradient that indicates the initial and final occurrences across the procedural contexts (phases).

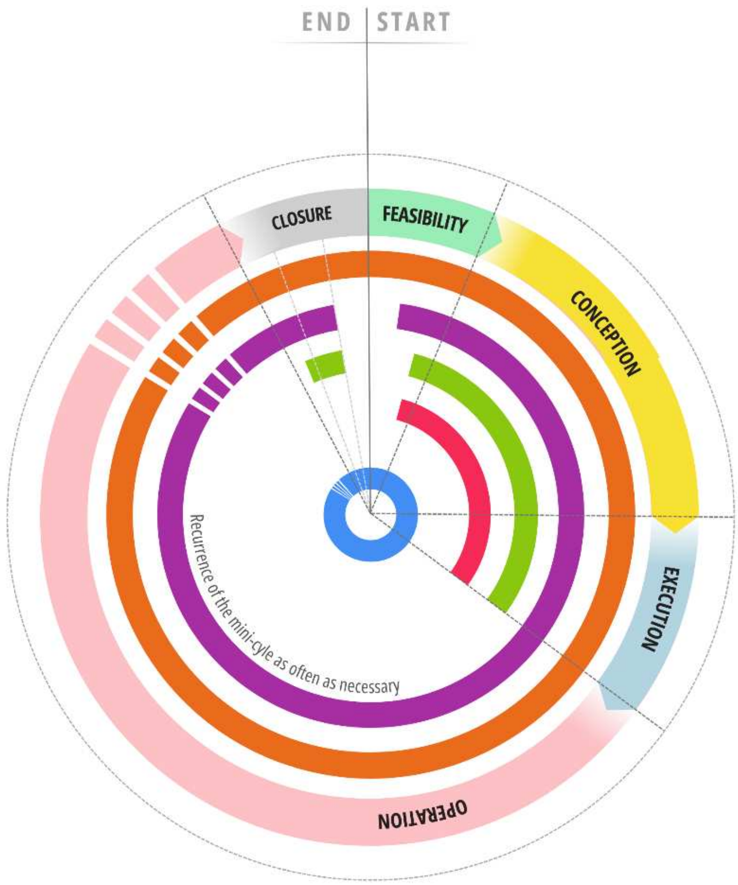


Fig. 4.3 DPL Core
Source: the Author (2024)

4.3.1.3 Information loop

The DPL considers (and represents) the possibilities of mini-cycles occurring throughout the operational phase, representing the trigger events. In this scenario, the "n" mini-cycles (where *n*=occurrences that aim to extend the useful life) and therefore occur semantically aligned to the primary action [Modify] and secondary [Reform; Rehabilitate; Deconstruct or Demolish]. Figure 4.4 illustrates the mini-cycle, associated with the flow (project lifecycle graph) which presents the information loop (trigger events), since Modify action.

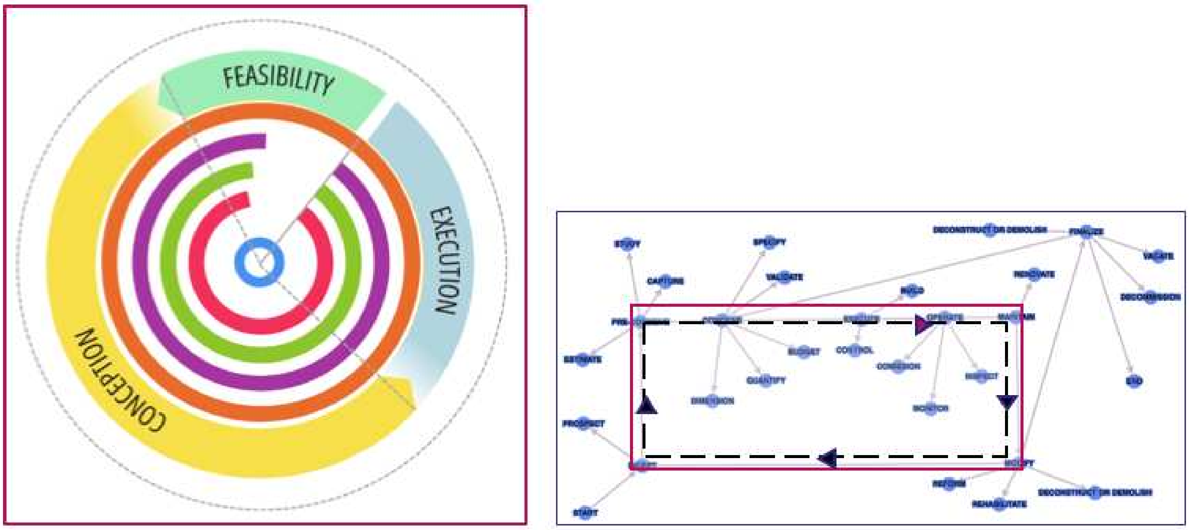


Fig. 4.4 DPL Mini-cycle
Source: the Author (2024)

The shaded image of other mini-cycles and interruptions until the final phase of the cycle indicates the possibility of occurring as many times as necessary until the intention to extend the useful life is exhausted. This dynamic represents the interactive nature of the project that renews itself and returns to the evolutionary path periodically, thus justifying the choice of its name. The artifact addresses the full procedural context of the project from the beginning to the end of the life cycle, including the possible trigger events predicted by ISO 19650-1, during the operation phase (Fig. 4.5). Table 4.6 presents the details about each phase of DPL.

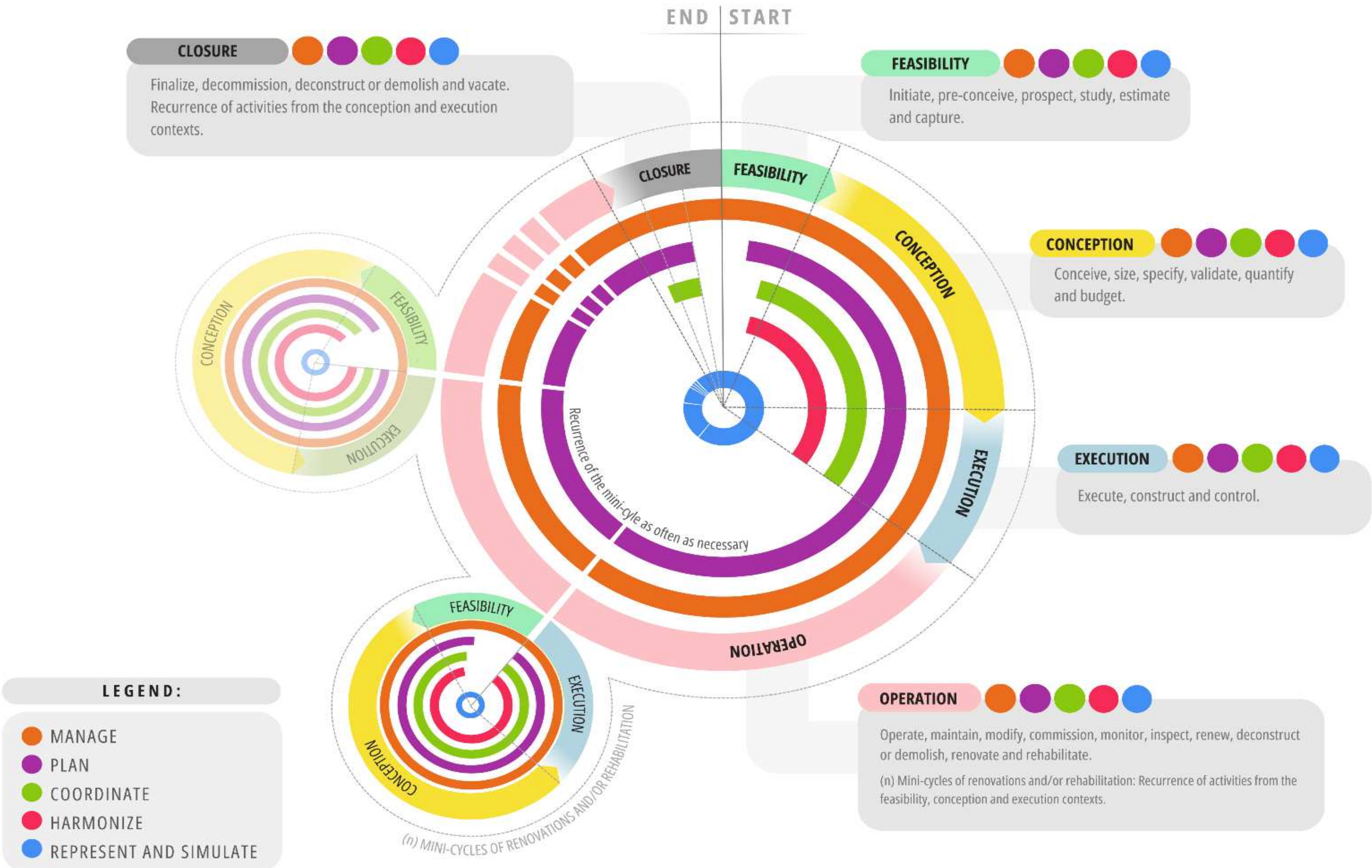


Fig. 4.5 DPL
Source: the Author (2024)

Table 4.6 Legend

CONTEXT / PHASE	MODEL	ACTIONS IN EVIDENCE	SECONDARY ACTIONS
Feasibility	Preliminary	Manage Plan Coordinate Represent and Simulate Verify	**Prospect; Study; Estimate; Capture** **Deliverables:** Templates used in the Design Phase
Conception	Advanced	Manage Plan Coordinate Represent and Simulate Verify	**Dimension; Specify; Validate; Quantify; Cost Estimate** **Deliverables:** Templates used in the Execution Plan
Execution	As-built	Manage Plan Coordinate Represent and Simulate Verify	**Build; Control** **Deliverables:** Models used in the Operation Phase
Operation	*As-is* Models not originally designed in BIM and/or Preliminary Advanced As-built	Manage Plan	**Commission; Monitor; Inspect; Renew** (*n*) Mini-cycle: **Deconstruct or Demolish; Reform; Rehabilitate** Coordinate Represent and Simulate Verify (*n*) Recurrence of the previous Phases: Viability; Conception; Execution **Deliverables:** Templates used in the Current Phase and/or Final Phase
Closure	Preliminary Advanced	Manage Plan Coordinate Represent and Simulate Verify	**Decommission; Deconstruct or Demolish; Vacate** Single recurrence of the predecessor Phases: Conception; Execution **Deliverables:** Templates used in the Current Phase

Source: the Author (2024)

IFC 4.3 specifies IfcProject.Phase [41] through IfcLabel, from Resource layer of IFC architecture data, to inform the phase of a model [4]. Semantically, the highest level of specification could be using a Core layer entity option, such as IfcPropertySet. In this scenario, IfcPropertyEnumeration represents one option to offer the full lifecycle phases, and IfcEnumeratedValue is a data type to inform the precise current phase of a discipline model in development.

On the other hand, another property type can clear the main target [Objective] of a model [IfcPropertySingleValue] using a DPL second action such as reference. The entities together [42] specify the set [Pset_ProjectLifecycle].

For example, the structural model of bridge rehabilitation has identification framework specified by IfcProject [4]. The attribute Phase is revealed through IfcLabel, a type ['consequently will reflect what user informed on software work interface']. Using this proposal the user will select on the work software interface, one option to specify the phase of a model at a high semantic level. Listing 1 presents the solution [#100,#200,#300,#400] using Standard for the Exchange of Product model data - STEP [43,44] through STEP Physical file - SPF, as follows (first-order minimally), using a DPL such as reference (highlighted in red color).

Listing 4.1

```
ISO-10303-21;
DATA;

#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1687808747);
#83=IFCUNITASSIGNMENT((#19,#21,#22,#26,#27,#30,#31,#33,#34,#35,#37,#40,#42#46,#47,#48,
#49,#50,#51,#52,#53,#54,#55,#60,#62,#64,#67,#68,#69,#70,#71,#72,#73,#74,#75,#77,#78,#79,#80,#
81,#82));
#86=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,0.00001,#84,#85);
#93=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',2,0.00001,#84,#85)
#95=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2024-46','Structural
Rehability Model of Coimbra Bridge',$,$,'IfcLabel is not the best semantic way to
specify the lifecycle phase',(#86,#93),#83);

#100=IFCPROPERTYENUMERATION('PEnum_ProjectLifecycle',(IFCLABEL('FEASIBILITY'),IFCLABEL
('CONCEPTION'),IFCLABEL('EXECUTION'),IFCLABEL('OPERATION'),
IFCLABEL('FEASIBILITYDURINGOPERATION'),IFCLABEL('CONCEPTIONDURINGOPERATION'),
IFCLABEL('EXECUTIONDURINGOPERATION'),IFCLABEL('CONCEPTIONDURINGCLOSURE'),
IFCLABEL('EXECUTIONDURINGCLOSURE'),$);
#200=IFCPROPERTYSINGLEVALUE('Phase',$,(IFCLABEL('CONCEPTIONDURINGOPERATION')),
#100);
#300=IFCPROPERTYSINGLEVALUE('Objective of a Model',$,IFCLABEL('Rehability'),$);
#400=IFCPROPERTYSET('0S3JFtqoD4CAgDGe3IafZV',#18,'Pset_ProjectLifecycle',$,(#200,#300));
#500=IFCRELDEFINESBYPROPERTIES('0kMl4E8H1E_h3yCPd6IE1J',#18,$,$,(#95),#400);

ENDSEC;
END-ISO-10303-21;
```

IFC 4.3 added the property set ProjetCommon through the IfcProject framework to address the application of high-level project information. The set represents generally Financial data [4], with one exception [ProjectType property]. The options to specify sound a mix between first and second actions `[.MODIFICATION.,.NEWBUILD.,.OPERATIONMAINTENANCE.,.RENOVATION.,.REPAIR.]`. This scenario reveals the necessity to provide more details about the lifecycle phase of a model.

4.4 Analysis

Table 4.7 presents the descriptive narrative of each of the lifecycle phases that characterize DPL.

Table 4.7 PDL Phases

Phase	Description
Feasibility	Subset of actions of the initial stage of the cycle that involves the process of Conceive and Pre-Conceive of the project represented by BIM models that address the feasibility context such as: Mass studies; Estimates; Preliminary conception of disciplines and preliminary project coordination.
Conception	Subset of actions that contemplate the context of the project design process such as: Conception of model disciplines; Automated information requirements checks; Performance analysis; Project coordinate.
Execution	Subset of actions corresponding to the project's production process, with the execution of activities that consolidate the actions of the previous phases such as: Pre-fabrication; Construction; Physical and financial schedule controls; Security controls.
Operation	Subset of activities aimed at the operation process and sustainability of the project: Operation and Maintenance; Systems monitoring; Security monitoring; Deconstruction or Demolition; Renovation and Rehabilitation.
Closure	Subset that contextualizes the project closure process aiming at the end of the life cycle.

Source: the Author (2024)

Secondary actions [Deconstruct or Demolish] can occur in different procedural contexts: linked to the primary action [Modify] within the operational context, and linked to the primary action [Finalize] within the closure context. However, it is important to note that, in the

Operation context, secondary actions may involve partial demolition of the project or, more sustainably, deconstruction. The deconstruction phase leaves room reusing building elements in other projects. In the Closure context, the actions are intended to remove the entire built structure, characterizing the end-of-life of the cycle and its end. In this scenario, represents the opposite semantics from the other phases of the lifecycle.

The final stage of the cycle is characterized by high volumes of demolition waste and contemplates two general practices: conventional demolition and selective deconstruction. Deconstruction plays an important role in the circularity of projects, allowing the asset to be dismantled, part by part, avoiding damage and seeking to maintain value through reuse in different contexts [42]. It is presented as an alternative to classic (conventional) demolition, which tends to be an arbitrary and destructive process, although faster, and creates substantial amounts of waste [43].

The option to reduce demolition waste, still in the design phase, requires that demolition itself, as a traditional method of dismantling and disposal, be replaced by the deconstruction of the built environment. In this way, deconstruction allows for a rational separation of waste, disposing of it in a more environmentally appropriate way, which includes the reuse of these materials in other projects, closing the cycle and reducing the need to extract new materials from the environment [44]. The circular approach is the field of development of the practice of deconstruction as a strategy for the circular economy [32], in this direction the new life cycle model represents a semantically capable mechanism to assist professionals in the precise identification of the BIM Use of the model to be developed and, consequently, in the detailed preparation of execution plans.

4.5 Validation

The artifact validation was performed using two relevant references recognized in the literature (Table 4.8). The BEP Guide was chosen due to its relevant adherence by the civil construction sector in the Americas. The selection of the model proposed by LITE is justified by the broad and flexible focus, which is aligned with the dynamic context that the possibilities of uses of BIM models are exposed to.

Table 4.8 References used

	Bibliography	Source - Symbol
1.	BIM Uses - BEP Guide	Pennsylvania University (2023) - Circles
2.	Mode Uses	Succar et al. (2016) - Triangles

Source: the Author (2024)

The twenty-one BIM Uses cited by the BEP guide (ATTACHMENT 4.1) were mapped throughout the phases of the DPL, consistent with the gradient illustrated by the publication [Essential and Inheritance]. Due to the numerous combinations made possible by the model of LITE, examples [Model Use] representing each procedural context [Mode Uses Series] were considered (Tables 4.9 and 4.10).

Figure 4.6 illustrates the mapping of occurrences of the selected references. The mapping of twenty-one BIM uses revealed that only one use of an Essential nature is present in the Operation phase, which confirms the fragility of the BEP lifecycle standard phases in light of ISO 19650-1 (trigger events). The exploration of DPL phases demonstrates the potential of the developed solution since it permeated both the possibilities indirectly related to existing projects, as well as the context of a new project. The new model offers a broad scenario capable of clarifying precisely the current phase of the project and the related BIM usage model.

Thus, it is concluded that the DPL offers resources semantically aligned with the procedural contexts proposed by the global legislation and contributes to the fulfillment of the technological framework that underlies the IFC data schema addressing information lifecycle.

Table 4.9 Mode Uses Series and Mode Use

Mode Uses Series	Model Use example
Capturing and Representing	1. As-constructed representation
Planning and Design	2. Demolition Planning
Simulation and Quantifying	3. Constructability Analysis
Constructing and Fabricating	4. Construction Waste Management
Operating and Maintaining	5. Relocation Management
Monitoring and Controlling	6. Building Automation

Source: the Author (2024)

Table 4.10 BIM Uses x Mode Uses

Map symbols		Ocurrences along Project lifecycle standards	
21 Model Uses	Model Use 1 to 6	**BEP Guide**	**DPL**
Essential Enhanced	1. As-constructed representation	Plan Design Construct Operate	Feasibility (Site existing conditions) Conception (Site existing conditions) Execution (As-built) Operation (As-is) Mini-cycle (trigger): Execution (As-built)
	2. Demolition Planning	Plan	Feasibility Conception Mini-cycle (trigger): Feasibility, Conception Closure
	3. Constructability Analysis	Plan Design	Feasibility Conception Mini-cycle (trigger): Feasibility, Conception
	4. Construction Waste Management	Plan Design Construct	Feasibility Conception Execution Mini-cycle (trigger): Complete mini-cycle Closure
	5. Relocation Management	Operate	Mini-cycle (trigger): Complete mini-cycle
	6. Building Automation	Operate	Complete lifecycle

Source: the Author (2024)

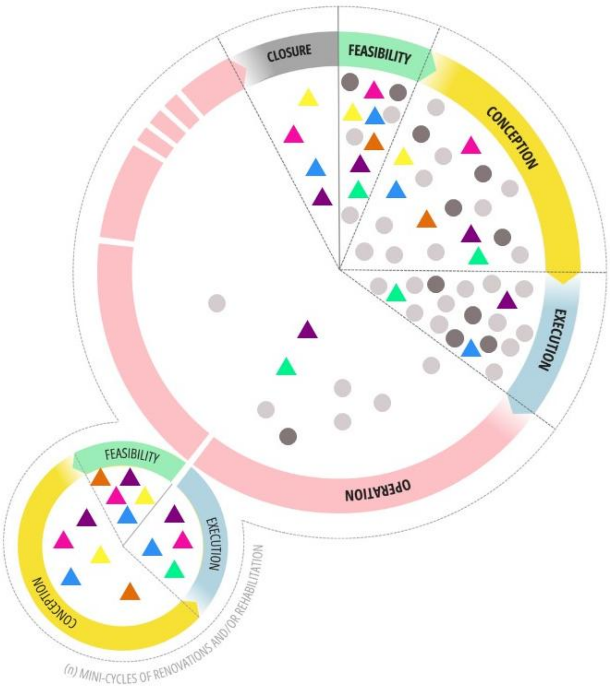


Fig 4.6 Mapping on DPL
Source: the Author (2024)

4.6 Conclusion

An analogy concerning nature could be used to conceptualize BIM as a system. As well as the human body, the great system is formed by subsystems (disciplinary models) characterized by different functions that work collaboratively. The human lifecycle can start from an insight, evolving into conception, birth, aging, and death along an evolutionary timeline characterized by phases. The subsystems, despite having their characteristics and a certain autonomy, need to interact with each other for the perfect functioning of the larger system. In addition, they can wear out over time and compromising the performance of the whole. Occasionally, they get sick and require interference to prolong their life span, until the moment the cycle ends with death.

This dynamic applies to the Project lifecycle, which is initially envisioned, conceived, and executed. Once occupied, it requires maintenance management to overcome the action of time, which can partially or fully compromise Project performance. In this scenario, renovations and/or rehabilitation become necessary to maximize project lifespan until, at a certain point, it is fully deconstructed or completely demolished [end of cycle].

In the Project lifecycle, the phases [Feasibility, Conception, and Execution] form the basis, the container of information lifecycle [Delivery Phase]. In contrast to the product data seen by the spectrum of other industries, there are still no standardized database structures for the product of the civil industry “The Project”. Only the IFC data specification, which aims at open-standard interoperability between parametric software, has been developed. Ideally, it is estimated that the service life of a Project may be of at least 50 years on average. In this scenario, it is clear that the data needs to be available for a long time to cover the entire Project lifecycle. For this reason, consistently exploring the longest phase of the cycle [Operation] represents a challenge that many other industries do not face.

During the literature review process, it was observed that the BIM Uses characteristics of the Operation and Closure phases are still little semantically explored. Considering the semantic spectrum proposed by the IFC data specification, this represents a demand for future research.

Aiming at sustainability, the IFC data becomes fundamental in promoting automated data transformation. Since longevity demands information triggers throughout the operational phase, the Project lifecycle and Information lifecycle must be aligned. This characteristic makes the

DPL standard a supportive tool for professionals, both in response to information requirements and adaptable to the constant technological evolution.

Since a Project has numerous disciplinary BIM models that collaborate with each other through neutral interoperability [OpenBIM], establishing precise yet flexible references is an urgent demand. BuildingSMART has provided consistent responses, to the global civil industry, as evidenced by the growing representation of its chapters, since its creation.

In this context, the IFC schema moves toward specialization capable of accommodating the typical fragmentation of the sector. Furthermore, it offers an approach for software manufacturers in the development of work tools capable of meeting the information and interoperability requirements demanded by the AECO segment.

Finally, the representation of the Project lifecycle in the circular standard was based on a cyclical dynamic that, ideologically, should delineate a beginning and an end. Additionally, the DPL successfully incorporated semantically broad applications, demonstrating its flexible yet coherent nature in alignment with the typical diversity of the civil industry. In this scenario, the set developed [Pset_ProjectLifecycle] revealed the alternative to specifying the phase of a model in high-level semantic. Since its theoretical foundation was primarily based on global normative framework the DPL can represent the state of the art in the construction industry's life cycle on a relevant scale.

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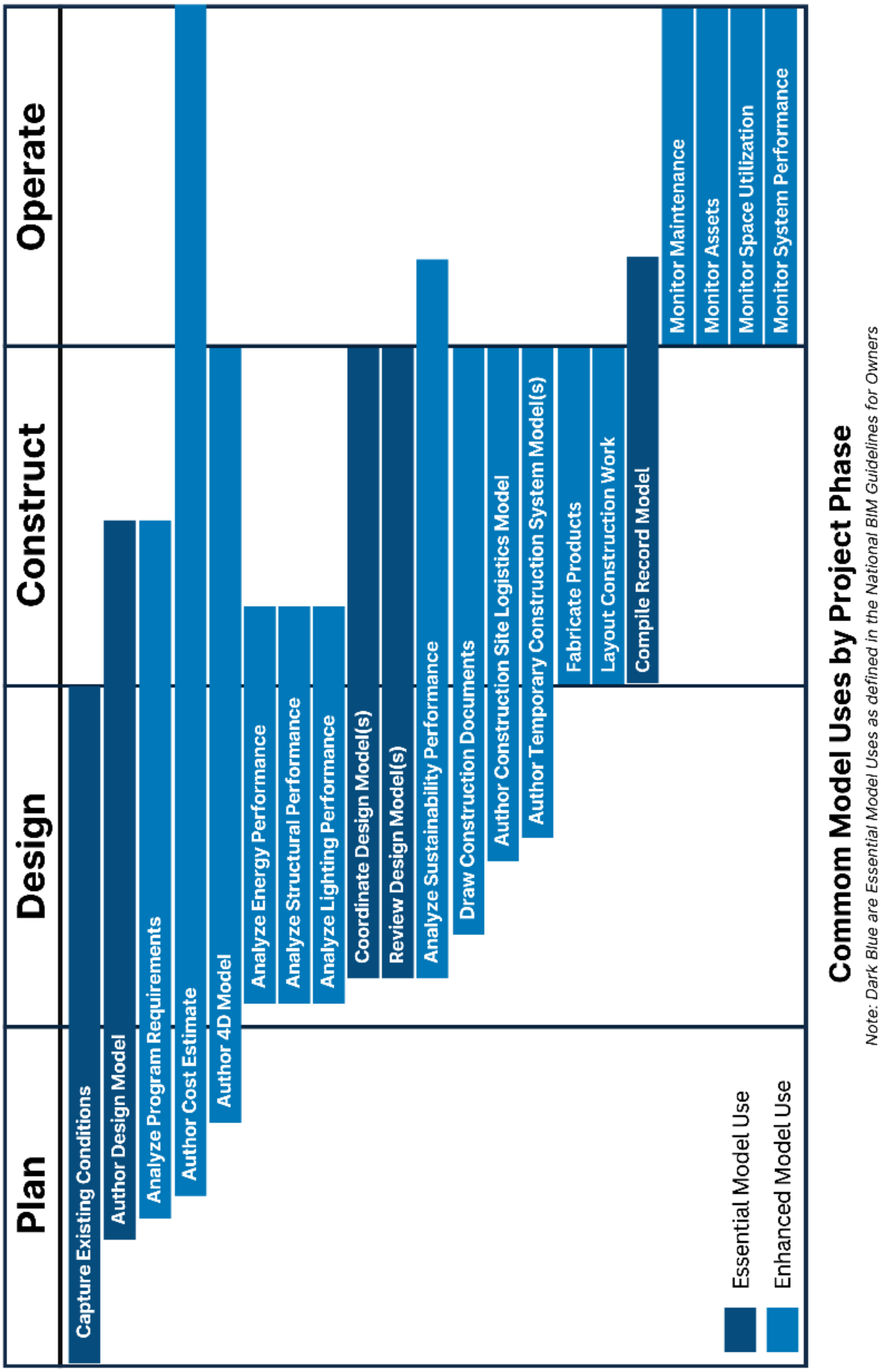
ATTACHMENT 4.1: Lifecycle standard of BEP Guide



CAPÍTULO 5 – AN ASSESSMENT OF THE IFC INTEROPERABILITY FOR GEODETIC AND GEOTECHNICAL SPECIFICATION IN A GEOPHYSICAL CONTEXT

Este capítulo foi submetido em 25/10/24 para análise na revista científica: Antunes, M. L. R.; César Júnior, K. M. L.; Ribeiro, J. C. L.; Carvalho, J. M. F.;Oliveira, D. S.; Duarte, D.; Aguiar, C. C.; Nunes, L. A. An assessment of the IFC interoperability for geodetic and geotechnical specification in a geophysical context. ***Engineering with computers****. (2024)*
https://doi.org/10.21203/rs.3.rs-5389330/v1
Atualmente encontra-se em processo de transfer.

Abstract

Among the existing geotechnical exploration processes for bridges and dams, geophysics seems to be one of the most advantageous investigation methods. It contributes to worker safety during the prospecting process in submerged (or partially submerged) structures, precise identification of the terrain subsurface, and avoids the interpolation of geotechnical results. These factors can impact the efficiency of decision-making and resource allocation during the operational phase of assets. Using the Design Science Research approach (DSR), this article explores the potential of Industry Foundation Classes (IFC) to evaluate the interoperability of geotechnical data. Through the Standard for The Exchange of Product (STEP) and using an earth dam as the object of study, the results revealed a high semantic level of the IFC data schema. The study also addresses the specification of geodetic data using a bridge model highlighting the importance of operating between coordinate systems, an essential aspect of collaborative processes throughout the infrastructure project lifecycle.

Keywords: Interoperability. Industry Foundation Classes. Data Schema. Geophysics. Geotechnical data. Geodetic data.

5.1 Introduction

Geotechnical information is a prerequisite for civil engineering infrastructure projects. However, the modeling, representation, update, and exchange of geotechnical information may be challenging because they are managed by heterogeneous data models supported by two-dimensional representation that lacks integration [1]. Usually, a project represents a collection of solutions for a purpose. Historically, in the construction industry, it is associated with a context of geometric representation of a new or existing enterprise exposed to a wide array of interventions throughout its lifespan [2].

Object-oriented modeling can offer effective conditions for the parametric development of solutions and increases collaborative performance among professionals and the disciplines encompassed by the project process [3]. The Building Information Modeling (BIM) paradigm consistently contributes to the optimized resolution of all project phases and rationalizes decision-making [4]. Behind this scenario, the openBIM interoperability standard through Industry Foundation Classes (IFC) data schema has been enhanced to facilitate high-level semantic information exchange flows. The IFC 4.3.2.0 version incorporates specific domains [5,6] and has supported research worldwide, aiming to raise the semantic level of infrastructure models throughout the entire lifecycle.

Especially during the design, and operational phases, geotechnical surveys present several limitations, such as employee safety during the sample collection process in submerged (or partially) structures, difficulties in identifying anomalies or inconsistencies in the subsurface of the terrain, and the need for interpolation of results. These factors can impact the efficiency of decision-making on foundation and structural model development, and resource allocation in maintenance programs [7,8]. Bridges and dam structures incur annual operating, inspection, maintenance, and demolition expenses at the end of their service life, which usually vary between 0.4 % and 2% of their initial construction cost. Conducting inspections to assess the condition of projects is crucial for evaluating the status of structural stability (monitoring models). It helps identify issues such as nature, extent, and location, ensuring ongoing functionality and operability [9,10].

To address those model developments, BIM professionals meet information requirements about specific geometric and geodesic data that provides to support collaborative efforts effectively at a high semantic level [11]. In this scenario, stakeholders explore the resources provided by the software, especially the export configuration of the interoperable file. This is because geographic data, typically included in work interfaces, are limited to the horizontal datum (latitude and longitude) and, consequently, do not meet the global location requirements of infrastructure projects. The improvements of geodetic data in the export process were significant with the inclusion of semantically appropriate entities in the following versions: IFC 4 [IfcCoordinateOperation, IfcProjectedCRS, and IfcMapConversion]; 4X3_ADD1 [IfcMapConversionScaled, IfcGeographicCRS e IfcRigidOperation] [12,13].

Another difficulty seems to be related to the frequency of optional attribute declarations on IFC schema is significant but necessary to attend to the characteristic diversity in the civil industry [2]. To address specifying Organization information requirements (OIR) and Project Information Requirements (PIR), some requirements need to be met even if the BIM software used by the professionals involved in the project does not specify them (optionally). However, even though software manufacturers strive to keep up with the evolution of new versions of the IFC data schema, they do not always provide manuals that clarify the configured export of the interoperable file, thus presenting a challenge for professionals in the field, especially those without knowledge of Object-oriented principles and the EXPRESS data specification [14,15,16].

These findings justify the relevance of the research problem and highlight the need to explore the issues addressed in this paper, outlined by the information requirements that infrastructure project management organizations must consider achieving IFC 4.3 interoperability between GIS and BIM software. Additionally, this study explores the specification of geotechnical data, as these are fundamental for developing foundation, structural, and monitoring models.

As a research strategy, two infrastructure study objects were used: a bridge (Artifact A) and an earth dam (Artifact B). The bridge requires the specification of a global location, and the dam is inserted in a geophysical scenario to demonstrate the potential of integrated technologies and IFC data specification of the geotechnical results. The overall objective of this study is to determine the IFC specifier that encompasses the geotechnical data, and global localization of a project to attend to exchange information alignment IFC 4.3 schema. To achieve this goal, the specific objectives are:

- Geodetically specify an infrastructure model;

- Specify geotechnical data from geophysical prospecting;
- Develop entity inheritance diagrams capable of translating the IFC specifications analyzed on both artifacts;
- Test the artifacts.

The Design Science Research (DSR) method was selected to address the research objectives and explore a typical demand in public organizations that promote the management of infrastructure projects. Aiming for replicability, the structure of the study was inspired by three main topics: 1. Inheritance Diagrams - The inheritance structure of the entities involved was developed to support the constructs; 2. SPF - Developed solution using a simple notepad; 3. Validation of artifacts was realized to demonstrate the effectiveness of the solutions.

The first guideline of the DSR methodology presents the problem relevance. It sequentially involves mapping the potentially specifying data, aiming at the coordinate systems (geographic and geodetic) alongside the project context representation. Evolvingly, the data mapping outlined an in-depth investigation of the entities in the IFC data schema, potentially semantic to specify the geotechnical data. The main entities involved are [IfcGeometricRepresentationContext.TrueNorth and .WorldCoordinateSystem; IfcSite; IfcMapConversion; IfcRigidOperation; IfcGeographicElement; IfcBorehole; IfcGeoslice; IfcGeotechnicalStratum]. To mitigate the level of abstraction detected in this approach, entity Inheritance Diagrams were developed as data translators, which consist of two auxiliary research contributions to BIM actors.

5.2 Background

5.2.1 IFC Geodetic Data

Engineering, architecture, and construction projects must be positioned on the Earth surface using georeferenced coordinate systems, enabling the integration of topographic, geological, and environmental data, thus promoting better management and efficiency in all phases of a project. In this context, three-dimensional geodetic systems are used, which can be expressed in cartesian form with three coordinated axes (X, Y, and Z) or in ellipsoidal form as latitude (φ), longitude (λ), and geometric altitude (h).

Systems such a World Geodetic System (WGS84), and the Geocentric Reference System for the Americas (SIRGAS 2000) use the Geodetic Reference System 1980 (GRS80) ellipsoid, both adjusted to the International Terrestrial Reference System (ITRS) and realized through the International Terrestrial Reference Frame (ITRF) [17].

It is important to note that the geometric altitudes provided by ellipsoidal models do not have a physical meaning. Therefore, orthometric altitudes must be used in engineering projects, using the geoid as the altimetric reference. The geoid is an equipotential gravitational surface of Mean Sea Level (MSL) extended across continents, accounting for gravitational variations due to the uneven mass distribution inside the planet [18]. There are several global, national, and regional geoid models, such as the Earth Gravitational Model 2008 (EGM2008), United States Gravimetric Geoid 2012 (USGG2012), MAPGEO2015, and hybrid models like HgeoHNOR [19].

The integration between ellipsoidal and geoidal models formalizes a country or region Datum through the following parameters: origin, orientation, reference date or epoch, semi-major axis, flattening, gravitational model, vertical deviation components, and geoidal undulation [20]. Although modern and precise Datums are used for positioning engineering works, Cartographic Projection Systems are necessary to represent constructive elements in plans, charts, and maps.

However, representing part of the Earth, which is a curved surface, on a flat surface leads to distortions in areas, angles, and distances. For example, the Universal Transverse Mercator (UTM) system presents deformations determined by the Deformation Coefficient, which varies according to the position of objects in the zone [21]. There are many possible datums and Cartographic Projection Systems to materialize a Reference Coordinate System (CRS). The European Petroleum Survey Group (EPSG), and the Institut Geographique National de France (IGNF) have organized the world CRS using numerical codes, i.e. EPSG Code 4326 – WGS, used as the standard in GIS and BIM software; EPSG Code 4674 – SIRGAS 2000 (Planimetric); EPSG Code 5880 – SIRGAS 2000/Brazil Polyconic; among many other possibilities that integrate the UTM system [22].

Following the evolution of techniques such as the cartesian coordinate system and observation methods of crustal deformation and gravity, that accurately expresses the geoid has been established internationally. SIRGAS 2000 is used as a coordinate system in South America, expressing a shape of the earth, where the center of gravity (of the earth) and the center of the Earth ellipsoid are aligned.

The coordinate system consists of three mutually orthogonal axes, of which origin is the center of gravity of the earth: positive direction of x axis represents the intersection of the Equator and the Prime Meridian (longitude 0 degrees) passing near the Greenwich astronomical observatory; the positive direction of y axis is the intersection of the Equator and the Meridian (90 degrees East); z axis coincides with the rotation axis where the North is positive [23].

IFC data schema uses the geodetic reference system WGS84 therefore, projects that use other coordinate reference systems need to be properly clarified so that other software can recognize the global positioning of the Project. This allows to placement of the project coordinate system on earth (normally using eastings, northings, elevation above horizontal and vertical datum, and orientation) [24].

On IFC schema, the precise geospatial information of a site shall be derived from the georeferencing entities that relate the IfcProject to the real world, using sets of EPSG datum [25]. The representation context of the project refers to global positioning, i.e. the local engineering coordinate system of the project has a mapping to a defined projected coordinate system, a rectangular map coordinate system, as used in GIS systems.

The coordinate specified by the attribute IfcGeometricRepresentationContext.WorldCoordinateSystem, which specifies the project base point (0.,0.,0.), should preferably coincide with the coordinate specified by IfcLocalPlacement established by IfcSite [26]. The IFC 4.3 spatial structure is illustrated in Figure 5.1, applied to a bridge: IfcProject; IfcSite; IfcBridge [or other IfcFacility]; IfcBridgePart [or other FacilityPart]; IfcSpace.

The spatial structure of the data schema originates from IfcProject, with IfcSite occupying the second order. The main hierarchical difference between the entities is that while IfcProject is a subtype of IfcContext and has a unique instance (by rule), IfcSite is an IfcObject subtype and can have one or more instances `[.COMPLEX.,.ELEMENT.,.PARTIAL.]`.

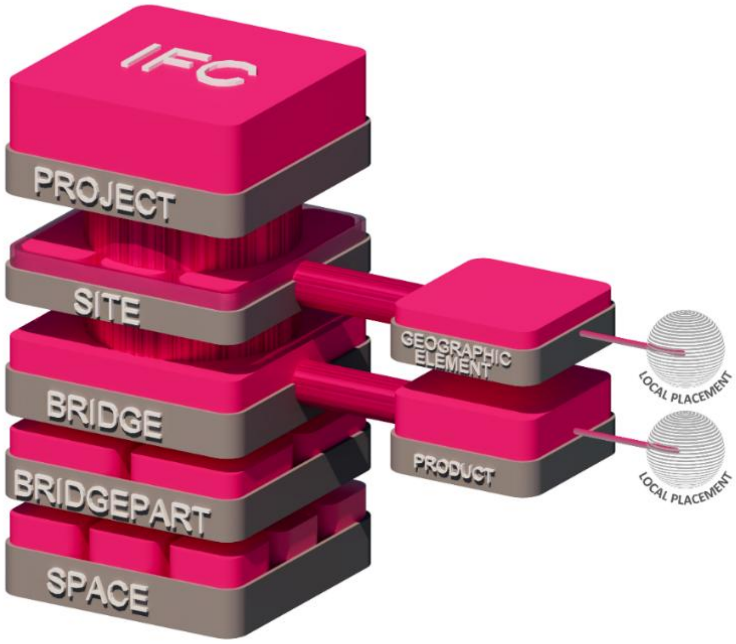


Fig. 5.1 IFC Spatial Structure
Source: the Author (2024)

The geometrical placement of the site is defined by the IfcLocalPlacement, and may always be relative to the spatial structure element, in which this site is included, or absolute [27]. The surface of a terrain is represented by IfcGeographicElement and has a spatial connection with IfcSite through IfcRelContainedInStructural relationship, unlike IfcProduct subtypes, whose geometrical placement are defined by IfcLocalPlacement, through IfcBridge, or another facility.

5.2.2 Geotechnical Data

Geophysics, as a science that investigates the physical properties of the Earth, offers a diverse set of methods and techniques usually applied in other areas and sectors, such as basic geology, for example. In recent years, the convergence between geophysical techniques and civil engineering has been remarkable, justifying the term "Applied Geophysics." Some areas of study, such as the one detailed in this study, are currently underway, presenting consistent and innovative results. The applicability of geophysical tests ranges from the initial stage of subsurface characterization, through the design and execution phases, to the operational stage of the asset, when there is a need for investigation of possible changes in the behavior of the subsurface due to applied forces, weathering, or any other modifications to the originally anticipated conditions. This occurs, for example, in the monitoring of stability of bridges and dams.

Collapses of structures of this nature that have occurred in recent years, as well as their appalling consequences, have led science to seek reliable solutions for the entire lifecycle of the project: Preliminary phase (including geotechnical investigation of the subsurface); Design phase (development of disciplinary models); Construction phase (verification of execution according to the design); Operation and maintenance phase (monitoring of structural stability). In addition to the temporal context, which is characteristic of this phase, environmental modification and/or degradation can represent significant aggravating factors and, this way, negatively impact the stability of structures. This condition is even more extreme for bridge and dam infrastructures due to their proximity to watercourses and bodies of water.

In the operational phase of the cycle, the potential of geophysical methods has been notably consolidated, especially in monitoring internal flow and deformations in the massif, applied to earth dams. The most common applications of Electrical Resistivity (ER) surveys in earth dams include delimitation of contact zones between materials with different electrical resistivity [28,29] mapping of the water table [30], and detection of preferential flow paths through the massif [31,32]. These features are usually associated with regions showing anomalous resistivity bands compared to their surroundings.

Geophysical and geotechnical information are essential sources of mathematical data in engineering. Although they are distinct in their approaches and methods of acquisition, the integration of both provides security and reliability in interpreting the real conditions of subsurface materials [33]. Geophysical methods respond to the physical properties of the subsurface media (rocks, sediments, water, voids, etc.), constituting a set of indirect subsurface investigation methods. They are, therefore, non-destructive methods, providing a quick recognition of the main physical characteristics of the area of interest through tests. In the field of geophysics, this work focuses on the use of the Electrical Resistivity Tomography (ERT) method, detailed in section 2.3.2.

Based on the geophysical data, soft clay typically has low electrical resistivity (< 50 Ωm), which invariably affects its load-bearing capacity due to its low shear strength and high compressibility. This implies that engineering foundations laid on soft clay may require specific considerations in terms of design to prevent excessive settlement and ensure stability.

On the other hand, lateritic soils have high electrical resistivity (>300 Ωm), which invariably affects the strength and load-bearing capacity of the lateritic soils, especially compacted and dry ones, making them suitable for supporting foundation engineering.

However, the strength of lateritic soils usually decreases when wet, therefore moisture control is critical in engineering design. The low electrical resistivity encountered in clay-accumulated soil indicates the presence of high pore-water pressure in soft clays, which invariably reduces load-bearing capacity [34]. In addition to meeting the demand for BIM Uses applied to the foundation and structural models, geological/geotechnical models serve as auxiliary mechanisms for monitoring activities during the operational phase of the lifecycle, contributing to the sustainability of the assets.

5.2.3 Interoperability

The sight of the BIM paradigm, viewed through the project expanded spectrum is related to lifecycle phases. This may well increase the demand for interoperability capable of contemplating the diverse parametric tools used by the professionals involved in collaborative processes [35]. The interoperability should be characterized by an open data standard that ought to support file exchange among BIM software as it must utilize the same machine-to-machine language and represent a mechanism that enables computer systems to automatically share and exchange data without requiring translation or human intervention.

The IFC created to promote interoperability in civil industry, has been widely adopted by large software companies [36]. This adoption is due to the substantial number of attributes that are defined as optional (meaning are not mandatory) consequently meeting the high fragmentation, a typical characteristic of the segment.

ISO 16739-1 presents the formal representation bSI uses to formally define the information structure [37]. Due to its wide adherence to ISO 10.303:2016 (Industrial automation systems and integration - Product data representation and exchange), it encompasses a substantial number of documents providing a standardized methodology for the representation and exchange of digital product information across different systems and throughout the lifecycle of a product. Specification data language EXPRESS is specified by ISO 10.303-11 [38]. The case of the IFC is dealt with in ISO 10.3030-21 (Standard for The Exchange of Product Data - STEP) [39].

The SPF is a specific format used within STEP to store and transfer standardized data physically. The logic behind STEP is rooted in graph theory, a mathematical model characterized by connections that can represent real-world scenarios, including hierarchical relationships and connections between elements within a defined set [40]. This resource was taken into consideration to illustrate part of the SPF in the analysis of Artifact B [41].

5.2.3.1 Geometric, Geographic and Geodetic Framework

The geometric framework declared by IfcProject specifies many qualitative and quantitative data to address the representation context for all other information regarding the various components constituting a construction model. From the IfcProject.RepresentationContexts statement, specified through IfcRepresentation, the geometric representation contexts (and derived subcontexts) are defined for the model [2].

The geographic location of the project (geographic framework) relates to IfcSite through the attributes [RefLatitude; RefLongitude; RefElevation], which satisfy small-scale projects. Projects characterized by linearity and/or geodetic reference systems other than WGS84 require the specification of horizontal and vertical datum [2] for the precise and global location of the project. In these cases, the geodetic framework is specified through the attribute [HasCoordinateOperation], which enables its connection with geometric and geographic frameworks.

IfcCoordinateOperation is the abstract entity that mandatorily declares the SourceCRS and TargetCRS attributes, aiming for transformation between coordinate systems:

SourceCRS	Select data between the local engineering coordinate system, represented by the IfcGeometricRepresentationContext, or another coordinate reference system [IfcCoordinateReferenceSystem]
TargetCRS	Inform the coordinate system-related world by datums [IfcProjectedCRS or IfcGeographicCRS]

The projected coordinate reference system specified by IfcProjectedCRS [bSI] defines the map projection, which inherently includes distortions from the real world and transforms it into a flat surface, which is usually a UTM. The geographic coordinate reference system specified by IfcGeographicCRS is related to the geodetic context.

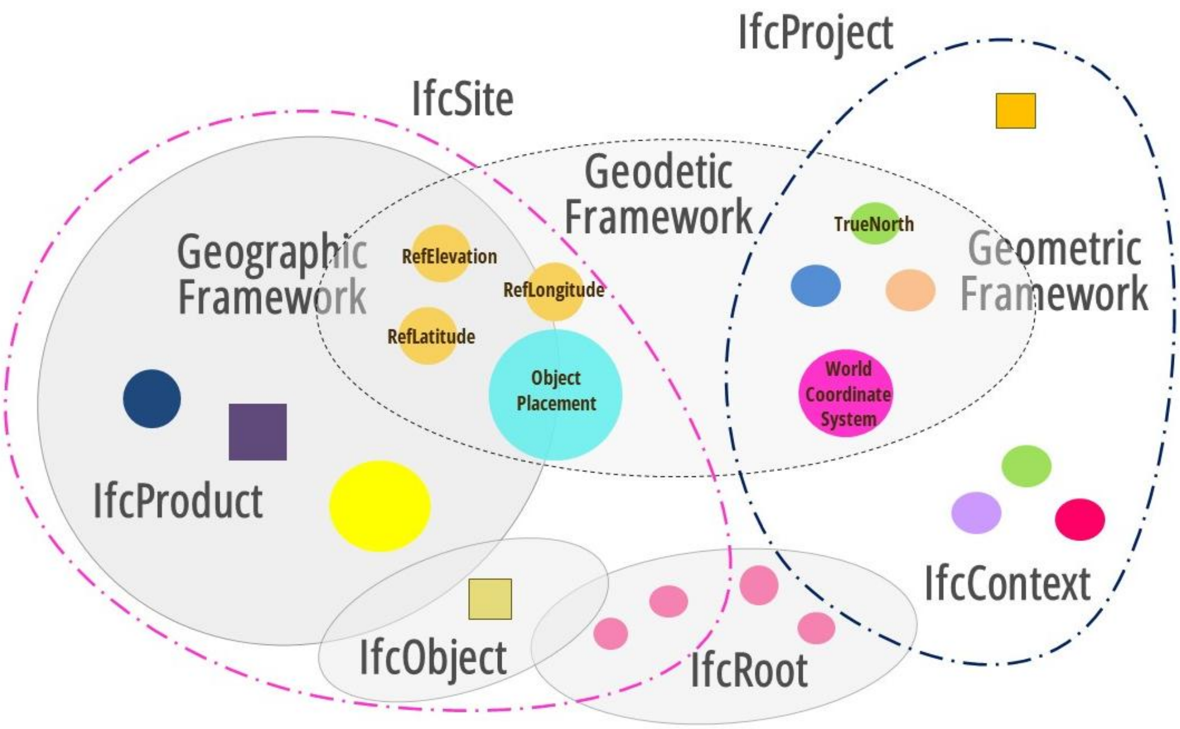
The coordinate transformation is a mathematical operation on coordinates that usually includes a datum change. The parameters of a coordinate transformation are empirically derived from data containing the coordinates of a series of points in both coordinate reference systems. This computational process is usually 'over-determined', allowing derivation of error (or accuracy) estimates for the transformation. Furthermore, the stochastic nature of the parameters may result in multiple (different) versions of the same coordinate transformation.

Several transformations may exist for a given pair of coordinate reference systems, differing in their transformation method, parameter values, and accuracy characteristics [42]. IfcMapConversion defines a local engineering coordinate system, with translation, rotation, and a scale, relating to a plan coordinate reference system, specified by IfcProjectCRS. IfcRigidOperation works the same way, but using translation along X,Y, and Z axis (using length unit) or using plan angles if specified by geographic reference system through IfcGeographicCRS. Table 1 may clarify this narrative and the inheritance diagram (Fig. 5.2) developed from IfcProject.RepresentationContexts illustrates the data at stake.

The coordinate system transformation operation is specified by IfcMapConversion and/or IfcMapConversionScaled, which consider the following coordinate systems: World Coordinate System or Project Base Point (topocentric CRS); 2D projected (ProjectedCRS). IfcMapConversionScaled inherits the instance of IfcMapConversion instance, and specifies three additional attributes [FactorX; FactorY; FactorZ], through IfcReal. The entity was inserted since IFC 4x3_ADD1, but the attributes description is continuous on "not available" status [43].

When the operation involves a special 3D translation, the semantically appropriate entity becomes IfcRigidOperation. The incorporation of new data (in 2021), was a response by bSI to researchers who demonstrated that IfcMapConversion was unable to support more complex transformation operations. Georeferencing is very important for data conversions and data linking between different data formats [44].

The datums involved in the transformation operations between coordinate systems are clarified by IfcCoordinateOperation (abstract, highlighted with a gray background) and must inform them unequivocally. The GeodeticDatum attribute specified by IfcIdentifier clarifies the general Datum by EPSG code. However, the Name attribute could clarify it in more detail, even though it is specified by IfcLabel. Figure 5.3 and Table 5.1 support this narrative.



IfcObjectDefinition, IfcPropertyDefinition, IfcRelationship, and inverse attributes were omitted

Fig. 5.2 Frameworks inter-relations
Source: the Author (2024)

EPSG codes are organized and used by the Open Geospatial Consortium - OGC, which develops open standards for geoprocessing and interoperability, aiming to ensure that geospatial data and geographic information systems can be shared and used by different systems, platforms, and technologies in a standardized way.

In this scenario, it is expected that BIM and Geographic Information System (GIS) software (and vice versa) will be able to recognize geodetic specifications for the precise location of the project.

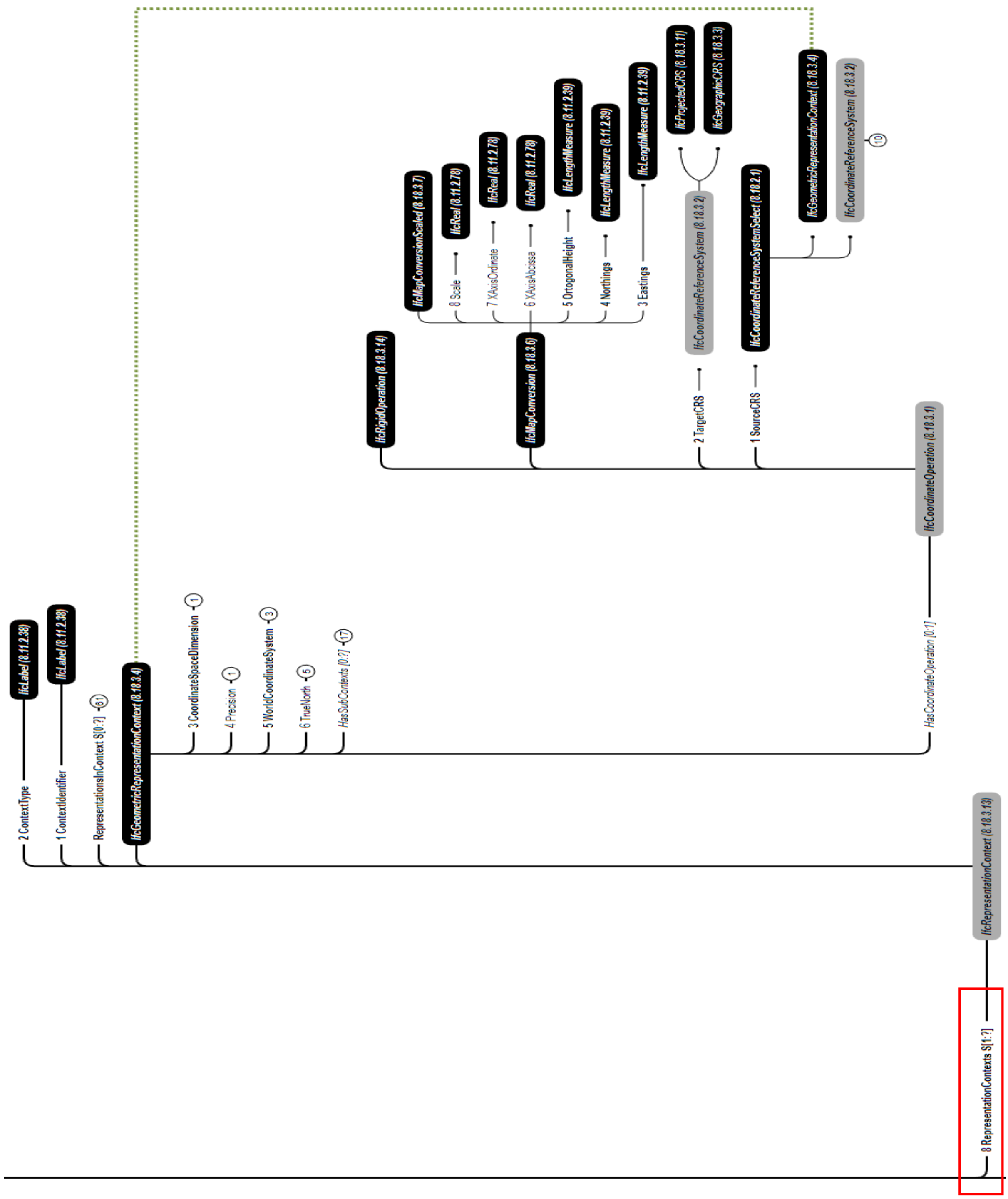


Fig. 5.3 Inheritance Diagram from IfcProject.RepresentationContexts
Source: the Author (2024)

Table 5.1 Frameworks connection

Frame work	Entity / .Attribute	State	Description
GEOMETRIC / GEODESIC	IfcProject.RepresentationContexts IfcGeometricRepresentationContext		
	.WorldCoordinateSystem	Mandatory	Engineering coordinate (Project Base Point). Default considers WGS84 datum.
	.TrueNorth		Geographic northing direction is relative to the underlying 2D project coordinate system. The default standard is established [0.,1.] when TN was not informed.
	HasCoordinateOperation [0:1] FOR SourceCRS		Establishment of the reference coordinate system and 3D geometric representation context [Model]
	IfcCoordinateOperation.**SourceCRS**	Mandatory	Select type between WCS of a model [WGS84] or another CRS
	IfcCoordinateOperation.**TargetCRS**	Mandatory	Selected type of CRS [Projected or Geographic]
	IfcCoordinateReferenceSystem		
	.Name		Global localization [EPSG code, preferably]
	.Description		Horizontal datum
	.GeodeticDatum		EPSG code of vertical datum
	IfcProjectedCRS		
	.VerticalDatum		Identification
	.MapProjection		Identification
	.MapZone		Identification
	.MapUnit		Unit of the map CS
	IfcMapConversion WHERE TargetCRSOnlyProjected		
	.Eastings	Mandatory	[X Axis] of horizontal datum
	.Northings	Mandatory	[Y Axis] of horizontal datum
	.OrthogonalHeight	Mandatory	[Z Axis] relative to the vertical datum
	.XAxisAbscissa		Easting axis
	.XAxisOrdinate		Northing axis
	.Scale		The default standard is 1 when not informed
	IfcMapConversionScaled		IfcMapConversion type. Specify 3 more mandatory attributes [Factor X, Y, and Z] to scale coordinates (not units). No descriptions are available yet on the bSI documentation.
	IfcRigidOperation WHERE SameCoordinateType [Apply to First and Second coordinates]		
	.FirstCoordinate	Mandatory	Apply to translation
	.SecondCoordinate	Mandatory	Apply to translation
	.Height		CRS Translation / Relative to datum [Projected/Vertical and Geographic/Geodetic]
GEOGRAPHIC	IfcCoordinateReferenceSystem		
	.Name		Global localization [EPSG code, preferably]
	.Description		Horizontal datum
	.GeodeticDatum		EPSG code of vertical datum
	IfcGeographicCRS		
	.PrimeMeridian		Zero longitude
	.AngleUnit		Latitude and longitude plane angle unit on coordinate axes compose
	.HeightUnit		Height length unit on a coordinate axis
	IfcSite.CompositionType		Predefined spatial structure
	IfcSite.RefLatitude		Applied to a reference point
	IfcSite.RefLongitude		Applied to a reference point
	IfcSite.RefElevation		Relative to sea level applied to a reference point

Source: the Author (2024)

5.2.3.2 IFC Geotecnhical Data

Until IFC 4, the entity IfcGeographicElement.PredefinedType offered IfcGeographicElementTypeEnum options `[.SOIL_BORING_POINT.,.TERRAIN.,.VEGETATION.,.USERDEFINED.,.NOTDEFINED.]` to specify the terrain surface. IFC 4.3 removed `[.SOIL_BORING_POINT.]` and directs that the specification be made by IfcBorehole (6.6.3.1 IFC documentation item) [45]. The entity represents the concept of a linear geological and geotechnical model, which is usually an interpretation, but sometimes created directly from ground penetrating measurement. The assembly may contain one or more strata and other elements such as capping and lining [46]. Through the principle of inheritance (Appendix C), IfcProduct allows the attribute [ConnectedTo] to specify the connection of each instance of the borehole to the object that specifies the terrain geometry, specified by IfcGeographicElement (5.4.2.12 IFC documentation item).

IfcGeotechnicalStratum [47] explores the layers of the borehole, and Pset_SolidStratumCapacity reports the results obtained, prospected through different methodologies: ERT [IfcGeoslice], SPT [IfcBorehole] which represent special value for geotechnical data. Semantically aligned with the geological and/or geotechnical planar sectional context, it is generated from ground-penetrating measurements containing one or more strata and anthropogenic elements [47].

The ERT methodology visualizes (in two and three dimensions) the prospected subsurface and measures the electrical resistivity of the soil and rocks. The physical principle involves injecting an electrical current through electrodes inserted into the ground and measuring the potential difference generated between other electrodes. The apparent resistivity is calculated using the geometric relationship of the electrode arrangement. The combination of dipole–dipole and gradient arrangements was adopted for the execution of ERT, keeping a spacing of 1 m between the electrodes. This arrangement has a good signal-to-noise ratio and a good horizontal resolution for resistivity variation being suitable for the detection of anomalies along geological layers of the massif.

The electrical resistance of different types of rocks and soils varies according to their intrinsic properties. These data are essential for determining critical geotechnical conditions, such as identifying zones of weakness or detecting fluid movement underground. In the IFC 4.3 schema, they are specified through the IfcElectricResistanceMeasure property.

The effectiveness of applying the resistivity method through the inversion process occurs due to the mathematical processing capable of adjusting the parameters of the resistivity model generated from the data observed during field acquisition through the inversion process, made possible by a finite element mesh [48]. The electrical resistivity values of the subsurface on a graphical scale for the prospected section are made possible by the spontaneous potential (SP) technique, which is based on the fact that, in the absence of an artificial electric field, it is possible to measure a potential difference between electrodes inserted into the ground [52].

Until IFC 4, the results of the geophysical prospecting scenario can be specified through IfcGeoslice, thus precisely representing the upper surface of geological layers. The modeling of upper surfaces of each stratum leaves room for an accurate visualization of terrain sections, aiming at the interpretation of topographical and geological data [23]. IfcGeotechnicalAssembly and IfcGeotechnicalStratum densely complement the specification of geotechnical data in the IFC schema, which is justified by the typological diversity of infrastructure projects and the wide range of available technologies.

5.3 Method

Design Science Research (DSR) as a methodology for developing the science of creating artifacts consists of the activities of building and evaluating, typified in four possible research outcomes [49]: (i) Constructs, which form the basic language of concepts used to characterize a phenomenon; (ii) Model, a set of propositions or statements expressing the relationships of the constructs; (iii) Methods, which constitute the way to perform activities for a purpose, based on the constructs and models; (iv) Instantiation, the physical implementation of the artifact in its environment, thereby operationalizing constructs, models, and methods.

Design Science serves as the epistemological basis and DSR is the foundation and operationalization for conducting research when the objective is an Artifact [50,51,52]. Considering the research-specific objectives, that method has been considered appropriate for this study because its form aims to produce innovative constructions to solve real problems. The DSR guidelines [53] are detailed in Appendix A.

Initially, an in-depth investigation into the IFC data schema was conducted to translate the identified problem of research semantically. Gradually, the research was guided by mapping information requirements that may be demanded by organizations in the development of bridge models.

5.3.1 Information Requirements Mapping

The relationship between the potential semantic entities present in the IFC data schema and the demand for the geographic, geodetic, and geotechnical information and the engineering choices were explicitly stated, as follows:

i. Specifying the geodetic reference system of a project - Meets to define a precise global position and information requirements;
ii. Specifying the IFC geotechnical data - Meets the results of a site geo-prospection.

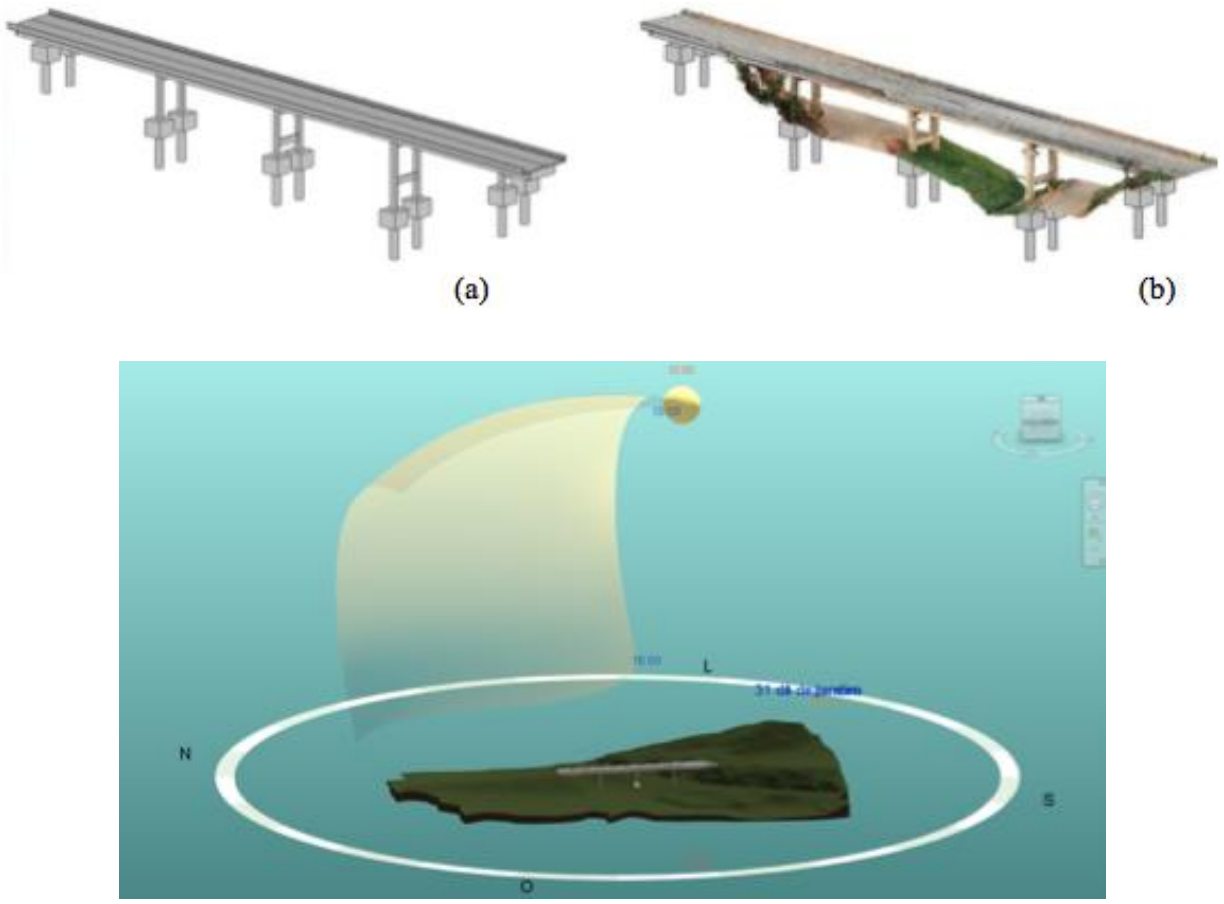
5.3.2 Objects of Study

To address specific objectives i and ii the scenario was inspired by a real demand experienced by a Brazilian public organisation that requires the contracting of infrastructure projects [54].

5.3.2.1 Object of study A

The object of study is represented by the part of the STEP Physical File - SPF generated from the export process of a bridge model [configurated exportation] through Revit software (v. 2025) [55]. The modeled structure is the same one that is explored in the analysis of IFC interoperability applied to the project representation context (Fig. 5.4(a)), which in this study includes the topographic surface (Fig. 5.4(b)).

Artifact A was developed manually according to the IFC 4.3 schema (specific objective i.), demonstrating the operation between coordinate systems.



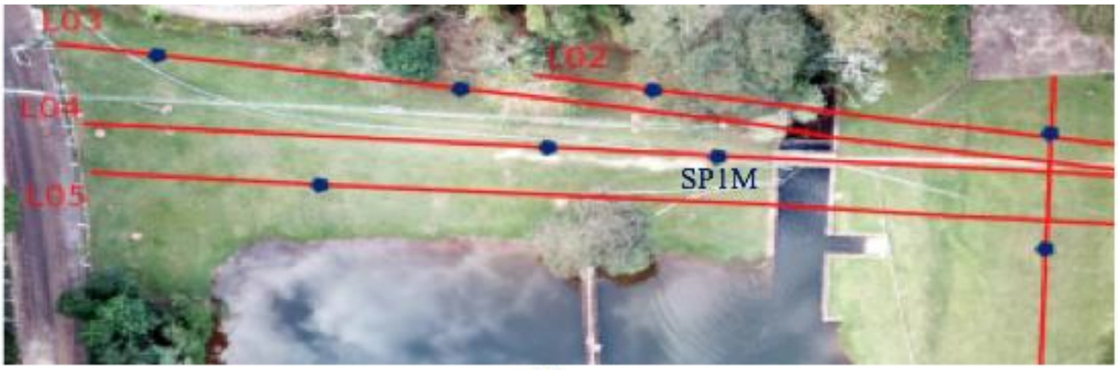
(c)

Fig. 5.4 Bridge model: (a) Structure; (b) Structure with topographic surface; (c) Geographic implementation
Source: the Author (2024)

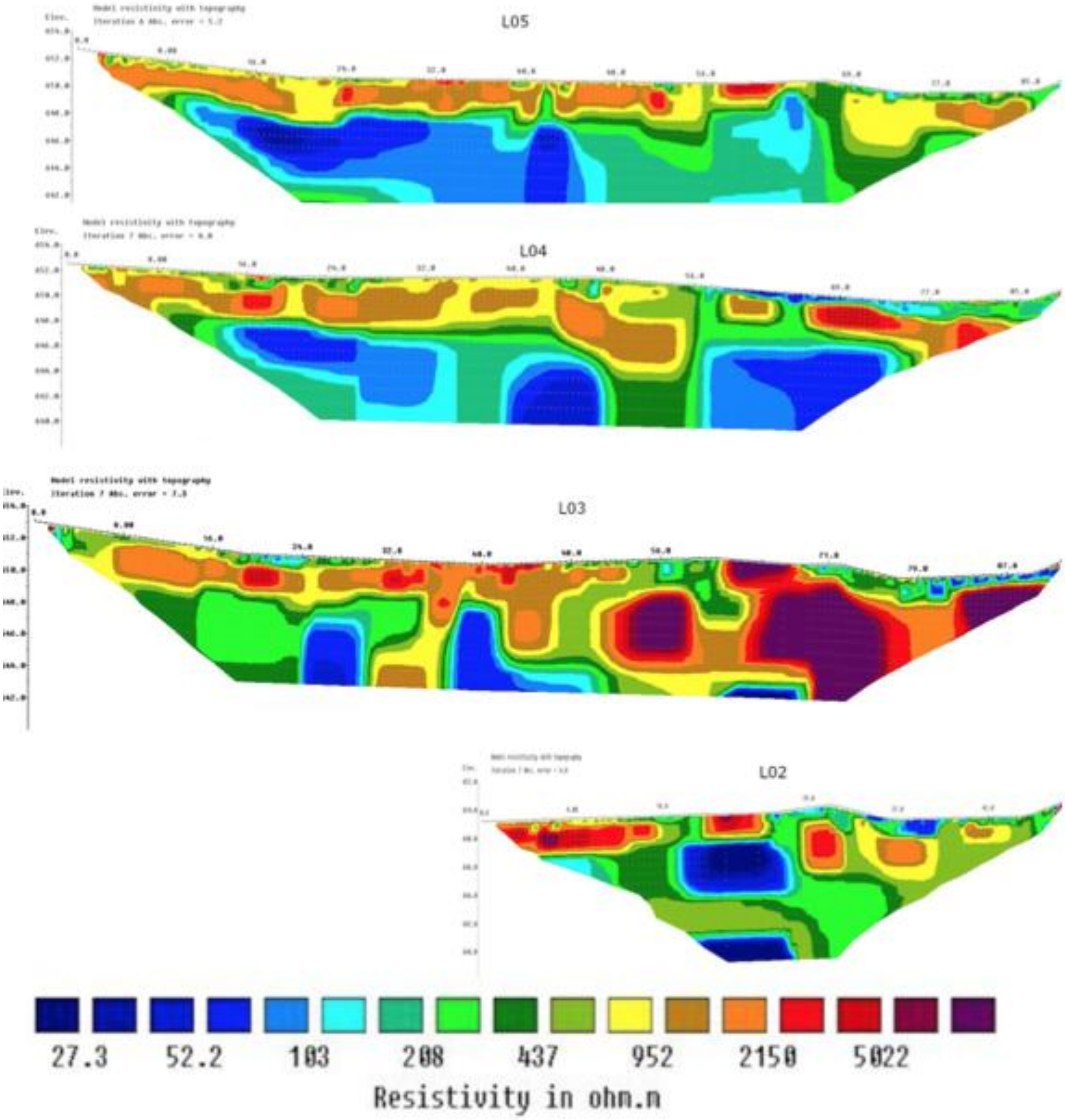
5.3.2.2 Object of study B

The object is represented by the specification of geophysical data and geotechnical parameters generated through the exploration of an earth dam located on UFV campus whose data collection process was addressed in a master's thesis [56]. In this study, the following were selected: Longitudinal section (L04); Borehole SP1M (Fig. 5.5) for the development of the geotechnical and geo-electrical profiles.

The geotechnical results were translated into the IFC 4.3 data schema, to attend to specific objective ii.



(a)



(b)

Fig. 5.5 Geophysical scenario: (a) Surface sections and boreholes; (b) ER Slices
Source: 'master thesis' Soares, Luis (2021)

5.3.3 Constructing a solution

The development of the complete solution was carried out manually to comply with the IFC 4.3 schema. Thus, the IfcRoot.GlobalId attribute was generated to fully meet the bSI documentation, in addition to the validation of the final SPF enabled by the platform. The identifiers were created through the Python console available in the Bonsai BIM software interface, and IfcOpenShell [57,58].

Artifacts were based on the inheritance diagrams of the entities: IfcProject.RepresentationContexts (Fig. 5.2), IfcProduct (Appendix B), IfcSite (Appendix C), IfcGeoslice and IfcGeotechnicalStratum (Appendix D), IfcBorehole and IfcGeotechnicalStratum (Appendix E), and IfcGeographicElement (Appendix F). For readability, the diagrams were presented from the inheritance of IfcProduct, with the exception of IfcProject.

Assisted by SPF files the artifacts were developed in two steps: Artifact A - new information was specified to address inform geodetic framework; Artifact B - new data and information were developed to notify geotechnical framework.

5.3.3.1 Artifact A

During the configured export process [IFC 4x3] offered by Revit software (v. 2025) the EPSG code corresponding to the geodetic location of the bridge was provided through the "Geographic Reference" tab, which automatically generates the identification and description of the horizontal datum, considering coordinate base Project Base Point (Fig. 5.6).

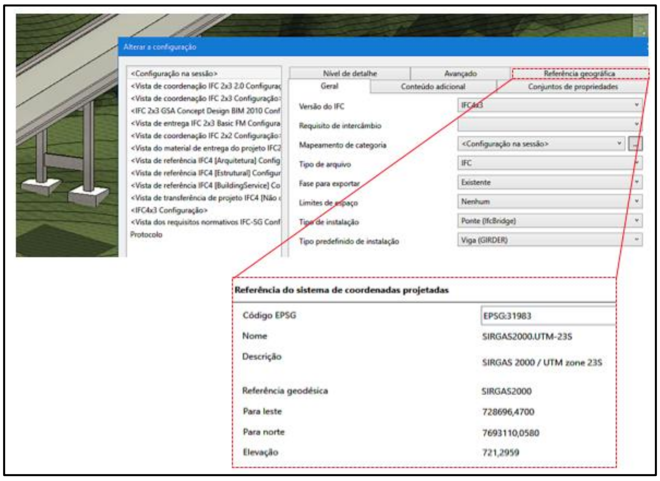
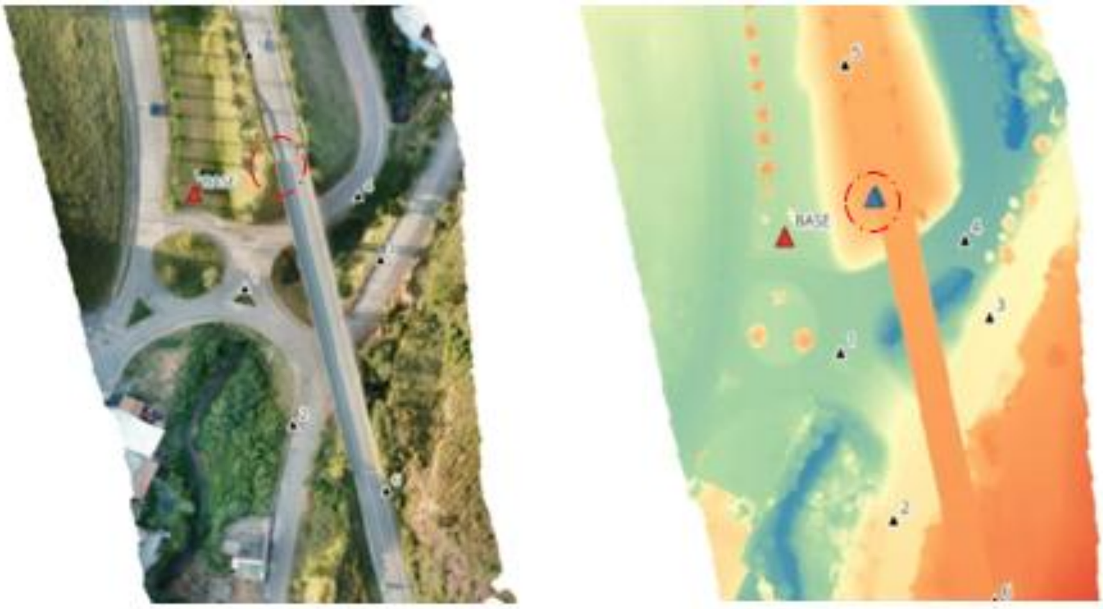


Fig. 5.6 Configured exportation
Source: the Author (2024)

The geolocation of this coordinate was carried out, through the capture of reality process by VANT, and 3D Laser Scanning techniques, on the Pre-BIM stage [59]. The engineering coordinate established for the project (PIR) must follow the convention used by the Organization (OIR), as it may represent the attribute WorldCoordinateSystem `[0.,0.,0.]`. This coordinate should ideally coincide with the internal origin point used by the modeling software.

This procedure is necessary for any project model and can consistently assist the 3D coordination process. For this reason, it should be referenced in the work plans of the professionals involved and part of the modeling protocol for each project model. The coordinate was defined using QGIS software based on the values indicated in six targets (Fig. 5.7).



▲ = Project Base Point (E=728696.47, N=7693110.0580, H=721.2959)

ID	N	E	H
1	7693093.690	728673.862	712.179
2	7693070.492	728686.995	711.889
3	7693027.659	728702.058	715.465
4	7693079.550	728729.159	714.381
5	7693099,285	728722.164	710.315
6	7693143.846	728688.340	719.682
BASE	7693100.062	728671.242	712.280

Fig. 5.7 Project Base Point georeferencing
Source: the Author (2024)

The SPF file generated was named Original, where part of it is presented in 1st and 2nd order, minimally when relevant to the analysis, due to its extent (Listing 5.1). The interventions were manually developed (Listing 5.2) in response to the inconsistencies identified (highligted in red), which will be analyzed and discussed in Section 4 (Artifact A). The color blue is used in Listing 2 to facilitate the identification of corrective actions.

Listing 5.1 - SPF Original

```
ISO-10303-21;
DATA;
#3=IFCCARTESIANPOINT((0.,0.,0.));
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1726701698);
#20=IFCAXIS2PLACEMENT3D(#3,$,$);
#21=IFCDIRECTION((0.23186,0.97274));
#22=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#20,#21);
#27=IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#28=IFCPROJECTEDCRS('EPSG:31983','SIRGAS 2000 / UTM zone 23S','SIRGAS 2000',$,$,$,#27);
#29=IFCMAPCONVERSION(#22,#28,728696.470,7693110.058,721.2959,0.97274,0.23186,$);
#32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'As-is Model',$,$,$,'Operate',(#22,#26),#121085);
#36=IFCBRIDGE('0SzwuVeZXBQRZ0Rk9mp2Ns',#18,'CoimbraI Bridge',$,$,#35,$,$,.ELEMENT.,.GIRDER.);
#40=IFCBRIDGEPART('3kSL0VGKv3gxJCujeqtuJj',#18,'Reference',$,'Level',#39,$,'Reference',
.ELEMENT.,$,$);
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-7,-605285),721.2959,$,$);
#44=IFCPROPERTYSINGLEVALUE('Reference',$,IFCIDENTIFIER('Phase of a project information'),$);
#45=IFCPROPERTYSET('3Uh8Ap4X9PEQ_fF9URCYLC',#18,'Pset_SiteCommon',$,(#44));
#46=IFCPROPERTYSINGLEVALUE('IsExternal',$,IFCBOOLEAN(.F.),$);
#47=IFCPROPERTYSET('0PaGoA5N1Lb5wJ8DbFp8s2',#18,'Pset_SpaceCommon',$,(#44,#46));
#48=IFCRELDEFINESBYPROPERTIES('1yTpTkm1FspRG6j1JPf1Bp',#18,$,$,(#43),#45);
#49=IFCRELDEFINESBYPROPERTIES('3FHcFwUWBTsdpdJx3tsNwK',#18,$,$,(#43),#47);
#119806=IFCGEOGRAPHICELEMENT('19H7fyXuv7qRd8OC7jA4Ux',#18,'Toposolid1',$,'Toposolid1',#83223,#
119805,'569745',.TERRAIN.);
#119938=IFCRELCONTAINEDINSPATIALSTRUCTURE('3kSL0VGKv3gxJCujiqtuJj',#18,$,$,(#237,#305,#388,
#426,#463,#500,#537,#574,#611,#661,#702,#724,#746,#780,#802,#824,#846,#905,#1010,#1093,#1187,#
1256,#1374,#1462,#1576,#1645,#1699,#1735,#2047,#2370,#2423,#2470,#2494,#2528,#2614,#2691,
#2795,#2868,#2941,#3018,#3108,#3183,#3256,#3330,#3404,#3534,#3664,#3768,#3872,#3976,#4080,
#4184,#4288,#4392,#4496,#28576,#80012,#80077,#80187,#80291,#80395,#80499,#80603,#80707,
#80811,#80915,#81019,#81123,#81227,#81331,#81435,#81539,#81643,#81747,#81851,#81955,#82059,
#82163,#82267,#82371,#82475,#82579,#82683,#82787,#82891,#82995,#83099,#83203,#119806),#40);
#121085=IFCUNITASSIGNMENT((#19,#73,#74,#255,#119884,#119887,#119892,#120623,#120637,#120644,
#120650,#120656,#120660,#120666,#120669));
END SEC
END-ISO-10303-21;
```

Listing 5.2 - Artefact A

```
ISO-10303-21;
DATA;

/*Geometric Framework*/
#3=IFCCARTESIANPOINT((0.,0.,0.));
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,$,$,1726599618);
#19=IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#21=IFCDIRECTION((0.23186,0.97274));
#22=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#20,#21);
#32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'As-is Model',$,$,$,'Operate',(#22,#30),#121085);
#40=IFCBRIDGEPART('3kSL0VGKv3gxJCujeqtuJj',#18,'Reference',$,'Level',#39,$,'Reference',
.ELEMENT.,$,.VERTICAL.);
#121085=IFCUNITASSIGNMENT((#19,#73,#74,#255,#119884,#119887,#119892,#120623,#120637,#120644,#1
20650,#120656,#120660,#120666,#120669));

/*Geographic and Geodesic Framework*/
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,(-20,-50,-52,-
901458),(-42,-48,-7,-605285),721.2959,$,$);
#46=IFCPROPERTYSINGLEVALUE('IsExternal',$,IFCBOOLEAN(.F.),$);
#47=IFCPROPERTYSET('0PaGoA5N1Lb5wJ8DbFp8s2',#18,'Pset_SpaceCommon',$,(#46));
```

```
#119939=IFCRELAGGREGATES('3$Y$m$roJ8zwX_N7i2$VCx',#18,$,$,#32,(#43));

/*Geodesic Reference by ProjectedCRS Target*/
#28=IFCPROJECTEDCRS('EPSG:31983','Sirgas2000Zone23S','EPSG:4674','EPSG:5779HNOR_IMBITUBA','Uni
versal Transversal Mercator','23 South',#19);
#29=IFCMAPCONVERSION(#22,#28,728696.470,7693110.058,721.2959,0.97274,0.23186,$);

/*Geodesic Reference by GeographicCRS Target*/
#70=IFCSIUNIT(*,.PLANEANGLEUNIT.,$,.RADIAN.);
#71=IFCDIMENSIONALEXPONENTS(0,0,0,0,0,0,0);
#72=IFCMEASUREWITHUNIT(IFCPLANEANGLEMEASURE(0.017453292519943278),#70);
#73=IFCCONVERSIONBASEDUNIT(#71,.PLANEANGLEUNIT.,'DEGREE',#72);
#150000=IFCGEOGRAPHICCRS('EPSG:31983','Sirgas2000Zone23S','EPSG:4674','EPSG:8901',#73,#19);

/*Relanshionship between IfcSite and IfcGeographicElement*/
#119938=IFCRELCONTAINEDINSPATIALSTRUCTURE('3kSL0VGKv3gxJCujiqtuJj',#18,$,$,(#237,#305,#388,#42
6,#463,#500,#537,#574,#611,#661,#702,#724,#746,#780,#802,#824,#846,#905,#1010,#1093,#1187,#125
6,#1374,#1462,#1576,#1645,#1699,#1735,#2047,#2370,#2423,#2470,#2494,#2528,#2614,#2691,#2795,#2
868,#2941,#3018,#3108,#3183,#3256,#3330,#3404,#3534,#3664,#3768,#3872,#3976,#4080,#4184,#4288,
#4392,#4496,#28576,#80012,#80077,#80187,#80291,#80395,#80499,#80603,#80707,#80811,#80915,#8101
9,#81123,#81227,#81331,#81435,#81539,#81643,#81747,#81851,#81955,#82059,#82163,#82267,#82371,#
82475,#82579,#82683,#82787,#82891,#82995,#83099,#83203),#40);
#150002=IFCRELCONTAINEDINSPATIALSTRUCTURE('0r1rWBp4959uhHNV5bdSUA',#18,$,$,(#119806),#43);
#119806=IFCGEOGRAPHICELEMENT('19H7fyXuv7qRd8OC7jA4Ux',#18,'Toposolid',$,'Toposolid1',#83223,#1
19805,'569745',.TERRAIN.);

END SEC
END-ISO-10303-21;
```

5.3.3.2 Artifact B

Artifact B was developed based on a topographic surface to specify geotechnical data aligned with the IFC 4.3 schema, through STEP standard. The strategy used in development was as follows:

- Step 1: The topographic surface represents a terrain (earth dam) and a geophysical scenario was used to reveal geotechnical data;
- Step 2: A single borehole comprises multiple segments (1 meter deph each) and represents different properties.

The instances of boreholes represent precise information about a subsurface. In this case, the interpolation process was unnecessary because plan sections can identify details between punctual reports, raising the relevance of the data reliability level. The borehole data can be converted into geological layers to represent the geological variation in the geological space [60]. In this study, this is not a demand because geophysical methodology represents a precise way to prospect the subsurface properties faithfully.

In this scenario, a single IfcGeoslice specifies each plan section prospected, and IfcBorehole details SPT and geoelectric profiles, specified by IfcGeotechnicalStratum instances (Fig. 5.8). The SPT report was applied to geotechnical data specification (ATTACHMENT 5.1).

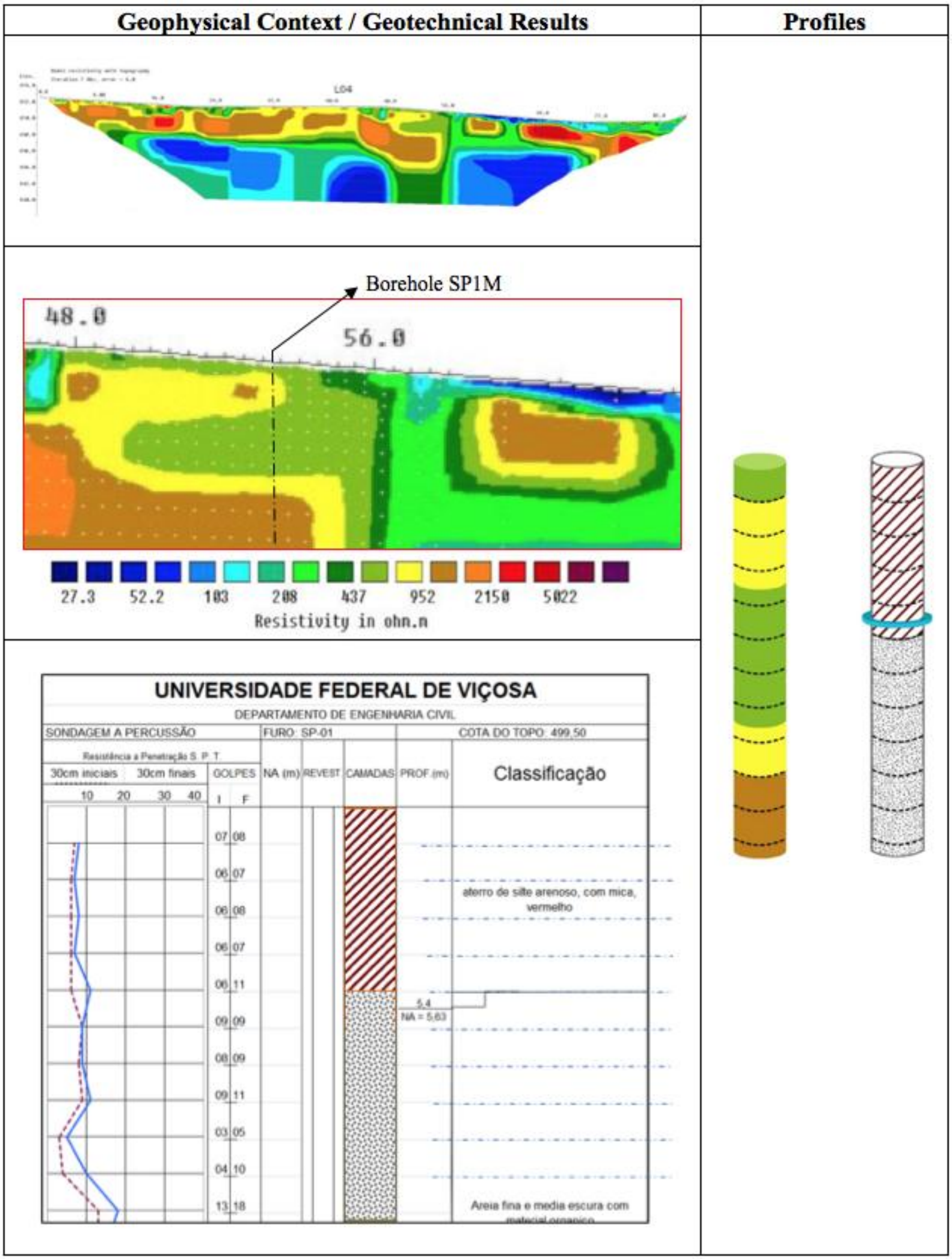


Fig. 5.8 Geotechnical profiles
Source: the Author (2024)

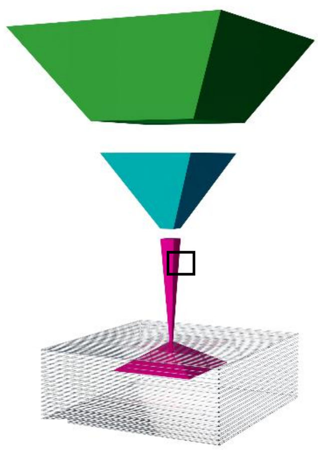
The representation of the IFC-Based Spatial Structure Element was based on spatial arrangement and positional relationship. IfcRelAggregates plays an essential role to connect [IfcProject to IfcSite], and IfcRelContainedInSpatialStructure to connect [IfcSite and

IfcGeographicElement] [61]. Between IfcGeographicElement and [IfcBoherole or IfcGeoslice] the relationship is semantically adequate by IfcRelConnectElements and between [IfcBorehole and IfcGeotechnicalStratum] by IfcRelConnectsWithRealizingElements [62].

The entity IfcRelConnectsWithRealizingElements is a specialization of IfcRelConnectsElements where the connecting operation has the additional attribute of (one or many) realizing elements that may be used to realize the relationship, defined as a ternary relationship [63] between IfcGeotechnicalStratum instances, and IfcBorehole.

In Table 5.2 the background color of each entity corresponds to the data architecture layer of origin, which, in parallel, matches the IFC spatial structure. In Table 5.3, the supertype targets and justifications are presented.

Table 5.2 Artifact B data

IFC Data Architecture	IFC Spatial Structure	Entity / Relationship / Property / Set
 Source: Antunes et al. (2024)	 Figure 1	**IfcProject**
		IfcRelAggregates
		IfcSite
		IfcRelContainedInSpatialStructure
		IfcGeographicElement
		IfcRelConnectsElements
		IfcGeoslice
		IfcBorehole
		[Metodology]
		[BoreHolePurpose]
		Pset_GeotechnicalAssemblyCommon
		[GroundwaterDepth]
		Pset_BoreholeCommon
		IfcRelConnectsWithRealizingElements
		IfcGeotechnicalStratum
		[Texture]
		[StratumColor]
		[IsTopographic]
		Pset_GeotechnicalStratumCommon
		[NValue]
		[Resistivity]
		Pset_SolidStratumCapacity

Source: the Author (2024)

Table 5.3 Targets and justificatives

Core and Interoperability entities	Supertype	Justification of selection
IfcProject	IfcContext	IFC **main** spatial container
IfcRelAggregates	IfcRelationship	IFC spatial demand
IfcSite	IfcObject	IFC **second main** spatial container
IfcRelContainedInSpatialStructure	IfcRelationship	IFC spatial demand
IfcGeographicElement	IfcElement	Elements within a geographical landscape
IfcRelConnectElements	IfcRelationship	Relationship to the other element to which this element is connected
IfcGeoslice	IfcElement	*ConnectTo* [0:?] OF IfcRelConnectElements FOR
IfcBorehole	IfcElement	Relating Element [IfcGeographicElement]
IfcRelConnectsWithRealizingElements	IfcRelationship	Assigns the realizing element to the connection, which provides the physical manifestation of the connection relationship
IfcGeothechnicalStratum	IfcElement	*IsConnectionRealization* [0:?] OF IfcRelConnectsWithRealizingElements FOR RealizingElements Representation of an identified geological feature [IfcBorehole]

Source: the Author (2024)

Stratigraphic property information mainly contains two types: One specifies characteristics of rock and (or) soil, including relevant information such as texture, and color of the stratum. The other is the physical and mechanical properties, which refers to the relevant parameters information and geotechnical characteristics by the method of experiments such as SPT blow count, and electrical resistivity (Table 5.4).

Table 5.4 Properties

Property Name	Property Type	Property Data Type	Description
Methodology	IfcPropertySingleValue	IfcText	Methodology used to specify the geotechnical assembly
BoreHolePurpose	IfcPropertyEnumeratedValue	IfcLabel	Reveal the borehole purpose
GroundwaterDepth	IfcPropertySingleValue	IfcPositiveLengthMeasure	Specify the level of the groundwater table found
Texture	IfcPropertySingleValue	IfcLabel	Inform the texture of the material found by a fraction
StratumColour	IfcPropertySingleValue	IfcLabel	Inform the coloration of the material found by a fraction
IsTopographic	IfcPropertySingleValue	IfcLogical	Clear if the specific fraction is on top of the topographic feature or not
NValue	IfcPropertySingleValue	IfcCountMeasure	Specify the blow count from SPT of a material found by a fraction
Resistivity	IfcPropertySingleValue	IfcElectricResistanceMeasure	Specify the electrical resistivity of a material found by a fraction (Ohm-m)

Source: the Author (2024)

Listing 5.3 and the respective graph (Fig. 5.9) illustrate the construct developed.

Listing 5.3

```
ISO-10303-21;
DATA;

/* IfcGeographicElement */
#1=IFCGEOGRAPHICELEMENT('0JXPcbt8P4jBecS76sGeE$',#100005,'Toposolid',$,$,$,$,$,.TERRAIN.);
#3000=IFCRELCONTAINEDINSPATIALSTRUCTURE('322HTexbz1PgWpOCRAv2uU',#100005,$,$,(#1,#100,#1000,
#15000),#100020);

/* IfcGeoslice L04 - Repeat for each longitudinal or transversal section */

#100=IFCGEOSLICE('3ChF8yb4f1YAULcymdJ$HG',#100005,'L04',$,$,$,$,$);
#200=IFCPROPERTYSINGLEVALUE('Methodology',$,IFCTEXT('Electrical Resistivity Tomography
ERT')),$);
#300=IFCPROPERTYENUMERATION=('PEnum_StrataAssemblyPurpose',(IFCLABEL('DEPOSIT'),
IFCLABEL('ENVIRONMENTAL'),IFCLABEL('FEEDSTOCK'),IFCLABEL('GEOLOGICAL'),IFCLABEL('GEOTHERMAL'),
IFCLABEL('HYDROCARBON'),IFCLABEL('HYDROGEOLOGICAL'),IFCLABEL('MINERAL'),IFCLABEL('STORAGE'),
IFCLABEL('PEDOLOGICAL'),IFCLABEL('SITE_INVESTIGATION'),IFCLABEL('NOTKNOWN'),
IFCLABEL('USERDEFINED'),IFCLABEL('NOTDEFINED')),$);
#350=IFCPROPERTYENUMERATEDVALUE=('Site Investigation',$,(IFCLABEL('GEOLOGICAL')),#300);
#400=IFCPROPERTYSET('2z$2wKkHb8aP6H7KIwJH1f',#100005,'Pset_GeotecnhicalAssemblyCommon',$,
(#200,#350));
#500=IFCRELDEFINESBYPROPERTIES('1W9yxVygP4Hg3VMW43gyD0',#100005,$,$,(#100),#400);
#600=IFCRELCONNECTSELEMENTS('3i46T6vwDC9fCkcZt_JkjU',#100005,$,$,$,#100,#1);

/* IfcBorehole SP1M - Repeat for each borehole */

#1000=IFCBOREHOLE('1xSIiFYMrB1epuBvFz1_E3',#100005,'SP1M on L04','Depth=17.45m',$,$,$,$);
#1100=IFCPROPERTYSINGLEVALUE('Methodology',$,IFCTEXT('Standart Penetration Test SPT'),$);
#1150=IFCPROPERTYENUMERATEDVALUE('BoreHolePurpose',$,(IFCLABEL('SITE_INVESTIGATION')),#300);
#1300=IFCPROPERTYSET('02Y7vyERL1kPH7upIT7g7d',#100005,'Pset_GeotechnicalAssemblyCommon',$,
(#1100,#1150));
#1400=IFCRELDEFINESBYPROPERTIES('0swLB_yc98ExkNwno7vmqm',#100005,$,$,(#1000),#1300);
#1500=IFCPROPERTYSINGLEVALUE('GroundwaterDepth',$,IFCPOSITIVELENGTHMEASURE(5.63),$);
#1600=IFCPROPERTYSET('2wu_da9SrFlPywrlzM3BmB',#100005,'Pset_BoreholeCommon',$,(#1500));
#1700=IFCRELDEFINESBYPROPERTIES('0ABD$jZtr21ff$rUoRxI4S',#100005,$,$,(#1000),#1600);
#1800=IFCRELCONNECTSELEMENTS('0R9Lt$yJPCUByW4cpm_sCo',#100005,$,$,$,#1000,#1);

/* IfcGeotechnicalStratum - First fraction of borehole by meter - Repeat for the other
fractions of the respective borehole */
#15000= IFCGEOTECHNICALSTRATUM('1$S5EjcMbFFOQP6sb2sPHy',#100005,'Fraction 1','Depth=1m',
$,$,$,$,.SOLID.);
#15100=IFCPROPERTYSINGLEVALUE('Texture',$,IFCLABEL('Sandy silt fill with mica'),$);
#15200=IFCPROPERTYSINGLEVALUE('StratumColour',$,IFCLABEL('red'),$);
#15300=IFCPROPERTYSINGLEVALUE('IsTopographic',$,IFCLOGICAL(.T.),$);
#15400=IFCPROPERTYSET('1B$Gtq7PT2SvshEg6Im0dY',#100005,'Pset_GeotechnicalStratumCommon',$,
(#15100,#15200,#15300));
#15500=IFCRELDEFINESBYPROPERTIES('0RNLEqx5v4cg4V9lRyWJ1W',#100005,$,$,(#15000),#15400);
#15600=IFCPROPERTYSINGLEVALUE('NValue',$,IFCCOUNTMEASURE(8),$);
#15601=IFCPROPERTYSINGLEVALUE('Resistivity',$,IFCELECTRICRESISTANCEMEASURE(437.00000),
#100073);
#15700=IFCPROPERTYSET('1OC9RAN3vE6RZqL87vvdxP',#100005,'Pset_SolidStratumCapacity',$,
(#15600, #15601));
#15800=IFCRELDEFINESBYPROPERTIES('3PNnI05OXBWepxe6Ci653g',#100005,$,$,(#15000),#15700);
#15900=IFCRELCONNECTSWITHREALIZINGELEMENTS('0ESUrzM0T7fQqPwI4bKUQV',#100005,$,$,$,#1000,#1,
(#15000),'Joint');

/* IfcProject, IfcSite, and relationship */

#100005=IFCOWNERHISTORY(#100003,#100004,$,.NOTDEFINED.,$,$,$,1122650864);
#100010=IFCPROJECT('2z1QNIvAf9twcRFIjiffrX',#100005,'Validation',$,$,$,$,(#100011),#100060);
#100011=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#100040,$);
#100012=IFCGEOMETRICREPRESNTATIONSUBCONTEXT('Body','Model',*,*,*,*,#100011,$,.MODEL_VIEW.,$);
#100022=IFCLOCALPLACEMENT($,#100040);
#100040=IFCAXIS2PLACEMENT3D(#100041,#100042,#100044);
#100041=IFCCARTESIANPOINT((0.,0.,0.));
#100042=IFCDIRECTION((1.,0.,0.));
#100044=IFCDIRECTION((0.,0.,1.));
#100060= IFCUNITASSIGNMENT((#100061,#100062,#100063,#100064));
```

```
#100061= IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);
#100062= IFCSIUNIT(*,.AREAUNIT.,$,.SQUARE_METRE.);
#100063= IFCSIUNIT(*,.VOLUMEUNIT.,$,.CUBIC_METRE.);
#100064= IFCSIUNIT(*,.PLANEANGLEUNIT.,$,.RADIAN.);
#100020=IFCSITE('3VzhhIG5L9$gCpjBqV3FN$',#100005,'Site',$,$,#100022,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-7,-605285),721.29590,$,$);
#100021=IFCRELAGGREGATES('2csf7j9KH1xgebWuj$nZp0',#100005,$,$,#100010,(#100020));

ENDSEC;
END-ISO-10303-21;
```

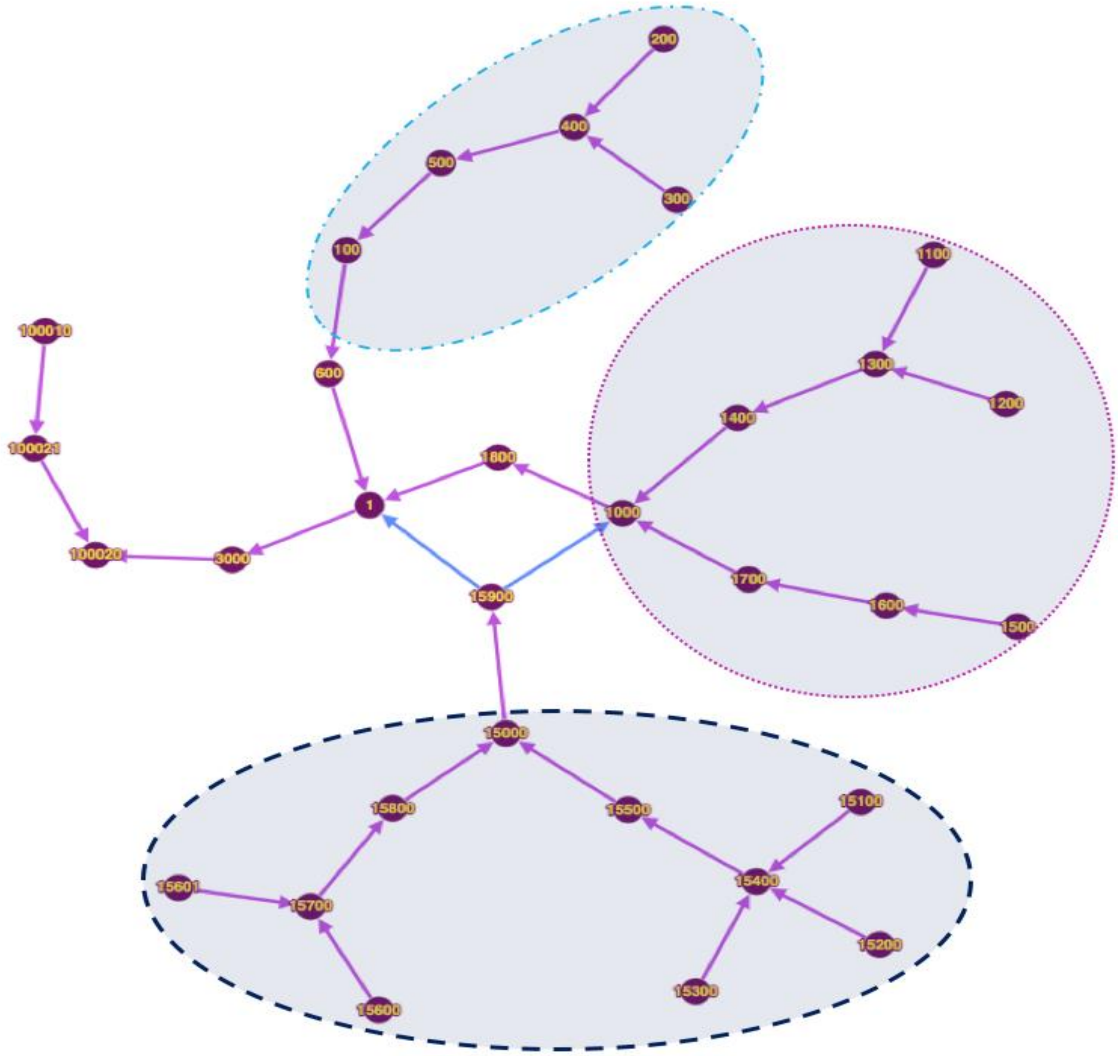


Fig. 5.9 Main graph
Source: the Author (2024)

5.4 Analysis

The configured export process represents an alternative path for the professional to meet the information requirements of the project and the organization, as established in their BIM Execution Plan, especially in the absence of the MVD version aligned with the infrastructure project domain.

Although the modeling software offered the [IFC 4x3] export, the vertical datum was not clarified, unlike the horizontal datum, even though both have optional declaratory status in the schema. Additionally, the export is restricted to projected coordinate reference, and in this case, specification through geographic coordinate is not an option. The problems identified in Artefact A and their respective assessments are presented in Table 5.5.

Table 5.5 Artifact A

Listing 1 Data Missing / Deprecation / Error	Consequences	Listing 2 Data
#28=IfcProjectCRS	The name attribute can specify the CRS by EPSG code [IfcLabel] Vertical Datum specifies by EPSG code [IfcIdentifier]	Informed: 'EPSG:4674' Informed: 'EPSG:5779 HNOR_IMBITUBA'
#xx=IfcGeographicCRS	No option to specified	#150000
#40=IfcBridgePart.UsageType	Out off IFC data specification	Corrected
#44=IfcPropertySingleValue.Reference	Out off IFC 4.3 data	Deleted
#45=IfcPropertySet		Deleted
#47=IfcRelDefinesByProperties		Adjusted
#119938=IfcRelContainedInSpatial Structure	Spatial structure error: Relationship between [IfcBridgePart and IfcGeographicElement]	#150002 Relationship between [IfcSite and IfcGeographicElement]

Source: the Author (2024)

The quantitative evaluation of the artifact reveals nine new occurrences: one adjusted and three informed attributes from the default original SPF (GeodeticDatum, VerticalDatum, MapProjetion, and MapZone, respectively); IfcGeographicCRS inform four different attributes, and IfcRelContainedInSpatialStructure represents a new instance of relationship, essential to attend the IFC spatial structure. IfcBridgePart also did not specified UsageType mandatorily (Table 5.6).

Table 5.6. Quantitative evaluation

Data	Original SPF	Artifact A
ProjectedCRS Attributes informed	**4**	**7**
GeographicCRS Attributes informed	**0**	**4**
IfcBridgePart.UsageType Attribute mandatory	**0**	**1**
IfcRelContainedInSpatialStructure A new instance with [RelatingStructure] attribute	**0**	**1**
Total	**4**	**13**

Source: the Author (2024)

Aiming to analyze the semantic level of the original SPF and the artifact, scores were assigned and considered (Table 5.7):

0= Information do not meet the bSI standard specification;

1= Absent ($) or information does not meet the bSI standard value;

2= Information meets bSI standard specification by default or lacks meaning (´ `) or (0.);

3= Information meets bSI standard specification and has meaning.

Table 5.7 Semantic level evaluation

IFC object	Original SPF	Artifact A
IfcProjectedCRS	8 [Σ (3,3,1,1)]	21 [Σ (3,3,3,3,3,3,3)]
IfcGeographicCRS	0	12 [Σ (3,3,3,3)]
IfcBridgePart	0	3
IfcRelContainedInSpatialStructure	0	3
Total	**8**	**39**

Source: the Author (2024)

This finding demonstrates that the artifact data allow software manufacturers to enhance semantic performance and consequently, improve information interoperability between GIS and BIM software to 487,50% better. As Artifact B SPF was developed from scratch, there is no original database that can be used for comparison.

5.5 Artifact Validation

Artifact A was validated using usBIM.browser (v. 1.6.73) visualization software [64]. The findings are illustrated and detailed in a report (Appendix G) designed based on the geodesic framework. The lines analyzed in the SPF file are highlighted at the top of the document, and the visualizations were illustrated according to the software interface. The status indicates what each viewer was able to recognize and also demonstrates the results throughout the solution developed.

Artifact B was fully validated successfully by five parameters [STEP Syntax; IFC Schema; Normative IFC Rules; Industry Practices; bSDD Compliance] by bSI Validation Service (online).

5.6 Discussion

The research gaps in general arise from failures during the modeling process due to either lack of information input (modeler), absence of data (software), or some inconsistency (data schema). Table 5.8 presents the list of issues, nature, specific data, and responsibility from Listing 5.1 (orginal SPF).

Table 5.8 List of issues found

# of Listing 1	Issue Nature	Data	Responsibility	
#28	Information	IfcProjectedCRS	Software	No data available on interface and /or Geographic Localization tab through configurated exportation
#xx	Data	IfcGeographicCRS		
#40	Data	IfcBridgePart.UsageType		Attribute is not OPTIONAL
#44	Data	IfcPropertySingleValue. Reference		Unmet [Deprecated]
#119938	Data	IfcRelContainedInSpatial Structure		Unmet [Spatial structure of the data schema]

Source: the Author (2024)

Those issues demonstrated how relevant BIM actors seek guidance in the bSI documentation to specify the requirements imposed by the execution plans they are obliged to meet, which are optionally not declared by the software they used. In this way, the most significant contribution of this work is presented of potentially semantic entities aimed at specifying IFC data responsible for the geodetic framework.

Artifact A demonstrates that the IFC data schema enables geodetic specification and represents an option for professionals to replicate it until software fully meets the requirements established by the IFC 4.3 schema. The investigative scenario supported by the inheritance diagrams strengthens the theoretical foundation and represents a mechanism capable of assisting both in the development of an execution plan and its implementation [2]. The translation of data by Entity inheritance diagrams can help professionals identify the relevant specifications to support choices in their collaborative work plans.

The diagrams become evident especially when compared to the bSI options, which only present the entities direct attributes. Some characteristics, such as inverse attributes, and cardinality are not given. This logic may be understood by professionals with skills in object-oriented programming, but it can pose a difficulty for users who are not yet familiar with the subject.

In this way, diagrams present may assist managers and modelers in translating data that aim to clarify the information requirements of the organization and the project. Therefore, they represent a relevant research auxiliary contribution. This theoretical foundation underpinned the development of the Artifact A, whose efficacy in specifying the geodesic framework is presented, standing as a strong point that it can be used for BIM actors, and organizations in different scenarios and geographic regions.

The insertions and changes made possible by the SPF file were manually performed using a simple notepad. In this regard, the process can be replicated from SPF files generated by other BIM software, provided they include versions compatible with the mapped entities. The validation of the generated SPF files was carried out successfully displayed the data and information insertions with a high level of adequate clarity.

Geotechnical data, in general, are not available in the working interfaces of BIM software, and in this context, Artifact B reveals that the IFC data schema contains semantically appropriate entities to specify them. The validation of geotechnical artifact was submitted to bSI Service Validation [Listing 3]. Figure 5.10 revels 100% of data validated.

The availability of this information enables information management throughout the entire life cycle: in the initial phases, it supports the development of disciplinary models; in the operational phase, it sustains important stability analyses through monitoring models. Consequently, the artifact effectively contributes to the sustainability of assets.

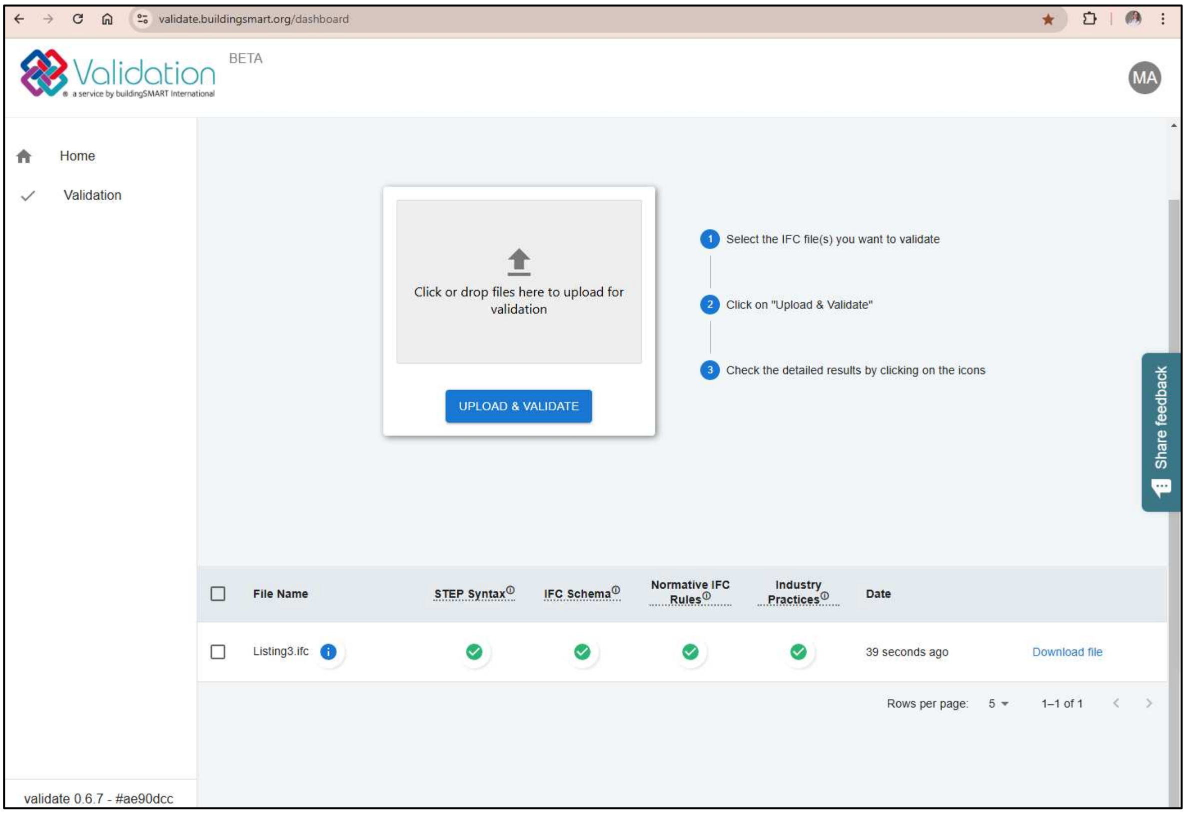


Fig. 5.10 Service Validation
Source: bSI, 2024 (adjusted)

5.7 Conclusion

The study revealed that the IFC 4.3 data schema may be useful for software manufacturers to specify the representation context of an infrastructure project at a high semantic level. The analyses enabled by the developed Artifact A presented a significant semantic increase, demonstrating that the interoperable performance of the software can be improved.

Although the IFC 4.3 schema broadly met the research demand, Revit exported the geodetic required information restricted to projected operation and could do it satisfactorily. However, from the spatial hierarchy IFC data schema view, the essential relationship between

IfcGeographicElement and IfcSite was stabilized incorrectly. Despite having a mandatory declaratory nature, IfcBridgePart.UsageType was specified as optional.

This occurs may because this version does not include an official Model View Definition and consequently, the software cannot yet be certified. On the other hand, IfcFacility (Bridge) and IfcFacilityPart (BridgePart) were considered, so positive feedback was observed, showing that software manufacturers have been anticipating developments, demonstrating continuous evolution in line with IFC 4.3 schema.

The entities IfcMapConversionScaled and IfcRigidOperation were added after relevant research demonstrated the importance of researchers' efforts and the good buildingSMART answer. In this scenario, new studies are necessary to test the benefits of the new data. IfcProjectedCRS and IfcGeographicCRS represent targets to specify the operation between different CRS and can be a choice in a specific project demand.

The specification of IfcCoordinateReferenceSystem.GeodeticDatum (IfcIdentifier) and .Name (IfcLabel) for projects located in countries with a small geographical extent may refer to the same EPSG code, and occasionally, one attribute can make it unnecessary to specify the other one. However, for projects located in countries characterized by large territorial extensions, such as Brazil, the two attributes may clarify more specific codes.

In these cases, GeodeticDatum would specify the code corresponding to the geodetic reference system used in the country, while .Name would specify the code for the precise location of the project, for example. Since the codes are different, they could enhance the accuracy of the project's global location. This would also justify changing the data type to IfcIdentifier for both atributes, to target the highest level of semantics.

The bSI documentation is constantly evolving and is essential for guiding professionals in the civil construction industry, as well as software manufacturers. This study was limited to the proprietary modeling software used by Brazilian management organization. It would be enriching for other studies to apply the same approach using different BIM software, and Geographic Information System (GIS) for semantic performance analysis. The accuracy of specialization is the main way to construct solutions, as Artifact B revealed.

The selected approach aligns with this context, as it uses geophysical prospecting applied to the specification of geotechnical parameters. Unlike the application of specific techniques, ERT does not require interpolation and/or interpretation of results, thus increasing the reliability of the investigated subsurface model.

The data specified through geophysics applied to the civil construction industry proved to be more accurate and, consequently, can add significant value in supporting analysis, design, and performance assessment. Geophysical can offer the general but precise subsurface prospection to best target analyses to guide punctual prospections such SPT method.

Although this study did not explore the geometry of the borehole, but their precise localization and visualization may add especial value for disciplinary BIM software. In this way, future researchs are necessary to support geotechnical models which represent a relevant value to project lifecycle.

Aligned with the IFC 4.3 schema, the artifacts can be replicated in any SPF regardless of the BIM software that generated them through a simple notepad. This way, the developed construction becomes even more adherent and reinforces the sustainable, neutral, and open aspect that OpenBIM aims to provide to the industry.

Finally, it is worth noting that the IFC data schema still does not offer a semantically appropriate entity to represent a dam. Following the same approach taken with bridges, a dam could be specified by IfcFacility and IfcFacilityPart, as IfcDam and IfcDamPart.

The structural characteristics could be classified through the attribute PredefinedType (IfcDamTypeEnum), as it inherits the attributes of IfcObject and IfcProduct. In the example applied in this study, the enumerated type could be [`.EARTHDAM.`], and in the case of a reinforced concrete dam, it would follow the same guidelines that direct the specifications for objects with this structural typology.

Given the considerable number of structures of this nature, bSI must add the necessary semantics for proper representation of dams, as well as analyze facilities through a broad spectrum.

This demand arises because some assets can additionally absorb functionalities from others: a dam can overcome natural obstacles and be characterized by vehicle traffic, a classic definition more commonly associated with bridges, i.e. Hoover Dam (USA). Similarly, a bridge can incorporate building functionalities in its superstructure, as seen with the Vecchio Bridge (Italy). Just as bridges are considered part of the Road, Rail, or Waterways domain, dams require a similarly thorough analysis.

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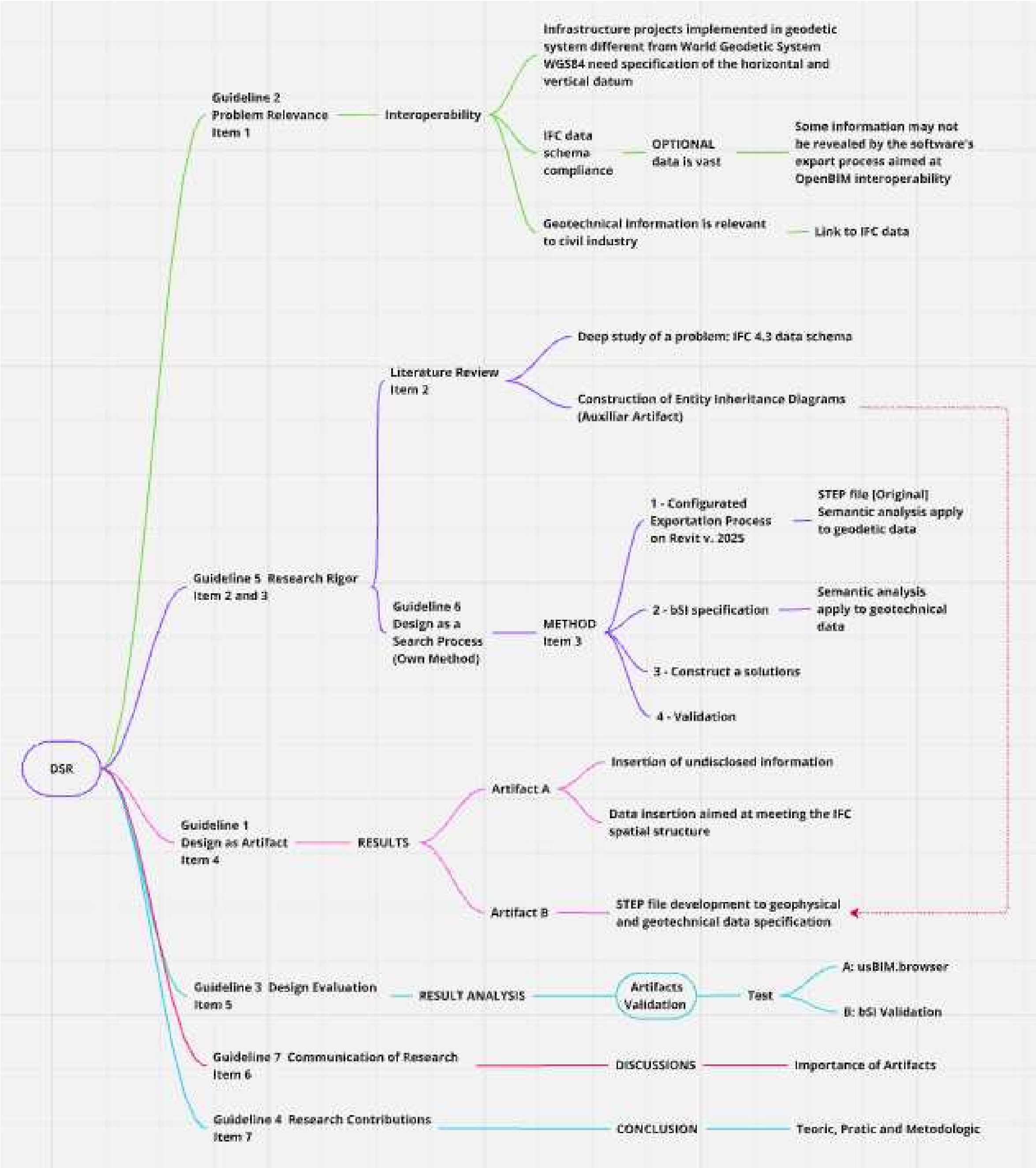
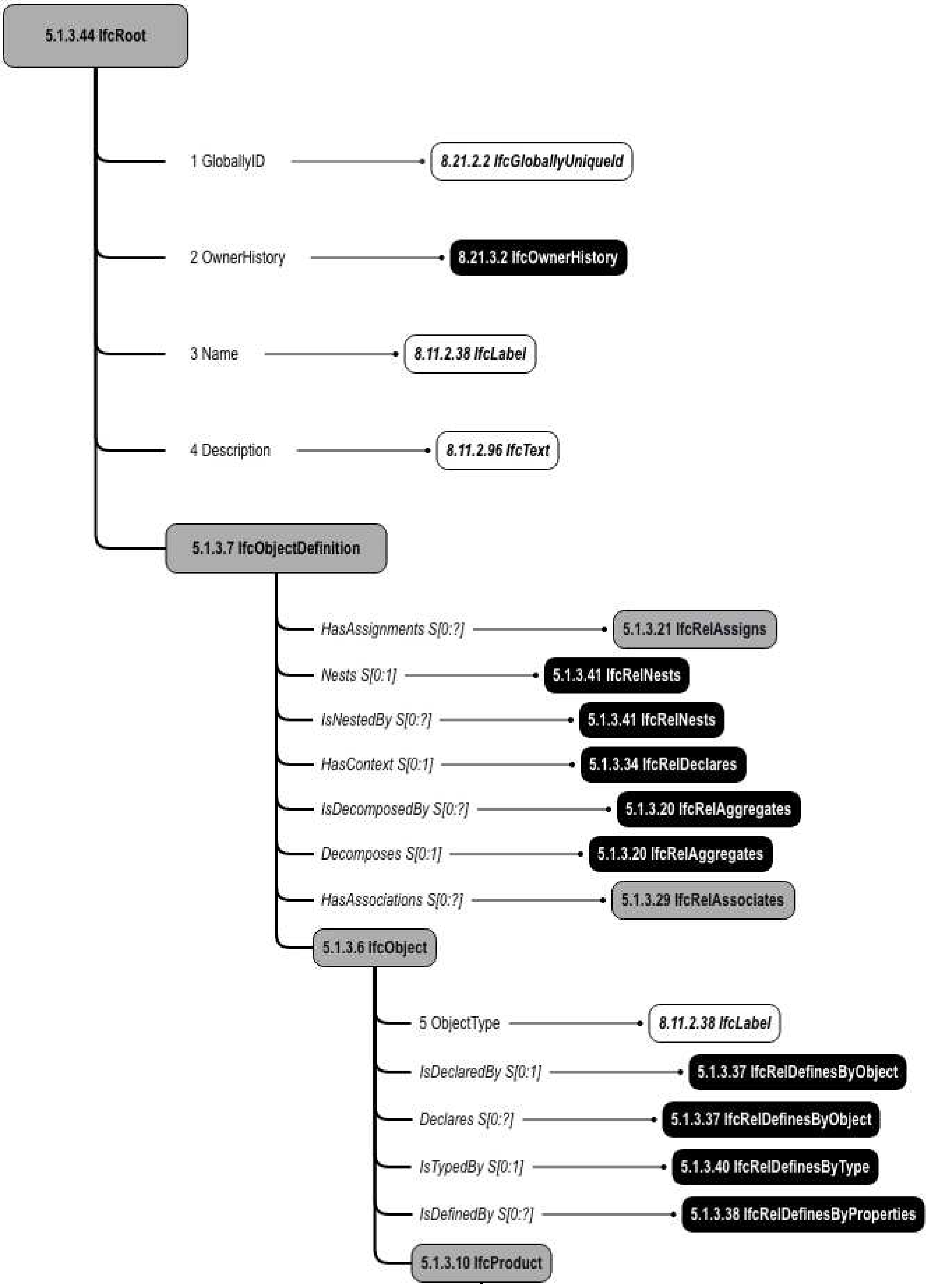
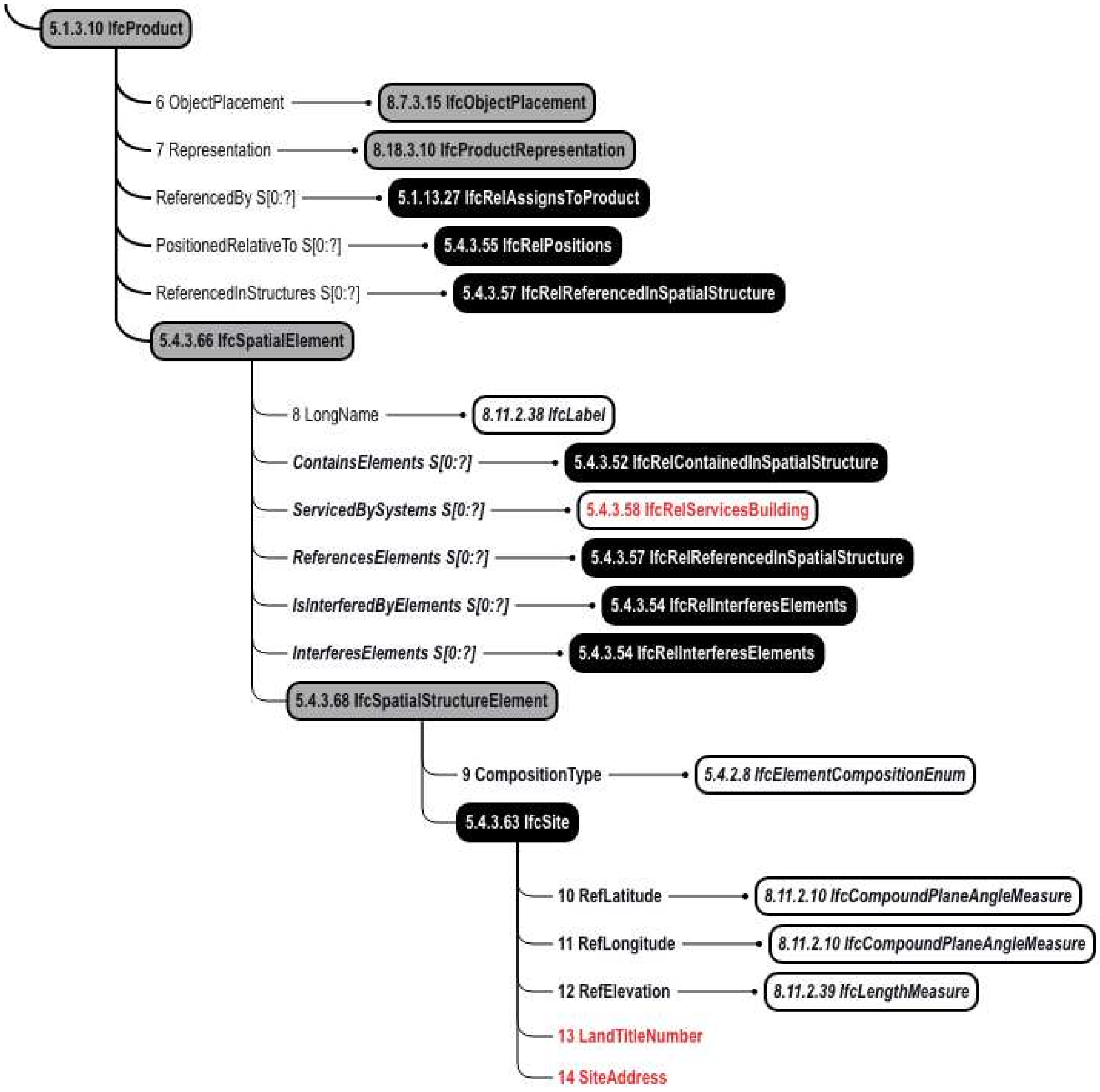
APPENDIX 5A: DSR – Method Guidelines



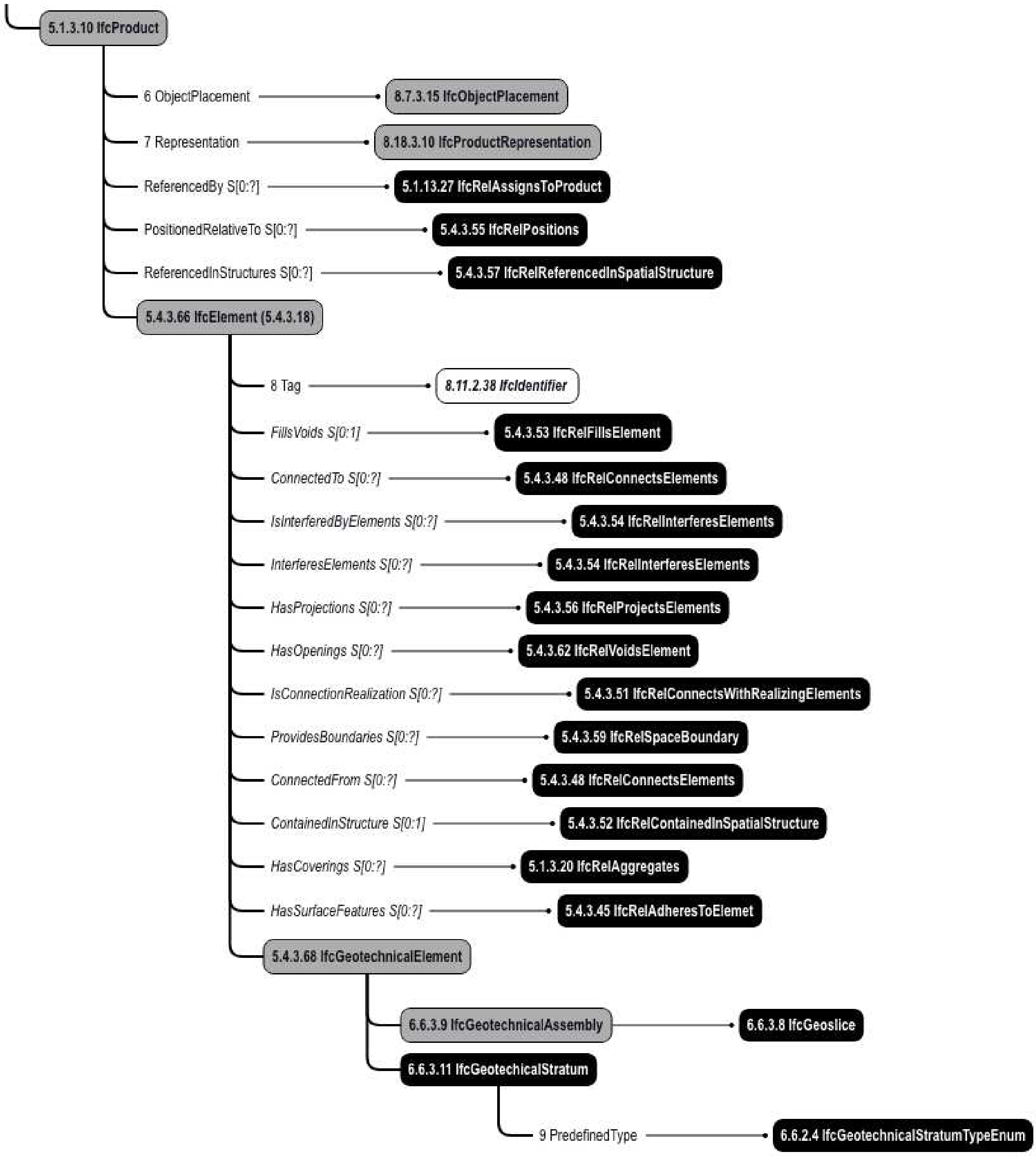
APPENDIX 5B: IfcProduct Inheritance Diagram



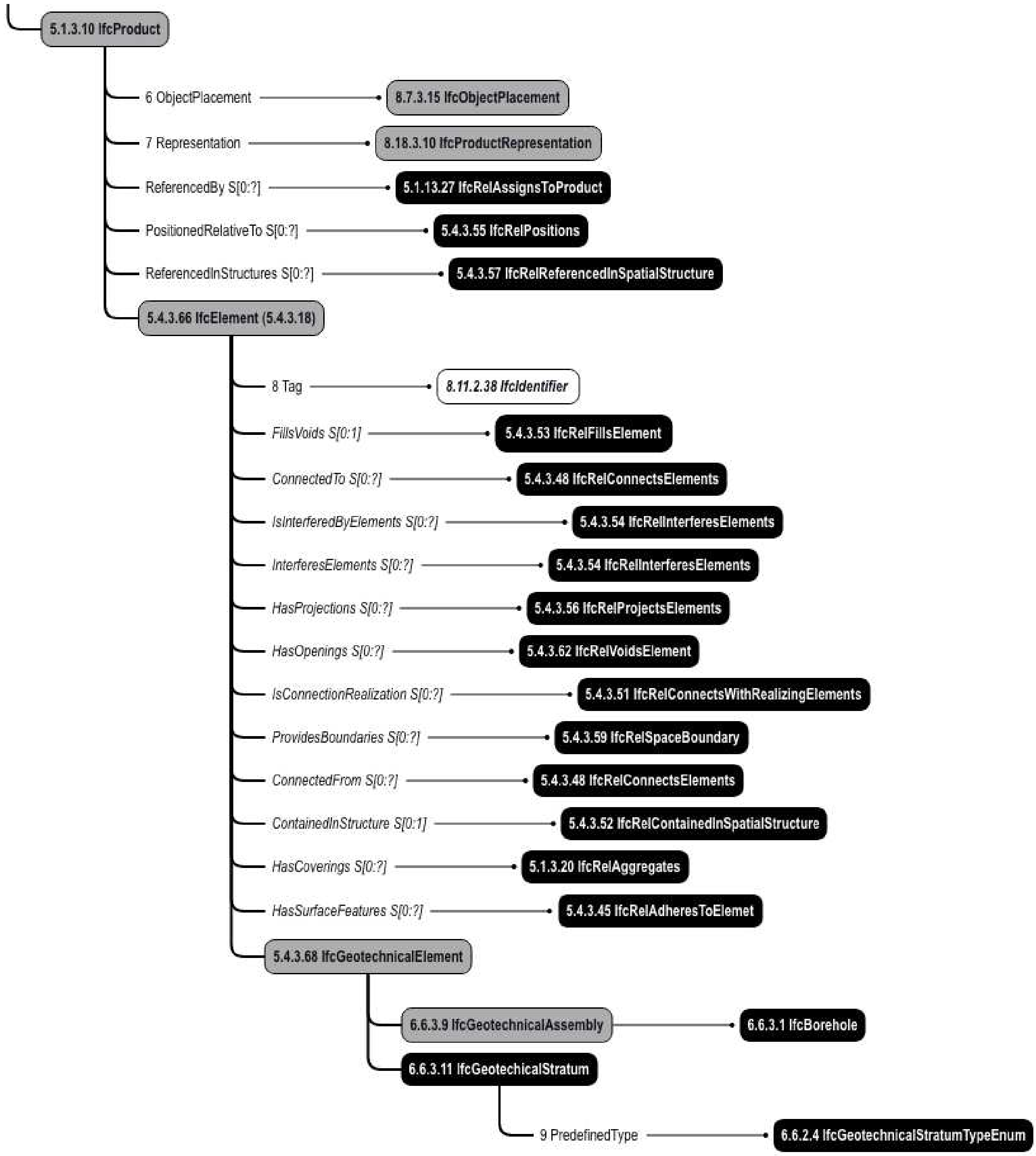
APPENDIX 5C: IfcSite Inheritance Diagram (from IfcProduct)



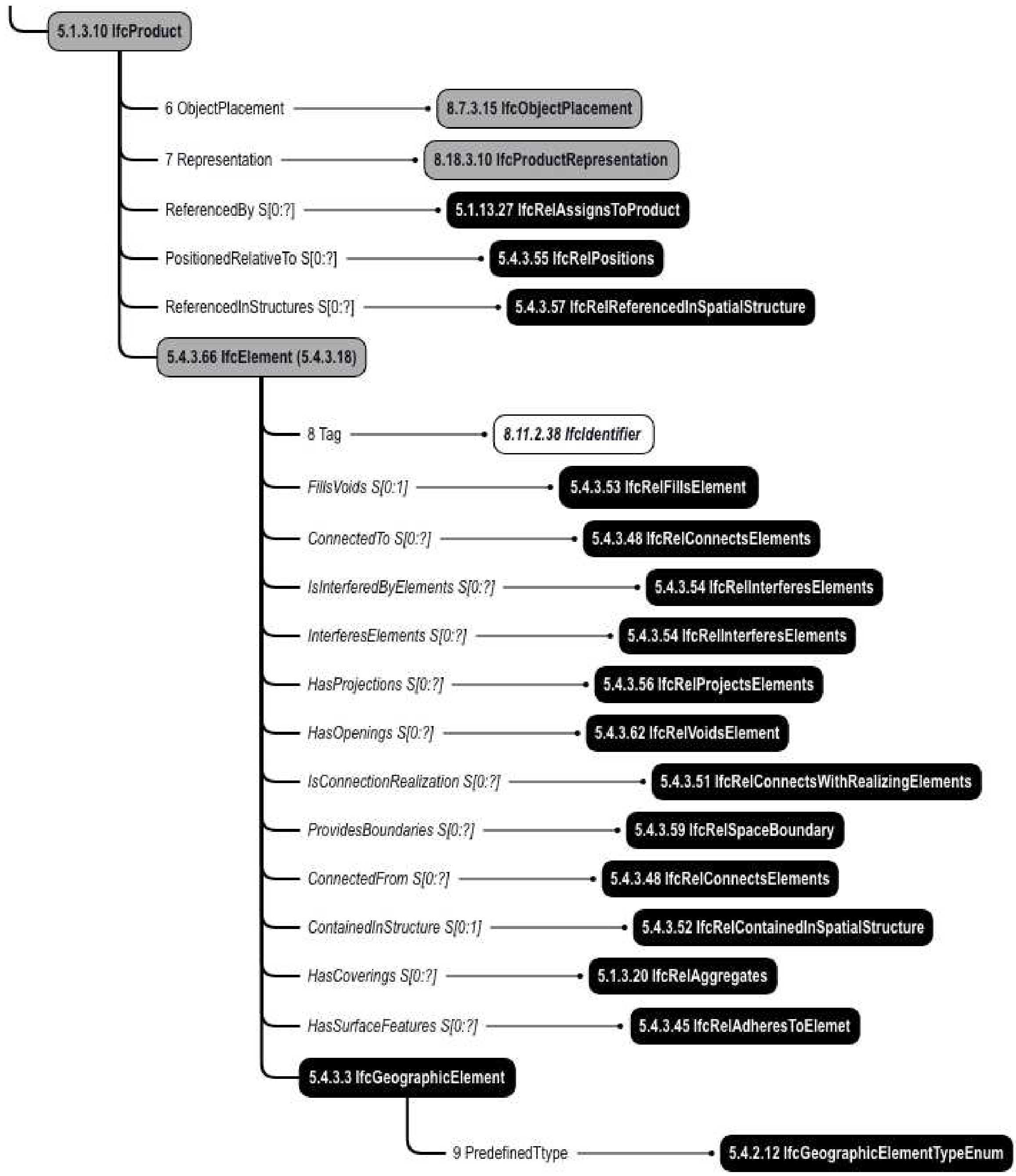
APPENDIX 5D: IfcGeoslice, and IfcGeotechnicalStratum Inheritance Diagram (from IfcProduct)



APPENDIX 5E: IfcBorehole, and IfcGeotechnicalStratum Inheritance Diagram (from IfcProduct)



APPENDIX 5F: IfcGeographicElement Inheritance Diagram (from IfcProduct)

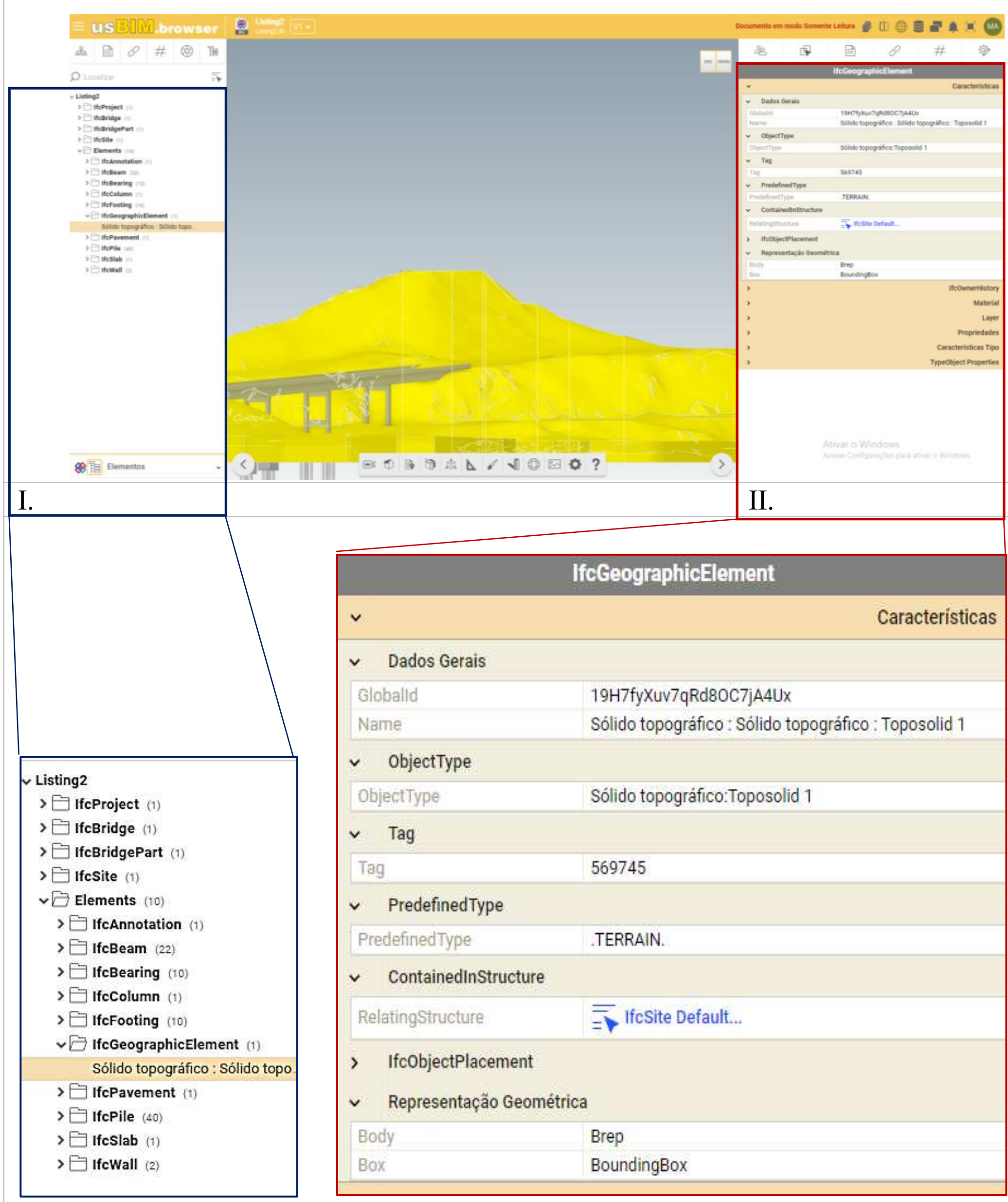


APPENDIX 5G: Validation_Report / Artifact A

GEOMETRIC / GEODETIC FRAMEWORK

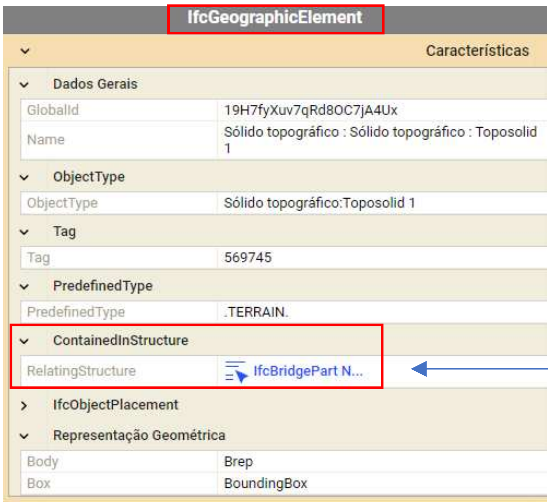
```
#28=IFCPROJECTEDCRS('EPSG:31983','Sirgas2000Zone23S','EPSG:4674','EPSG:5779HNOR_IMBITUBA',
'Universal
Transversal Mercator','23 South',#19);
#29=IFCMAPCONVERSION(#22,#28,728696.470,7693110.058,721.2959,0.97274,0.23186,$);
#32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'As-is bridge model',$,$,'','Operate',(#22,
#30),#121085);
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,(-20,-50,-52,-
901458),(-42,-48,-7,-905285),721.2959,$,$);
#150002=IFCRELCONTAINEDINSPATIALSTRUCTURE('0r1rWBp4959uhHNV5bdSUA',#18,$,$,(#119806),#43);
#119806=IFCGEOGRAPHICELEMENT('19H7fyXuv7qRd8OC7jA4Ux',#18,'Toposolid',$,'Toposolid1',
#83223,#119805,'569745',.TERRAIN.);
```

<u>IFC Spatial Structure</u>:

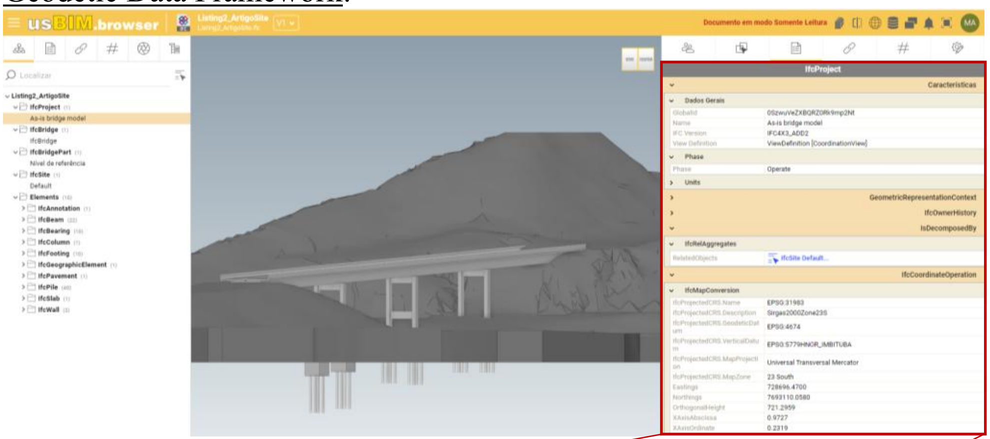


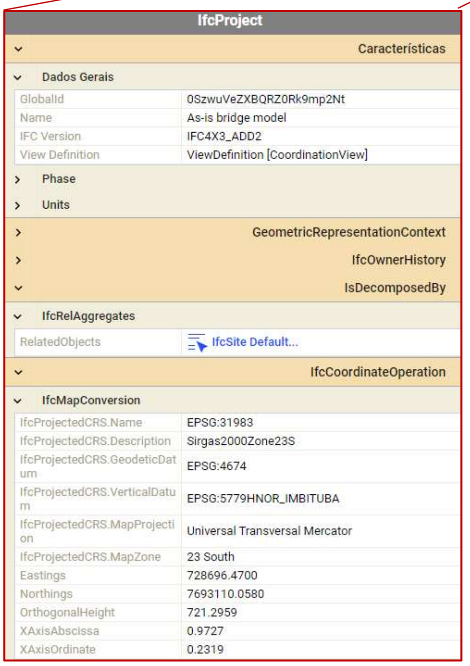
Status:
I. The representation does not follow the spatial structure defined by bSI;
II. The relationship between IfcGeographicElement and IfcSite was fully recognized.

Note for comparison: The original SPF (Listing 1) presented a spatial structure error [Relationship between IfcBridgePart and IfcGeographicElement].



Geodetic Data Framework:

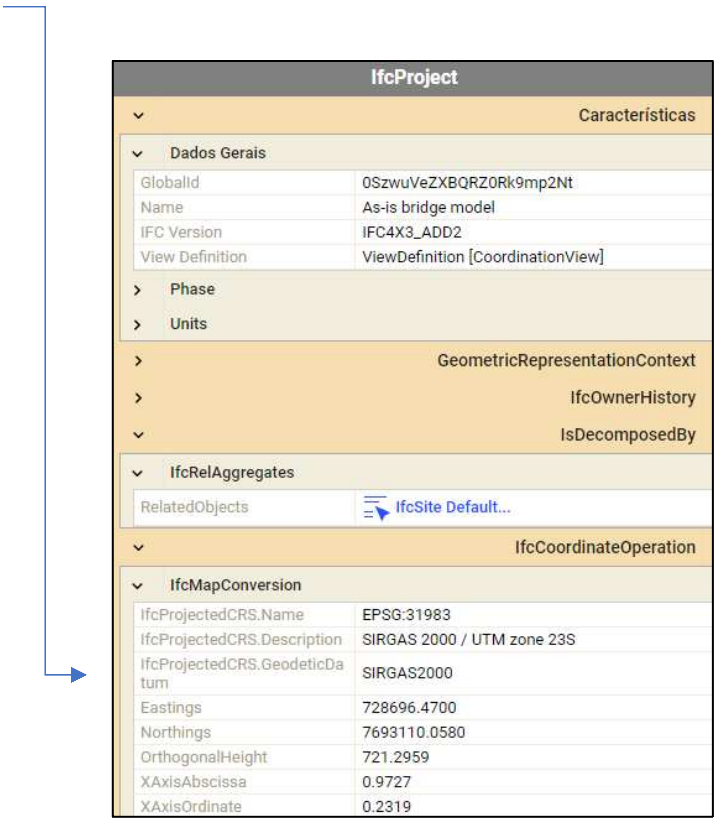




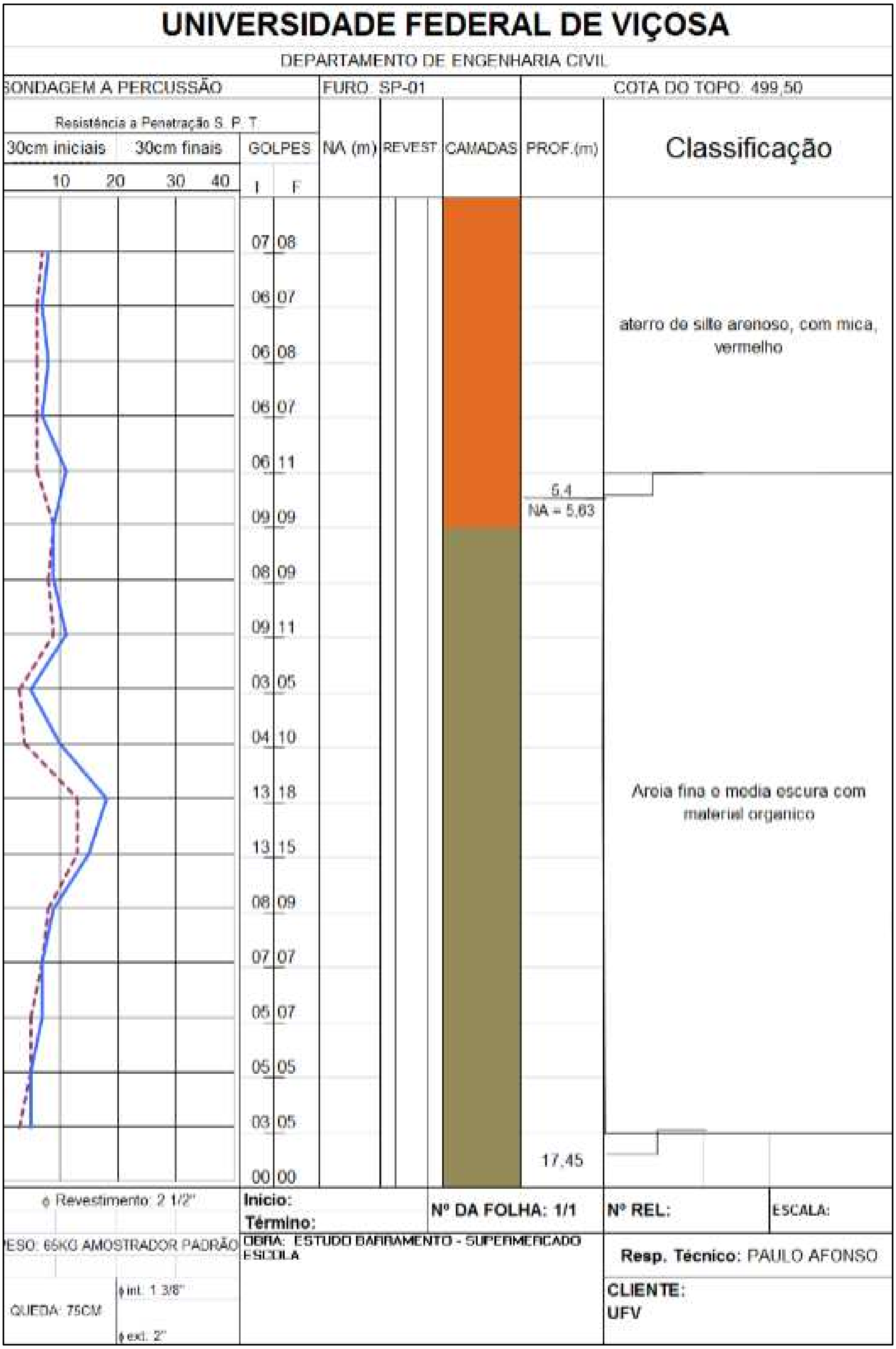
Status:

Geodetic framework was fully informed.

<u>Note for comparison:</u> IfcCoordinateOperation on the original SPF (Listing 1) not informed EPSG code of GeodeticDatum, EPSG code of VerticalDatum, MapProjetion, and MapZone attributes.



ATTACHMENT 5.1: Borehole Report



CAPÍTULO 6 - INFORMATION DELIVERY SPECIFICATION – IDS APPLIED TO THE AUTOMATED VERIFICATION OF PROJECT REQUERIMENTS

Este capítulo foi submetido em 30/01/2025 como um artigo em revista científica: Antunes, M. L. R.; Nunes, L. A.; Teixera, G. P.; Flores, D. A. N.; César Júnior, K. M. L.; Ribeiro, J. C. L.; Carvalho, J. M. F.; Oliveira, D.S. Information Delivery Specification – IDS applied to the automated verification of project requirements. ***Automation in Construction*** *(2025).*
https://dx.doi.org/10.2139/ssrn.5131256
Atualmente em processo de revisão.

Abstract

Information represents the primary target of a project throughout its lifecycle, serving as the foundational basis for decision-making processes and the development of new solutions. In a landscape where engineering increasingly needs to integrate technical performance with sustainability, the BIM system supported by the Industry Foundation Classes (IFC) data schema represents an innovation for bridge management. This study adopts the Design Science Research methodology to investigate the application of the Information Delivery Specification (IDS) in defining and validating the information requirements applied to a bridge model. The proposed approach ensures automated compliance with the spatial structure of the IFC leveraging its robust diversity. The results reveal the flexible nature of the neutral standard data as well as its potential to enhance the model's reliability. Furthermore, the study demonstrates the benefits of applying the IDS standard in the context of asset management, addressing practices that drive innovation in bridge engineering.

Keywords: Information. IFC Data Schema. Information Delivery Specification. Interoperability. Bridge Management.

6.1 Introduction

Technological innovation has added significant value to bridge management and maintenance processes through electronic databases aimed at developing models that enhance design, construction, and maintenance techniques [1,2]. Although this approach addresses a large part of the project life cycle, the lack of maintenance and intervention processes, which are a characteristic of the operational phase [3], represents one of the main causes of bridge collapses. These events may stem from internal and external origins. The qualitative context, combined with the quantitative scope of these assets, amplifies the challenges faced by bridge managers.

In this scenario, advancing the capability of computer modeling and analysis tools and techniques is clearly in the best interest of bridge engineering practice. Without consensus regarding standard data exchange protocols in the civil construction industry, there is no common way to integrate the bridge design and construction, or benefit from that information in the inspection, maintenance, and operational phases associated with its asset management [4].

Research has devoted considerable efforts to the field of Automated Compliance Checking (ACC). The knowledge generated enables access to automated verifications tailored to the specificities of organizations and projects, as well as a nation's codes and standards. This has been achieved through the maturation of parallel research fields aimed at meeting the sophisticated needs of ACC, with the OpenBIM standard representing one of them [5]. In this context, the digitization of data has been enabled with greater precision and agility, bringing the built environment into the same context as new developments.

Parametric technology, supported by the Object-Oriented Programming (OOP) paradigm and based on the Industry Foundation Classes (IFC) data structure, combined with multidisciplinary collaboration processes, represents a promising scenario for asset managers. One of the most relevant benefits to the construction industry is the accessibility of information both in the early phases of the project life cycle and during the operational phase, aiming for a sustainable context through asset control and monitoring [6,7].

Especially in governance, the BIM system has demonstrated consistent adherence due to its ability to promote neutrality and equity, as required by bidding processes, since it is based on OpenBIM interoperability [8]. In this context, tenders address information and interoperability requirements (Exchange Information Requirements - EIR) with the aim of meeting the specific needs of organizations (Organizational Information Requirements - OIR) and projects (Project Information Requirements - PIR) [9].

To legislate on terminology and standards used in the global construction industry, the regulatory framework, particularly ISO 19650-1; ISO 19650-2; ISO 16739-1; ISO 10303-11; ISO 10303-21 [10,11,12,13] has been widely referenced. In addition to the normative guidelines, bidding processes must include the BIM Execution Plan (BEP), clarifying the parameters that companies must meet in developing their respective proposals [14].

The human skills applied to manual verification and control processes may also pose an additional challenge for managers due to the vast array of information requirements involved in a single project, as well as the volume of bidding processes for built assets [15]. For this reason, the automated data validation enabled by the Information Delivery Specification (IDS) becomes essential in the procedural context. Developed by BuildingSMART (bSI), the IDS standard aims to facilitate communication between project teams and machines through the Xtended Markup Language (XML) format [16,17], thus serving as a link between the fields of collaboration and interoperability (Fig. 6.1).

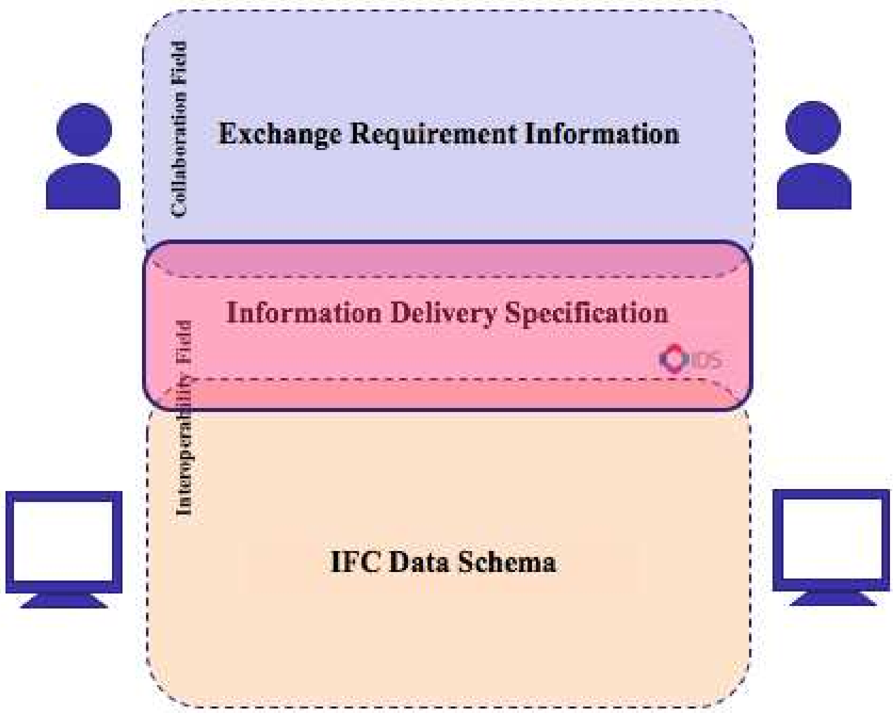


Fig. 6.1 IDS Interoperability
Source: the Author (2025)

In light of the Design Science Research (DSR) methodology, the primary objective of this study is to present the guidelines of the Information Delivery Specification (IDS) within the scope of the information requirements demanded by a bridge project that complies with the spatial structure of the IFC schema [IfcProject, IfcSite, IfcFacility, IfcBridge].

As the object of study, a bridge project managed under Brazilian governance was selected, considering the following specific objectives:

i. Schema and exchange analysis: Analyze the SPF to explore the IfcBridge framework;
ii. Gap analysis: Identify the gaps and develop a solution to address the requirements of the IFC4.3.2.0 spatial structure (Artifact A);
iii. Exchange requirements: Develop the IDS standard that enables automatic verification of requirements addressed by the frameworks specified by IfcProject, IfcSite, and IfcBridge (Artifact B) and validate it.

To mitigate the level of abstraction, inheritance diagrams of the entities involved are presented as supporting artifacts.

6.2 Background

6.2.1 IFC Spatial Structure

The spatial structure of the IFC schema establishes, at the highest hierarchical level, the entity IfcProject (a subtype of IfcContext), followed by IfcSite (a subtype of IfcProduct) [18]. These entities are foundational, as they define the geometric framework of the model, including internal origin coordinates, project base point coordinates, geodetic and geographic coordinates, as well as general aspects such as identification and financial information [19,20].

Starting from IfcSite, IfcFacility leaves room for instantiation of the asset in a broader context, which will subsequently be further specified. This organization was strategically designed to accommodate a considerable array of combinations, as one asset can be contained within another [21]. In this context, the CompositionType attribute is present in the data structure of both IfcFacility and its subtypes [IfcBuilding, IfcBridge, IfcRoad, IfcRailway, IfcMarineFacility]. It can clarify the context of the asset at stake through IfcElementCompositionEnum [`.COMPLEX.`,`.ELEMENT.`,`.PARTIAL.`].

For example, in the case of a bridge model: to provide a broader semantic context, the bridge also represents one of the segments of the roadway it is implemented. In this scenario, IfcFacility specifies the roadway as a set of segments `[.COMPLEX.]`.

Regarding this approach, IfcBridge declares the option `[.PARTIAL.]`, meaning a specific segment of the highway.

At the same time, each asset is composed of its respective parts, which vary according to functional specifics. To address this diversity, the FacilityPart attribute of the respective assets clarifies the nature of the part `[.LATERAL.,.LONGITUDINAL.,.VERTICAL.,.REGIONAL.,.USERDEFINED,.NOTDEFINED.]` by IfcFacilityUsageEnum [22].

This organization allows the structural elements of the bridge (IfcProduct Subtypes) to relate to their respective parts, as well as to establish geometric links through IfcLocalPlacement (Fig. 6.2).

IfcLocalPlacement is a critical entity in the IFC schema that defines the local coordinate system and placement of elements relative to other elements within the model. It ensures that each structural component is positioned correctly within the spatial context of the overall asset, enabling precise alignment and interaction among parts of the bridge model.

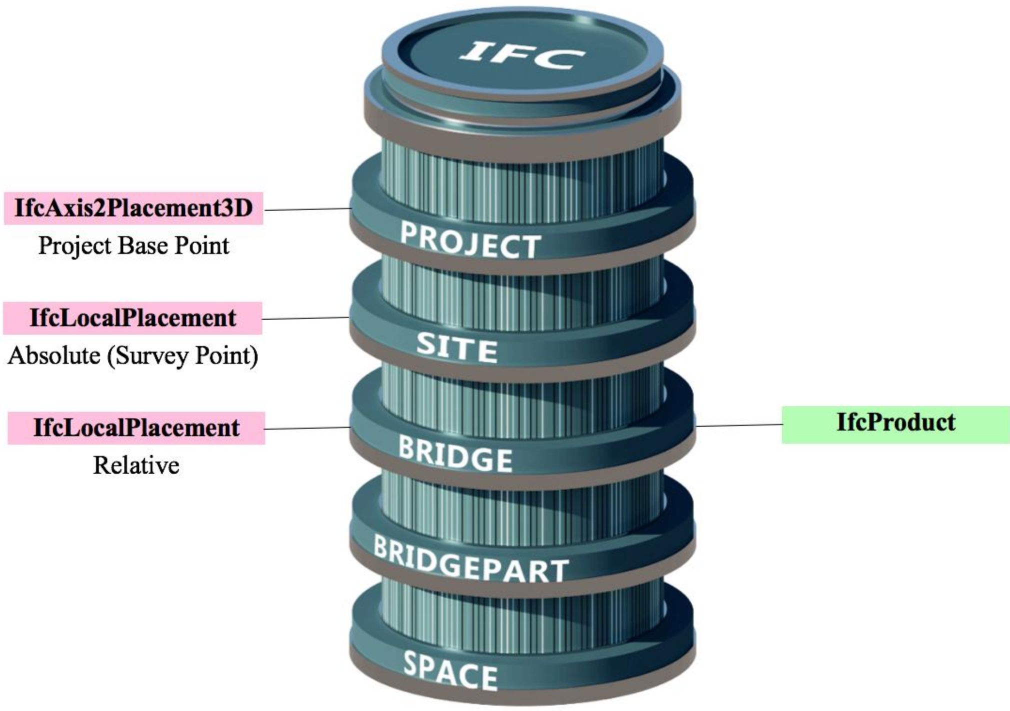


Fig. 6.2 IfcBridge on IFC Spatial Structure
Souce: the Author (2025)

The structural typology of bridges is informed by IfcBridge.PredifinedType [ARCHED.,.CABLE_STAYED.,.CANTILEVER.,.CULVERT.,.FRAMEWORK.,GIRDER.,.TRUSS., .SUSPENSION.,.USERDEFINED.,.NOTDEFINED.] through IfcBridgeTypeEnum [23]. The structural elements are specified by IfcBridgePart.PredefinedType through IfcBridgePartTypeEnum [.ABUTMENT.DECK.,.DECK_SEGMENT.,.FOUNDATION.,.PIER.,.PYLON., .PIER_SEGMENT.,.SUBSTRUCTURE.,.SUPERSTRUCTURE.,.SURFACESTRUCTURE.,.USERDEFINED., .NOTDEFINED.].

6.2.2 Information Delivery Specification

The interoperability resource defines information requirements in a computer-interpretable form for automated verification of IFC model compliance with data exchange requirements, which increases quality control and fidelity of data.

IDS also aids delivery of model data, by setting expectations and providing guidelines for what needs to be exchanged, the reason why it can auxiliary BIM actors to specify how objects, classifications, materials, properties, and values should be delivered in an IFC model.

The IDS files can be used to represent any exchange requirement that needs to be checked in the information exchange process. A specification is designed to be easy for humans to understand but is also highly structured so that computer software can automatically and accurately check information requirements with no ambiguity. Each specification has cardinality and needs to answer three contexts (Table 6.1).

Table 6.1 Specification

Specification	Description	Objective
Description (HOW)	Rationale for the specification and instructions of **how to achieve it**	Designed for humans to read and understand why information is being requested
Applicability (WHICH object)	**Identifies the subset** of the data that intends to specify	The subset can be identified via the available facet
Requirement (WHAT information)	Defines **what information** is required for the subset identified	Constraints that the model parts must fulfill to comply with the specification

Cardinality

minOccurs	maxOccurs	Type	Meaning
1	Unbounded	Required	Is required in the model
0	Unbounded	Optional	Expectations and value constraints are defined, but not obligatory
0	0	Prohibited	Cannot be present in the model

Source: the Author (2025)

Applicability and Requirements are described using a collection of Facets which describes information that a single entity may have. The six facets describe its information precisely using fixed Facet Parameters for precise machine understanding (Table 6.2).

Table 6.2 IDS Facets

Facet Type	**Facet Parameters**
Entity	IFC Class and Predefined Type
Attribute	Name and value
Classification	System and value
Property	Property Set, Name, and Value
Materials	Value
Parts	Entity and Relationship

Source: the Author (2025)

6.2.2.1 Information Requirements

Each specification can include data such as entities, attributes, properties, classification, materials, or more complex restrictions. Additionally, the first version IDS (v. 1.0) has proven to be a promising solution to civil construction, since vague constraints and complex constraints may represent a lack [24].

The IDS standard is particularly relevant for supporting the collaboration pillar of the BIM system and, in this context, aligns with the regulatory framework established by ISO 19650-2 which presents the Organization Information Requeriment (OIR), Project Information Requeriment (PIR), and Exchange Information Requeriment (EIR) to the development of Asset Model Information (AIM) [10].

6.3 Method

Initially, an in-depth investigation into the IFC schema was conducted to translate the identified problem of research semantically [25,26,27,28,29]. Gradually, the research was guided by mapping information requirements that organizations in developing bridge models may demand.

The IfcBridge (and IfcFacility) plus IfcBridgePart (and IfcFacilityPart) inheritance diagrams (Fig. 6.3 and Fig. 6.4) reveal the cardinality of the entity and represent auxiliary artifacts. The inheritance diagrams are prominently presented starting from IfcProduct and, as a reference, from the origin IfcRoot, detailed in Appendix 6A [20].

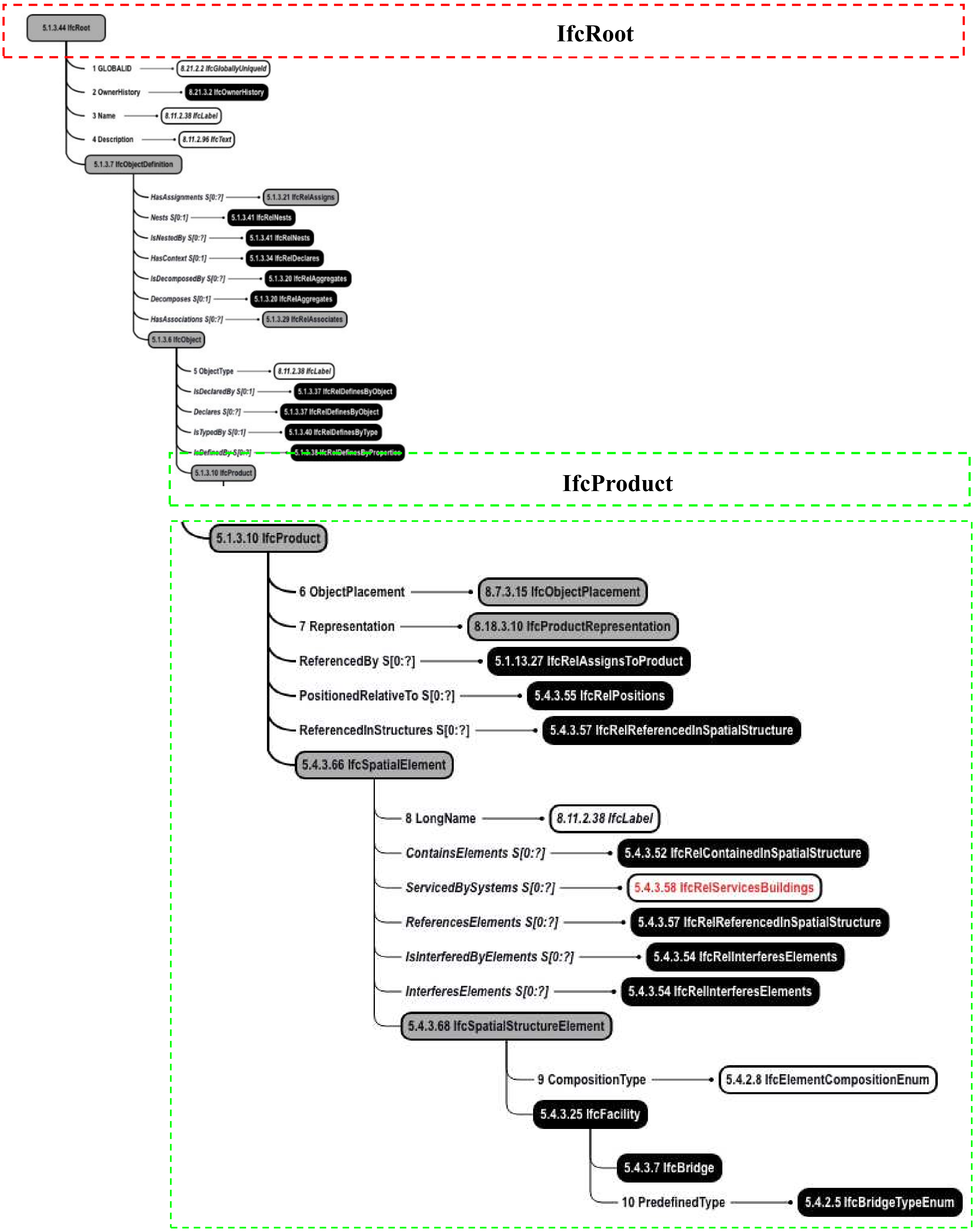


Fig. 6.3 IfcFacility and IfcBridge Inheritance Diagram
Source: the Author (2025)

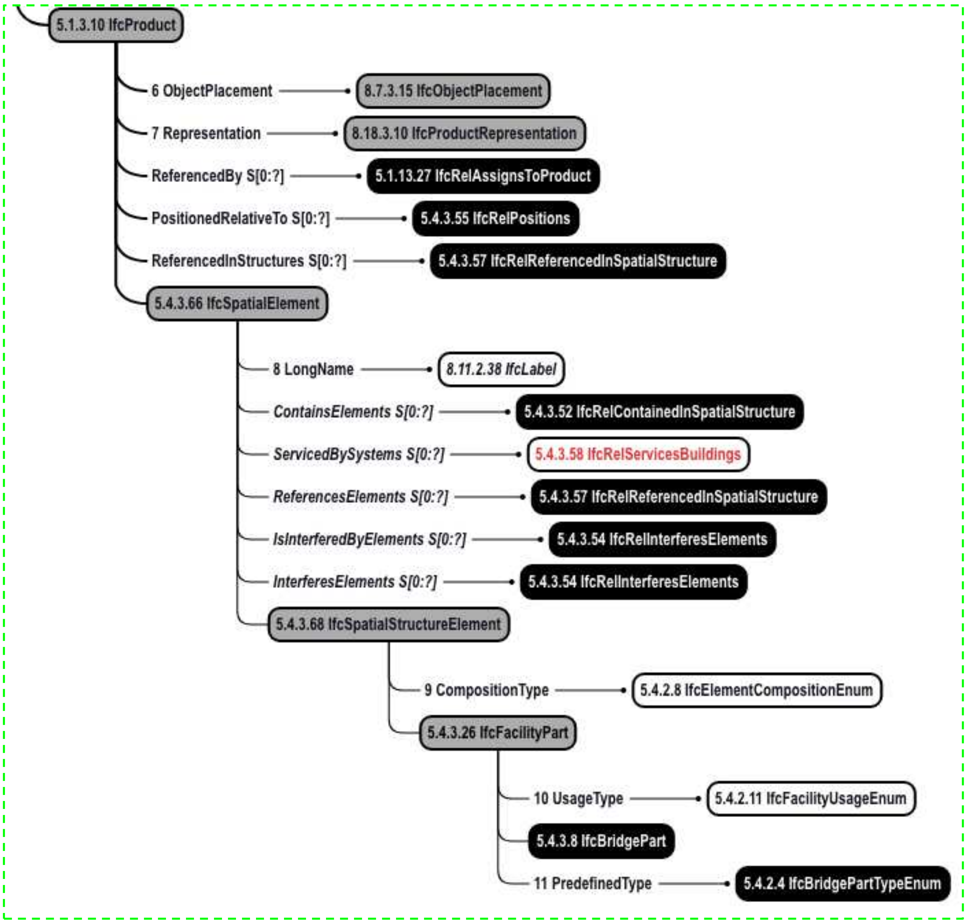


Fig. 6.4 IfcFacilityPart and IfcBridgePart Inheritance Diagram
Source: the Author (2025)

The IDS way allows anyone to create one IDS XML file, according to the IDS specification. Part of this structure is shown in Listing A.

Listing A

```
<ids:ids xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://standards.buildingsmart.org/IDS
http://standards.buildingsmart.org/IDS/1.0/ids.xsd"
xmlns:ids="http://standards.buildingsmart.org/IDS">
  <!--edited with usBIM.IDSeditor 2.2.29.0 (http://www.accasoftware.com)-->
  <ids:info>
    <ids:title>IDS_Identification</ids:title>
    <ids:version>1.0</ids:version>
    <ids:author>lnunes1412@gmail.com.br</ids:author>
    <ids:purpose>Identification data specification</ids:purpose>
  </ids:info>
  <ids:specifications>
    <ids:specification ifcVersion="IFC4X3_ADD2" name="Identification">
      <ids:applicability minOccurs="1" maxOccurs="unbounded">
        <ids:entity>
          <ids:name>
            <ids:simpleValue>IFCPROJECT</ids:simpleValue>
```

6.3.1 Objects of Study

To address specific objectives, the scenario was inspired by a real demand experienced by a Brazilian public organization that requires the contracting of infrastructure projects [30]. The contract object target is a bridge model called Coimbra I, located on the BR-120 highway state of Minas Gerais (Brazil).

6.3.1.1 Object of study A – SPF from Model View Definition

The configuration in the session, offered by the Revit (v. 2025) software in the [IFC4x3] MVD option [31], allows the modeler to select the respective type of facility `[Bridge]` (Fig. 6.5) in addition to clarifying the bridge typology `[.GIRDER.]`.

Part of the SPF file generated is presented in 1st and 2nd order, minimally when relevant to the analysis, due to its extent (Listing 6.1).

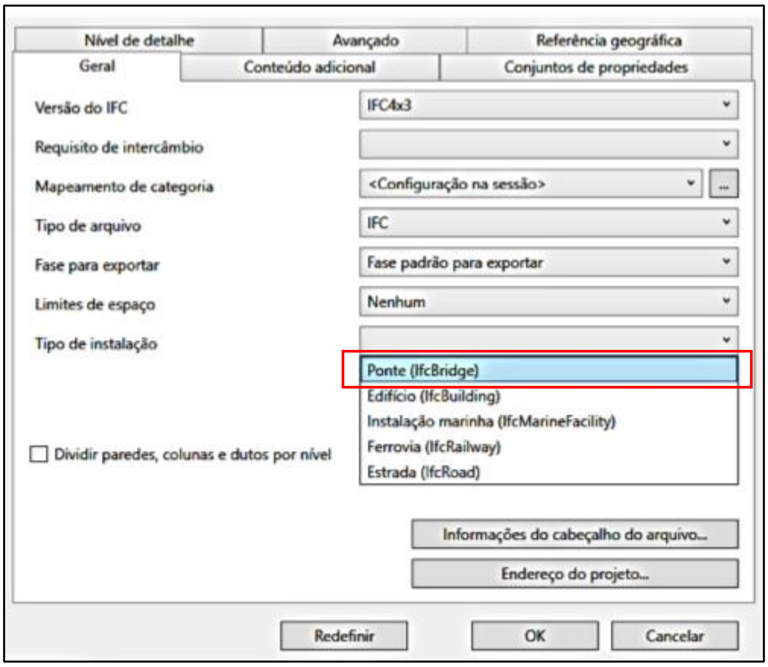


Fig. 6.5 Configurated MVD
Source: Revit (adjusted)

The IFC spatial structure entities have a background highlight in green color and a global identifier in blue.

Listing 6.1 – Original SPF

```
ISO-10303-21;
HEADER;

DATA;
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,#17,$,1726701698);
#22=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#20,#21);
#30=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',3,1.0E-5,#20,#21);
#32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2023-46','Hiring of
service for the development of the As-is Model of the Coimbra I
bridge',$,$,'Operation',(#22,#30),#121085);
#35=IFCLOCALPLACEMENT(#42,#34);
#36=IFCBRIDGE('0SzwuVeZXBQRZ0Rk9mp2Ns',#18,'',$,$,#35,$,'',.ELEMENT.,.GIRDER.);
#39=IFCLOCALPLACEMENT(#35,#38);
#40=IFCBRIDGEPART('3kSL0VGKv3gxJCujeqtuJj',#18,'Reference level',$,$,#39,$,
'Reference Level',.ELEMENT.,$,$);
#42=IFCLOCALPLACEMENT($,#41);
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-7,-605285),721.2959,$,$);
#119939=IFCRELAGGREGATES('3$Y$m$roJ8zwX_N7i2$VCx',#18,$,$,#32,(#43));
#119940=IFCRELAGGREGATES('1nwXrv5VLF2rwGZZfODt$G',#18,$,$,#43,(#36));
#119941=IFCRELAGGREGATES('0bEVwXRmbBleAvzFSJirAn',#18,$,$,#36,(#40));


END SEC
END-ISO-10303-21;
```

6.3.1.2 Object of Study B

The second artifact refers to IDS development aligned to IFC spatial structure of a bridge infrastructure project. For full contextualization, Artifact B need firstlly consider Project and Site frameworks explored in two papers [19,20] that use the same bridge model (Listing 6.2).

Listing 6.2

```
ISO-10303-21;
HEADER;

DATA;
/*IfcProject= Identification, Geometric and Units, Financial Frameworks*/
#3=IFCCARTESIANPOINT((0.,0.,0.));
#18=IFCOWNERHISTORY(#17,#2,$,.NOCHANGE.,$,#17,$,1726599618);
#19=IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#20=IFCAXIS2PLACEMENT3D(#3,$,$);
#21=IFCDIRECTION((0.23186,0.97274));
#22=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#20,#21);
#27=IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#28=IFCPROJECTEDCRS('EPSG:31983','Sirgas2000Zone23S','EPSG:4674',
'EPSG:5779HNOR_IMBITUBA','Universal Transversal Mercator','23 South',#19);
#29=IFCMAPCONVERSION(#22,#28,728696.470,7693110.058,721.2959,0.97274,
```

```
0.23186,$);
#30=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Plan',3,1.01E-5,#20,#21);
#32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2023-46','Hiring of
service for the development of the As-is Model of the Coimbra I
Bridge',$,$,'Operation',(#22,#30),#121085);
/*IfcSite= Geographic and Geodesic Frameworks*/
#42=IFCLOCALPLACEMENT($,#41);
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-07,-605285),721.2959,$,$);
#119939=IFCRELAGGREGATES('3$Y$m$roJ8zwX_N7i2$VCx',#18,$,$,#32,(#43));
#121085=IFCUNITASSIGNMENT((#19,#73,#74,#255,#119884,#119887,#119892,
#120623,#120637,#120644,#120650,#120656,#120660,#120666,#120669,#150003));
#800001=IFCPROPERTYENUMERATEDVALUE('ProjectType',$,(IFCPROPERTYENUMERATION(.OPERATI
ONMAINTENANCE.)),$);
#800003=IFCPROPERTYSINGLEVALUE('FundingSource',$,IFCLABEL('Resource from the
Ministery of Transport'),$);
#800004=IFCPROPERTYSET('0S3JFtqoD4CAgDGe3IafZV',#18,'Pset_ProjectCommon',$,(#800001
,#800003));
#800005=IFCRELDEFINESBYPROPERTIES('0kMl4E8H1E_h3yCPd6IE1J',#18,$,$,(#32),
#800004);

END SEC
END-ISO-10303-21;
```

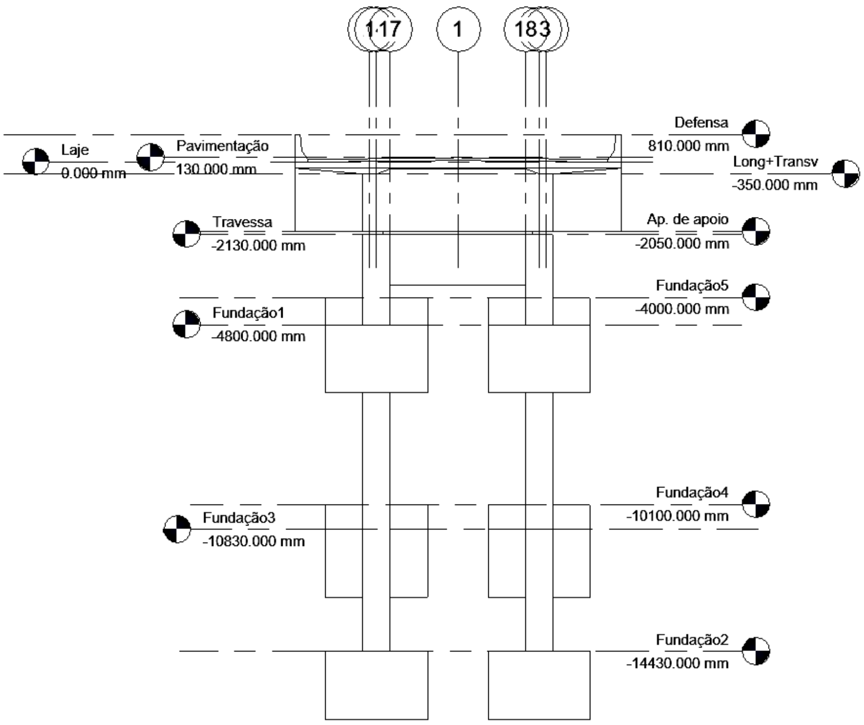
The data envolved of three frameworks specified by IfcProject, IfcSite and IfcBridge (Artifact A) represent the object of study to Artifact B development.

Constructing a solution (Artifact A)

The interventions were manually developed in response to the lack identified on spatial structure of bridge model. The Original SPF reveals the semantics of the bridge viewed as a standalone asset, consisting of a single part. Aiming for the semantic context that encompasses the bridge as part of a roadway, in addition to its respective parts, the Python console of the BonsaiBIM software [32], and IfcOpenShell [33] were used for the creation of the global identifier for the new entity occurrences.

According to the scenario where the bridge model is implemented, IfcFacility was instantiated `[#130000]` specifying the federal roadway `[BR-120]` managed by the contracting organization. The Brazilian standards classify the built elements of a bridge into Superstructure, Mesostructure (Substructure), and Infrastructure (Foundation). IfcBridgePart is the entity able to specify the respective parts (levels) of a bridge.

Figure 6.6 presents the bridge model levels (parts) and the respective eleven instances of IfcBridgePart, and Figure 6.7 reveals the IFC spatial structure applied.



#	Instances of IfcBridgePart
140000	('0zUiJQp5fChQE4cc0C9H23',#18,'Fundacao1',$,$,#46,$,$,.ELEMENT.,.VERTICAL., .FOUNDATION.)
140001	('2gmq8ydkP4CQ$EGa1PIYUU',#18,'Fundacao2',$,$,#34,$,$,.ELEMENT.,.VERTICAL., .FOUNDATION.)
140002	('2EUxG3HsjA7OgdakKc1wM$',#18,'Fundacao3',$,$,#38,$,$,.ELEMENT.,.VERTICAL., .FOUNDATION.)
140003	('2EUxG3HsjA7OgdakKc1w89',#18,'Fundacao4',$,$,#42,$,$,.ELEMENT.,.VERTICAL., .FOUNDATION.)
140004	('1Noy9Vwsf7o8wamnn124Tp',#18,'Fundacao5',$,#50,$,$,.ELEMENT.,.VERTICAL., .FOUNDATION.)
140005	('2dJ4yhxBHBNPb4vLiG84ns',#18,'Travessa or Pier Cap and Colum',$,$,#54, $,$,.ELEMENT., .VERTICAL.,.SUBSTRUCTURE.)
140006	('2dJ4yhxBHBNPb4vLiG84eL',#18,'Aparelho de Apoio or Bearing and Retaining Wall',$,$,#58,$,$, .ELEMENT.,.LONGITUDINAL.,.SUBSTRUCTURE.)
140007	('2dJ4yhxBHBNPb4vLiG84SB',#18,'Long+Transv or GirderSegment+Diapragm', $,$,#62,$,$,.ELEMENT.,.LONGITUDINAL.,.SUPERSTRUCTURE.)
140008	('3Aw$FV5MbAufEo59pkoNgA',#18,'Laje or Slab',$,$,#65,$,$,.ELEMENT. ,.LONGITUDINAL.,.SUPERSTRUCTURE.)
140009	('2dJ4yhxBHBNPb4vLiG84Rn',#18,'Pavimentacao or Pavement',$,$,#69,$,.ELEMENT. ,.LONGITUDINAL.,.SUPERSTRUCTURE.)
140010	('2dJ4yhxBHBNPb4vLiG84Fu',#18,'Defensa or Parapet',$,$,#73,$,$,.ELEMENT. ,.LONGITUDINAL., .SUPERSTRUCTURE.)

Fig. 6.6 IfcBridgePart
Source: the Author (2025)

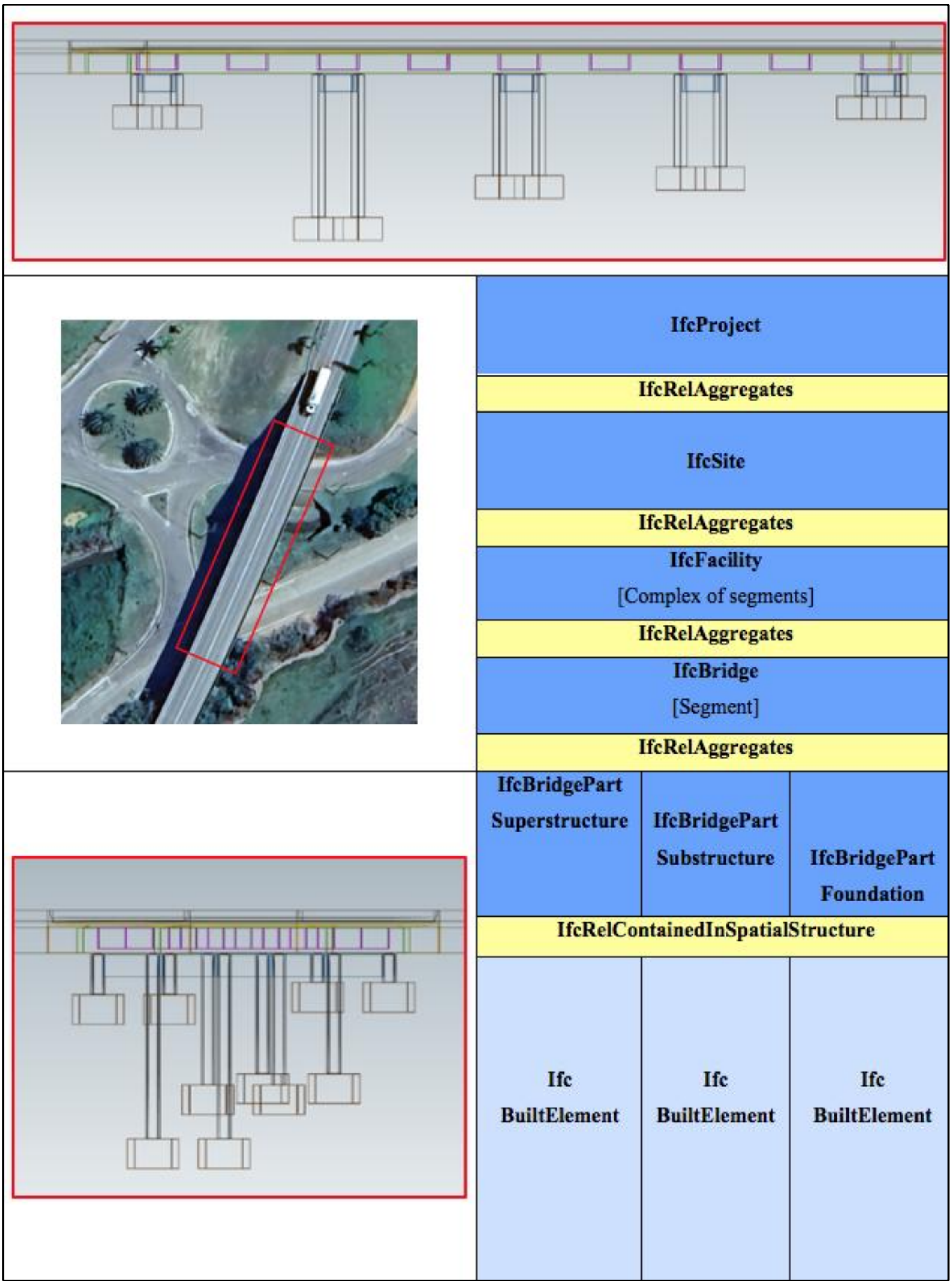


Fig. 6.7 Main spatial structure of a bridge
Source: the Author (2025)

The built elements are specified according to the semantics of a bridge model (Table 6.3). The IfcRelContainedInStructural specifies the relationship between the built element instances and the respective parts of a bridge.

Table 6.3 Built Elements

BuiltElements	Semantic	Instances	IfcBridgePart
IfcFooting	.PILE_CAP.	[#995,#1026,#1056,#1087,#1117,#1148,#1178, #1209,#1239,#1270]	.FOUNDATION.
IfcColumn	.COLUMN.	[#609,#640,#669,#700,#729,#760,#789,#820, #849,#880]	.SUBSTRUCTURE.
IfcBearing	.ELASTOMERIC.	[#972,#1300,#1322,#1344,#1366,#1388,#1410, #1432,#1454,#1476]	.SUBSTRUCTURE.
IfcBeam	.PIERCAP.	[#522,#538,#552,#566,#580]	.SUBSTRUCTURE.
	.DIAPRAGM.	[#378,#394,#408,#422,#436,#450,#464,#478,#492]	.SUPERSTRUCTURE.
	.GIRDERSEGMENT.	[#333,#349]	.SUPERSTRUCTURE.
IfcSlab	.FLOOR.	[#301]	.SUPERSTRUCTURE.
IfcPavement	.FLEXIBLE.	[#918]	.SUPERSTRUCTURE.
IfcWall	.PARAPET.	[#133,#265]	.SUPERSTRUCTURE.
	.RETAININGWALL.	[#936,#1491]	.SUBSTRUCTURE.

Source: the Author (2025)

Constructing a solution (Artifact B)

Aiming at the development of the IDS standard, the software usBIM.IDSeditor (v. 2.2.29.0) was used [34]. Through the filter feature, the specifications for the respective IFC classes were created, ensuring that the information requirements demanded by the managing organization (OIR) were provided.

Through the commands 'MUST HAVE', 'MAY HAVE', and 'MUST NOT HAVE', requirements related to the respective frameworks were assigned to the entities and/or properties.

Under the identification framework established by IfcProject, the context of project identification and general financial data for the tendered project and its respective process were specified. In this scenario, attributes were defined, and the values requested by the asset-managing organization were assigned. Table 6.4 describes the Identification framework specified by IfcProject [19] represented by Listing 2.3 (Chapter 2).

Considering the context of the Geometric framework, the filter was applied to the entity IfcGeometricRepresentationContext**,** imposing the respective values required by the bridge model and the organization. The TrueNorth attribute value informed corresponds to information added on the software interface (decimal format). The international system of units standardized in the country managing the project, including the financial unit, was specified. Instances of IfcSIUnit should clarify, through the Name attribute, values to identify the units in question. Table 6.5 presents the Geometric and Units framework specified by IfcProject, represented by Listing 2.3.

Table 6.4 Identification and Financial framework

Framework	Specification	
	Filter by IFC Class	**MEET the following requirements**
Identification	MUST contain Entity IFCPROJECT	**for attribute** ✓ MUST HAVE Name = '23114.907605/2023-46' ✓ MUST HAVE Description = 'Hiring of service for the development of the As-is Model of the Coimbra I bridge' ✓ MUST HAVE Phase = 'Operation'
Financial	MUST contain Property set PROJECTCOMMON	**for property** ✓ MUST HAVE ProjectType of PSet Pset_ProjectCommon (IFCLABEL) = .OPERATIONMAINTENANCE. ✓ MUST HAVE FundingSource of PSet Pset_ProjectCommon (IFCLABEL) = 'Resource from the Ministry of Transport'

Source: the Author (2025)

Table 6.5 Geometric and Units Framework

Framework	Specification	
	Filter by IFC Class	**MEET the following requirements**
Geometric	MUST contain Entity IFCGEOMETRIC REPRESENTATION CONTEXT	**for attribute** ✓ MUST HAVE ContextType = 'Model' ✓ MUST HAVE Precision = 1.0E-5 ✓ MUST HAVE CoordinateSpaceDimension = 3 ✓ MUST HAVE WorldCoordinateSystem [Project Base Point and Survey point should be coincidental] MUST HAVE TrueNorth = [-13.4068]
Units	MUST contain Entity IFCSIUNIT	**for attribute** ✓ MUST HAVE Name = .METRE.
		for attribute ✓ MUST HAVE Name = .SQUARE_METRE.
		for attribute ✓ MUST HAVE Name = .CUBIC_METRE.
		for attribute ✓ MUST HAVE Prefix = .KILO. ✓ MUST HAVE Name = .GRAM.
		for attribute ✓ MUST HAVE Name = .RADIAN.
	MUST contain Entity IFCCONVERSION BASEDUNIT	**for attribute** ✓ MUST HAVE UnitType = .PLANEANGLEUNIT. ✓ MUST HAVE Name = 'DEGREE'
	MUST contain Entity IFCMONETARY UNIT	**for attribute** ✓ MUST HAVE Currency = 'BRL'

Source: the Author (2025)

The angle of the true north of a Project `[-13.4068]` may inform directly on the software interface. This precise information is relevant because it impacts IfcGeometricRepresentationContext.TrueNorth and IfcMapConversion specifications.

Another pertinent observation is about WorldCoordinateSystem, an obrigatory attribute (specified by IfcAxis2Placement) which refers to the engineering coordinate system (Project Base Point).

Aligned with bSI documentation, the preferred practice refers to this point may be coincidental to the survey point, specified by IfcSite [35] (Listing 5.2 – Chapter 5). For these reasons, the global localization of a project (including EPSG code) and engineering coordinate system may established by OIR.

Table 6.6 describes the Geographic framework specified by IfcSite and the inter-relation between Geometric and Geodesic framework [20]. Aiming at the Geodetic framework of the model, the filter was applied to the IfcProjectedCRS entity (aligned with the specifications presented by the organization), including the datum involved in the geodetic reference system of a Project).

Table 6.6 Geodesic and Geographic Framework

Framework	Specification	
	Filter by IFC Class	**MEET the following requirements**
Geodesic	IFCPROJECTEDCRS	**for attribute** ✓ MUST HAVE Name = 'EPSG:31983' ✓ MUST HAVE Description = 'SIRGAS 2000 / UTM zone 23S' ✓ MUST HAVE GeodeticDatum = 'SIRGAS2000' ✓ MUST HAVE VerticalDatum = 'HNOR_IMBITUBA EPSG:5779' ✓ MUST HAVE MapZone = '23S'
Geographic	IFCSITE	**for attribute** ✓ MUST HAVE RefLatitude = [-20,-50,-52,-901458] ✓ MUST HAVE RefLongitude = [-42,-48,-07,-605285] ✓ MUST HAVE RefElevation = 721.2959 **for relationship** ✓ MUST HAVE IFCRELAGGREGATES with IFC class IFCPROJECT

Source: the Author (2025)

According to the OIR, the contextualization of the bridge implementation concerning the infrastructure project, IfcFacility.Name should specify the roadway `['BR-120 Road']`, Description attribute should provide more details such as `['BR 120 km x to km y']`, and CompositionType should clarify `[.COMPLEX.]` meaning a road infrastructure made up of several segments, one of which is represented by the bridge model.

Aligned with the PIR context, IfcBridge, as a subtype of IfcFacility, the CompositionType attribute should specify `[.PARTIAL.]` (Table 6.7). The Name attribute should specify the bridge identification `['Coimbra I Bridge']`, and PreDefinedType should define the respective structural typology, which in the case being studied is `[.GIRDER.]`.

Table 6.7 Bridge framework

<table>
<tr><th rowspan="2">Framework</th><th colspan="2">Specification</th></tr>
<tr><th>Filter by IFC Class</th><th>MEET the following requirements</th></tr>
<tr><td rowspan="5">Bridge</td><td>IFCFACILITY</td><td>for attribute
✓ MUST HAVE Name = 'BR120 Road'
✓ MUST HAVE Description = 'BR120 km x to km y'
✓ MUST HAVE CompositionType = .COMPLEX.
for relationship
✓ MUST HAVE relationship IFCRELAGGREGATES with IFC class IFCSITE</td></tr>
<tr><td>IFCBRIDGE</td><td>for attribute
✓ MUST HAVE Name = 'Coimbra I Bridge'
✓ MUST HAVE CompositionType = .PARTIAL.
✓ MUST HAVE PredefinedType = .GIRDER.
for relationship
✓ MUST HAVE relationship IFCRELAGGREGATES with IFC class IFCFACILITY</td></tr>
<tr><td>IFCBRIDGEPART</td><td>for attribute
✓ MUST HAVE Name = 'Name of each object referenced in Superstructure'
✓ MUST HAVE CompositionType = .ELEMENT.
✓ MUST HAVE FacilityPart = .LONGITUDINAL.
✓ MUST HAVE PredefinedType = .SUPERSTRUCTURE.
for relationship
✓ MUST HAVE relationship IFCRELAGGREGATES with IFC class IFCBRIDGE
✓ MUST HAVE relationship IFCRELCONTAINEDINSPATIALSTRUCTURE with IFC class IFCBEAM, IFCSLAB, IFCPAVEMENT, IFCWALL</td></tr>
<tr><td>IFCBRIDGEPART</td><td>for attribute
✓ MUST HAVE Name = '*Name of each object referenced in Substructure*'
✓ MUST HAVE CompositionType = .ELEMENT.
✓ MUST HAVE FacilityPart = .VERTICAL.
✓ MUST HAVE PredefinedType = .SUBSTRUCTURE.
for relationship
✓ MUST HAVE relationship IFCRELAGGREGATES with IFC class IFCBRIDGE
✓ MUST HAVE relationship IFCRELCONTAINEDINSPATIALSTRUCTURE with IFC class IFCCOLUMN, IFCBEAM, IFCBEARING, IFCWALL</td></tr>
<tr><td>IFCBRIDGEPART</td><td>for attribute
✓ MUST HAVE Name = '*Name of each object referenced in Foundation*'
✓ MUST HAVE CompositionType = .ELEMENT.
✓ MUST HAVE FacilityPart = .VERTICAL.
✓ MUST HAVE PredefinedType = .FOUNDATION.
for relationship
✓ MUST HAVE relationship IFCRELAGGREGATES with IFC class IFCBRIDGE
✓ MUST HAVE relationship IFCRELCONTAINEDINSPATIALSTRUCTURE with IFC class IFCFOOTING</td></tr>
</table>

Source: the Author (2025)

To address the semantics of the parts that make up the bridge, the model must contain instances of IfcBridgePart that are consistent with the legislation applied by the organization (OIR). In the case under study, the PredefinedType attribute may be `[.SUPERSTRUCTURE.]`, `[.SUBSTRUCTURE.]` or `[.FOUNDATION.]`. When `[.SUPERSTRUCTURE.]` the FacilityPart attribute should specify `[.LONGITUDINAL]`, and `[.SUBSTRUCTURE.]` or `[.FOUNDATION.]` should specify `[.VERTICAL.]`. In both cases, the FacilityPart attribute should specify `[.ELEMENT.]`.

6.4 Results

6.4.1 Artifact A

Listing 6.3 is a part of SPF including the Bridge framework. The insertions were highlighted in red to show the new instances of entities and relationships addressing an IFC spatial structure applied to a bridge Project, and respective built elements (Table 6.3).

Listing 6.3

```
ISO-10303-21;
HEADER;

DATA;
32=IFCPROJECT('0SzwuVeZXBQRZ0Rk9mp2Nt',#18,'23114.907605/2023-46', 'Hiring of
service for the development of the As-is Model of the Coimbra I bridge',$,$,
'Operation',(#22,#30),#121085);
...
/*IfcFacility added to clear the implementation context of a bridge*/
#130000=IFCFACILITY('0g989M915Byu9Dkklk2b0p',#18,'Coimbra I Bridge','BR-120 Road km
x to km y', $,$,$,$,.COMPLEX.);
...
#36=IFCBRIDGE('0SzwuVeZXBQRZ0Rk9mp2Ns',#18,'Coimbra I Bridge',$,$,#35,$,'Coimbra I
Bridge',.PARTIAL.,.GIRDER.);
...
/*#140000 to #140010=IFCBRIDGEPART */
...
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',#18,'Default',$,$,#42,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-7,-605285),721.2959,$,$);
...
#119939=IFCRELAGGREGATES('3$Y$m$roJ8zwX_N7i2$VCx',#18,$,$,#32,(#43));
#119941=IFCRELAGGREGATES('0bEVwXRmbBleAvzFSJirAn',#18,$,$,#36,(#140000,#140001,
#140002,#140003,#140004,#140005,#140006,#140007,#140008,#140009,#140010));
#145000=IFCRELAGGREGATES('2yGizieaPEJ85Y$Oq2F5If',#18,$,$,#130000,(#36));
#160000=IFCRELAGGREGATES('3wI$Yk_InC7QVzRcm2rjJQ',#18,$,$,#43,(#130000));
#170000=IFCRELCONTAINEDINSPATIALSTRUCTURE('33DEcqSgL4Sf8WnKElF8SI',#18,$,$,(#995,
#1026),#140000);
#170001=IFCRELCONTAINEDINSPATIALSTRUCTURE('2kYRh320f1OurZYbTmwGT9',#18,$,$,(#1056,
#1087,#140001);
#170002=IFCRELCONTAINEDINSPATIALSTRUCTURE('1dZImZNq53VBaPhamQfDTQ',#18,$,$,(#1117,
#1148),#140002);
#170003=IFCRELCONTAINEDINSPATIALSTRUCTURE('3tVlSyfnTDqR8e7ToubqRb',#18,$,$,(#1178,
#1209),#140003);
#170004=IFCRELCONTAINEDINSPATIALSTRUCTURE('3RHXpEYeT1Rwu78pvaXV2M',#18,$,$,(#1239,
#1270),#140004);
#170005=IFCRELCONTAINEDINSPATIALSTRUCTURE('1EqHmTOK563PjgeUZatnri',#18,$,$,(#609,
#640,#669,#700,#729,#760,#789,#820,#849,#880,#522,#538,#552,#566,#580),#140005);
#170006=IFCRELCONTAINEDINSPATIALSTRUCTURE('0I0XNq9sr7JQ44e_Ffl2u9',#18,$,$,(#972,
#1300,#1322,#1344,#1366,#1388,#1410,#1432,#1454,#1476,#936,#1491),#140006);
```

```
#170007=IFCRELCONTAINEDINSPATIALSTRUCTURE('2GZFkIpMr1wgazLMDwsMRf',#18,$,$,(#378,
#394,#408,#422,#436,#450,#464,#478,#492,#333,#349),#140007);
#170008=IFCRELCONTAINEDINSPATIALSTRUCTURE('3YAWF_fkH0ix5PGo4vxz9b',#18,$,$,(#301),
#140008);
#170009=IFCRELCONTAINEDINSPATIALSTRUCTURE('02BujaoJvBbQGapunQmWD0',#18,$,$,(#918),
#140009);
#170010=IFCRELCONTAINEDINSPATIALSTRUCTURE('2dJ4yhxBHBNPb4vLiG84ns',#18,$,$,(#133,
#265),#140010);

END SEC
END-ISO-10303-21;
```

6.4.2 Artifact B

The IDS standard is presented in eXtensible Markup Language (XML) file of considerable length. For this reason, the results that answer the specifications (Tables 6.3 to 6.6) are illustrated in Appendices (B, C, D, and E) through usBIM.IDS software (v.5.2.0).

6.5 Analysis

6.5.1 Artifact A

According to the IFC schema, a facility can establish spatial relationships with other facilities, which is suitable for the case of bridges, as they address the functionality of overcoming natural obstacles [35] represented by roadway segments. In this context, the organization proposed by Artifact A establishes a broad context for the tendered model, semantically aligned with the infrastructure of which it is part, through IfcRelAggregates and IfcRelContainedInSpatialStructure.

The creation of reference levels, especially when the modeling software does not offer specific resources for infrastructure projects (as is the case of Revit), represents an alternative to link the parts of the bridge to the instances of these objects [36].

Additionally, in the IFC spatial structure, an aggregation relationship may occur between instances of IfcBridgePart and instances of IfcSpace through IfcRelAggregates.

To ensure that the interoperability standard is met, it is essential that the information requirements for structural elements also be part of the modeling protocol. Similarly, certain geodetic information must be entered directly into the software interfaces, such as EPSG code, Vertical and Horizontal Datum, and True North of a project [19,20], as they impact the specification of IfcMapConversion. Such a consequence, the interoperability among infrastructure disciplinary models, and different systems (such as Geographic Information System - GIS) are impacted negatively.

Although the Units framework has been fully addressed, and consequently the measurement units specified by IfcSIUnit.Name have been verified, this does not guarantee that they have been properly considered in the model. To ensure this certainty, it is necessary to complement the verification in the instance of IfcUnitAssignment.

IfcSpace is an entity widely used in building models, and in the context of bridges, it applies to functional, operational, and analytical spaces, such as voids in structural elements intended for inspections or duct passage, access zones, restricted work areas, navigable spaces, traffic lanes, bike lanes, as well as spaces used for thermal performance and comfort analysis.

6.5.2 Artifact B

The results revealed that out of the seventy-one requirements specified by the frameworks explored, only four were not found, yielding an effectiveness percentile of 94.36% (Table 6.8). The responsibilities for the detected issues were analyzed under the following: IDS (standard limitation); usBIM.IDS (software limitation).

Table 6.8 Faults verification by Framework

Framework	Faults identified	Responsibility	Observation
Identification	x		
Financial	x		
Geometric	IfcGeometricRepresentationContext.WorldCoordinateSystem and .TrueNorthwere not found (Fig. 6.7)	IDS	Limitation to verify the entity instances linked with another
Units	x		
Geographic	IfcSite.RefLatitude and IfcSite.RefLongitude were not found (Fig. 6.8)	IDS	Limitation to IfcSimpleValue data type
Geodesic	x		
Facility	x		
Bridge	x		
BridgePart	x		

Source: the Author (2025)

The findings were illustrated through the working interfaces captured from the validation software. To clarify these occurrences, parts of the XML file (Listing B and C) were used to support the necessary considerations. The final file is present in Appendix 6A.

6.5.2.1 Geometric Framework

The TrueNorth attribute is not directly clarified in the instance of IfcGeometricRepresentationContext, but through the instance of IfcDirection (Listing 2):

```
#3=IFCCARTESIANPOINT((0.,0.,0.));
#20=IFCAXIS2PLACEMENT3D(#3,$,$);
#21=IFCDIRECTION((0.23186,0.97274));

#22=IFCGEOMETRICREPRESENTATIONCONTEXT($,'Model',3,1.0E-5,#20,#21);
```

Listing B reveals part of the XML file informing TrueNorth respective data type = SimpleValue, in this case, the standard could not recognize IfcDirection instance either (Fig. 6.8).

Listing B - Part of IfcGeometricRepresentationContext.ids

```
...
<ids:specification ifcVersion="IFC4X3_ADD2" name="Context of representation">
   <ids:applicability minOccurs="1" maxOccurs="unbounded">
    <ids:entity>
     <ids:name>
      <ids:simpleValue>IFCGEOMETRICREPRESENTATIONCONTEXT</ids:simpleValue>
     ...
    </ids:attribute>
    <ids:attribute cardinality="required">
     <ids:name>
      <ids:simpleValue>TrueNorth</ids:simpleValue>
     </ids:name>
...
```

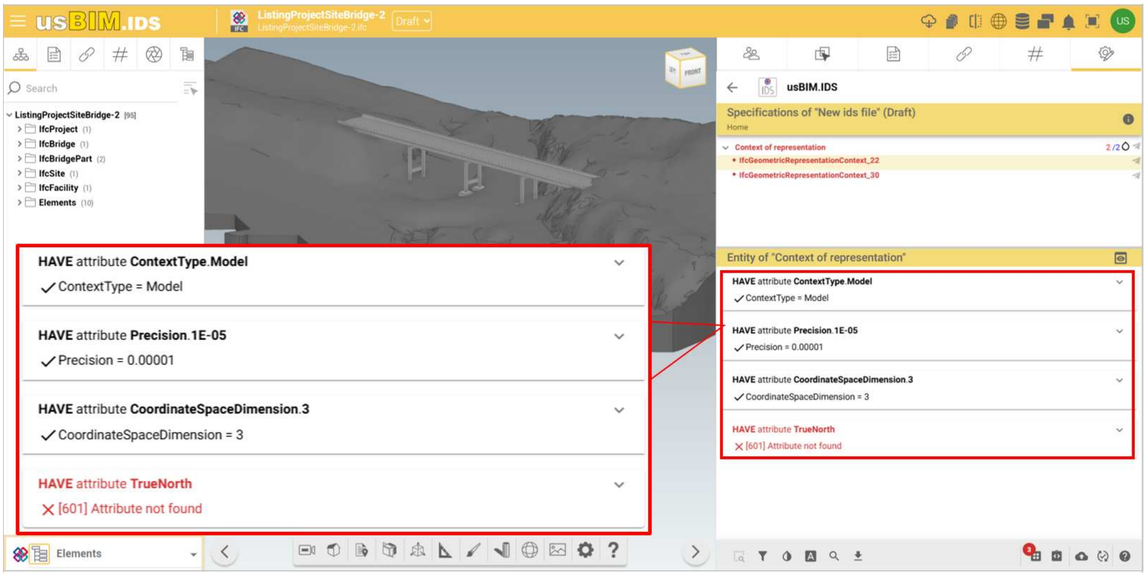


Fig. 6.8 TrueNorth fault
Source: the Author (2025)

Although the RefLatitude and RefLongitude attributes have been specified by IfcCompoundPlaneAngleMeasure were not recognized according to IDS standard (Listing C and Fig. 6.9).

```
#43=IFCSITE('0SzwuVeZXBQRZ0Rk9mp2Nr',    #18,    'Default',$,$,#42,$,$,.ELEMENT.,
(-20,-50,-52,-901458),(-42,-48,-7,-605285),721.2959,$,$);
```

Listing C

```
...
      <ids:simpleValue>IFCSITE</ids:simpleValue>
    </ids:name>
  </ids:entity>
</ids:applicability>
<ids:requirements>
  <ids:attribute cardinality="required">
    <ids:name>
      <ids:simpleValue>RefLatitude</ids:simpleValue>
    </ids:name>
  </ids:attribute>
  <ids:attribute cardinality="required">
    <ids:name>
      <ids:simpleValue>RefLongitude</ids:simpleValue>
    </ids:name>
  </ids:attribute>
  <ids:attribute cardinality="required">
    <ids:name>
```

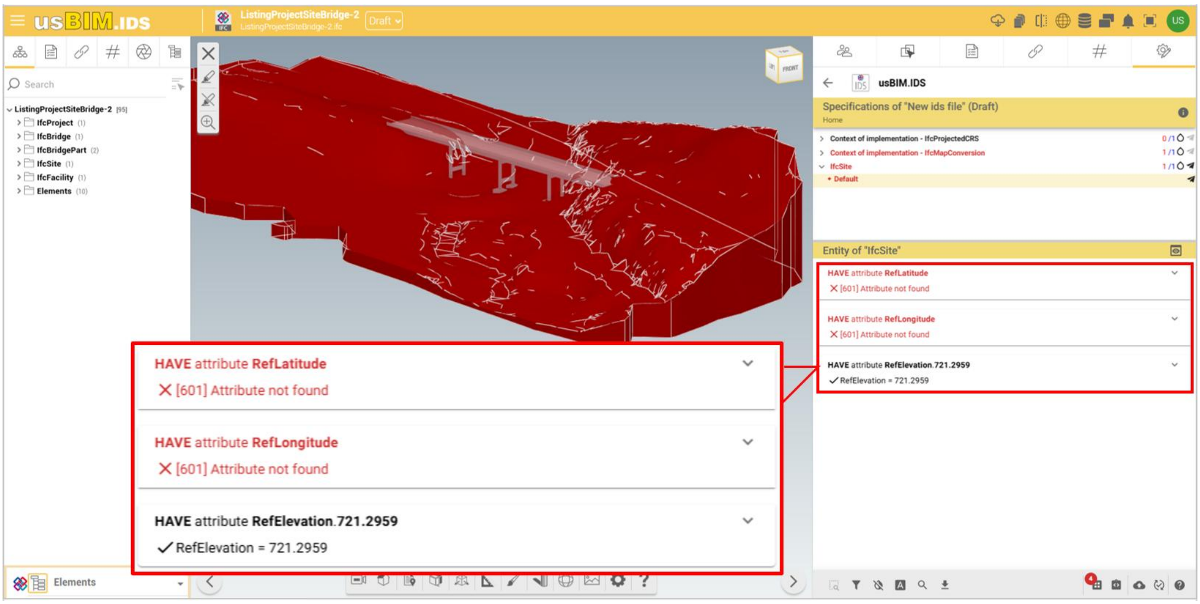


Fig. 6.9. RefLatitude and RefLongitude faults
Source: the Author (2025)

The results reveal a lack of IDS standard when one attribute is specified by another entity instance. Also, when data type not corresponds to IfcSimpleValue `[IfcInteger,IfcReal, IfcBoolean,IfcLogical,IfcIdentifier,IfcLabel,IfcText,IfcDataTime,IfcDate,IfcTime, IfcDuration,IfcTimeStamp,IfcURIReference]`.

6.6 Discussion

Unarguably, information is essential throughout the entire project lifecycle and, from an asset manager's perspective, it serves as the foundational basis for decision-making and reference for the development of new solutions [38].

Data interoperability is a persistent challenge in AEC that never seems to get resolved. Especially due to the diverse range of BIM software and the fairness of public tendering processes, collaboration among the involved stakeholders requires a basic understanding of the neutral file, which is crucial for OpenBIM [39].

At a minimum, BIM professionals need to understand the interrelationship of the data present in the working software interfaces with the IFC data structure. An example that illustrates this narrative is IfcProject.Name, which in this case must obligatorily clarify the Name attribute for model identification.

For some organizations, this identification could correspond to a name, a number, or both. In the case under study, the modeling software interface provides data corresponding to different attributes, for example Name of a project [IfcProject.LongName], Number of a project [IfcProject.Name], and Status [IfcProject.Phase], which could lead the professional to clarify the required information using the wrong data.

Thus, data mapping becomes essential in responses to information requirements. Especially due to the lack of specific knowledge in OOP and data specification language, inheritance diagrams (auxiliary artifacts) add significant value to the workflow process.

Another aspect related to this demand concerns the considerable universe of optional attributes present in the schema. On the one hand, this may be positive in terms of accommodating the diversity of the sector, and on the other, it might be negative due to the tolerance regarding the absence of information that may be required by contracting organizations and/or the specificities of projects.

This duality allows software vendors not to implement some data. If it is not possible to meet the information required by the BEP via software, one of the alternatives available to the professional is to clarify it manually via SPF, as Artifact A demonstrated in the specification of

IfcFacility and in the clarification of semantically appropriate attributes to specify IfcBridge and its respective parts.

6.6.1 Future work

The automatic data verification enabled by the IDS standard demonstrated satisfactory performance, especially considering it is its first version. The results presented in the study revealed considerable success, except for the difficulty in verifying requirements linked to instances of other objects, as well as the restriction to the Simple Data Type.

In this way, future research is necessary to assess the performance of other software to make comparisons and more detailed analyses of the limitations of IDS standard and verification software [40].

Similarly, the artifacts are inspired by a bridge infrastructure project modeled in Revit, which highlights the need to explore the approach for other types of infrastructure projects and other modeling software. This is particularly important because Revit is not designed for modeling projects characterized by linearity, especially those with a higher level of geometric complexity.

This study focused on the use of IDS applied to the spatial structure of a bridge, but it only explored the PropertySet linked to IfcProject. Thus, research related to properties and information requirements verifications are necessary, as they add significant value.

6.6.2 Contributions

The adoption of IDS offers significant benefits for the management and automatic verification of information requirements, helping to define data requirements in a structured and interoperable way, and enabling the integration of design, construction, and operation processes within the ISO 19650-2.

Among the main benefits of the artifacts developed in this study, the standardization of communication between professionals stands out, reducing inconsistencies in the exchange of information and increasing the reliability of BIM models, as it eliminates the need for manual verifications that are prone to errors and time-consuming.

Another contribution is the optimization of digital workflow, which enhances the quality of delivery, ensuring that contractual and regulatory requirements are met with greater effectiveness. This is particularly relevant for projects that demand high technical precision, such as infrastructure projects.

At the same time, the automation of data supports the use of advanced technologies, such as machine learning algorithms and predictive analytics, thereby contributing to improving the overall quality of decision-making processes.

6.7 Conclusion

In a landscape where engineering increasingly needs to integrate technical performance with sustainability, the BIM system represents an innovation for bridge management. Not only does the virtual environment expand the potential of the simulation context but also fosters an environment conducive to the development of solutions with a higher level of precision.

After the completion of the construction phase in the project lifecycle, the asset model becomes the information container that will serve as the basis for developing monitoring models during the operational phase. The management objective during this phase is to assess the health condition of the structures and, consequently, the longevity of the asset.

The study demonstrated that the IFC schema, in light of the civil infrastructure domain, exhibits coherent diversity. The entities IfcFacility and IfcFacilityPart, stand as an example, that leaves room for a facility to be part of another. This is the case of the Vecchio Bridge (Florence, Italy), where the superstructure includes a building, and of the Hoover Dam (California, United States) which functions as a bridge at the same time.

This broad range of possibilities highlights the importance of the flexible aspect of the IFC schema, combined with interoperability, enabling the integration of the model into a coherent semantic context.

Regarding artifact A, it is reasonable to conclude that the SPF generated by the configured export process demonstrated satisfactory performance, considering that the MVD version related to the IFC data schema [v.4.3.2.0] had not yet been published. The results show that software manufacturers have been proactive in seeking solutions to meet interoperability requirements.

The project and organization information requirements analyzed highlight the qualitative importance of the frameworks [Identification, Geometric, and Unit - IfcProject], [Geographic and Geodetic - IfcSite], and IfcBridge, which together form the main spatial foundation of a bridge. The absence of any of them indicates considerable difficulties for the management and 3D coordination teams, including issues related to: internal origin coordinates, engineering coordinates, measurement units, unit precision, true north orientation, and geodetic reference systems. In addition to negatively impacting the quality of model checks that compose the project, these issues may undermine the reliability of the models.

Regarding artifact B, the results highlight the importance of the modeling protocol in fully addressing the information requirements of OIR and PIR.

This demand reinforces the conclusions from artifact A, as the IDS aims to provide information that enables the contracted team to clearly understand the demands of the organization and each project through attributes or properties, strengthening the integration and consistency of information in BIM projects to promote OpenBIM interoperability.

Meanwhile, it enhances the use of automated methodologies applied in automatic verification, capable of adding distinctive value to the projects. The verification enabled by the IDS standard is the way forward in mitigating failures in checking the requested and delivered information, as well as increasing the level of control and reliability of the model.

Ultimately, one may conclude that it stands as an effective way to combine quality with information.

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APPENDIX 6A: IDS file

```
<ids:ids xmlns:xs="http://www.w3.org/2001/XMLSchema" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance" xsi:schemaLocation="http://standards.buildingsmart.org/IDS
http://standards.buildingsmart.org/IDS/1.0/ids.xsd" xmlns:ids="http://standards.buildingsmart.org/IDS">
  <!--edited with usBIM.IDSeditor 2.3.4.0 (http://www.accasoftware.com)-->
  <ids:info>
    <ids:title>IDS_Tese </ids:title>
    <ids:version>1.0</ids:version>
    <ids:description>Especificações para a modelagem da ponte Coimbra I. As especificações contidas
neste documento estão relacionados à estrutura espacial da ponte. O modelador deve se atentar à
classificação adequada dos elementos, atribuindo os parâmetros IFC que transmitem a semântica apropriada
para cada um deles.    </ids:description>
    <ids:author>antunesmarialuisa@gmail.com</ids:author>
    <ids:date>2025-03-14</ids:date>
    <ids:purpose>Modelagem As-is</ids:purpose>
    <ids:milestone>Operação</ids:milestone>
  </ids:info>
  <ids:specifications>
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            <ids:simpleValue>IFCSITE</ids:simpleValue>
          </ids:name>
        </ids:entity>
      </ids:applicability>
      <ids:requirements>
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            </ids:name>
          </ids:entity>
        </ids:partOf>
      </ids:requirements>
    </ids:specification>
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          </ids:name>
        </ids:entity>
      </ids:applicability>
      <ids:requirements>
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        </ids:partOf>
        <ids:attribute cardinality="required">
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            <ids:simpleValue>Name</ids:simpleValue>
          </ids:name>
          <ids:value>
            <ids:simpleValue>BR120 Road</ids:simpleValue>
          </ids:value>
        </ids:attribute>
        <ids:attribute cardinality="required">
          <ids:name>
            <ids:simpleValue>Description</ids:simpleValue>
          </ids:name>
          <ids:value>
            <ids:simpleValue>BR120 km</ids:simpleValue>
          </ids:value>
        </ids:attribute>
        <ids:attribute cardinality="required">
          <ids:name>
            <ids:simpleValue>CompositionType</ids:simpleValue>
          </ids:name>
          <ids:value>
            <ids:simpleValue>.COMPLEX.</ids:simpleValue>
          </ids:value>
```

```xml
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  </ids:requirements>
</ids:specification>
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      </ids:name>
      <ids:predefinedType>
        <ids:simpleValue>GIRDER</ids:simpleValue>
      </ids:predefinedType>
    </ids:entity>
  </ids:applicability>
  <ids:requirements>
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        </ids:name>
      </ids:entity>
    </ids:partOf>
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      </ids:name>
      <ids:value>
        <ids:simpleValue>Coimbra I Bridge</ids:simpleValue>
      </ids:value>
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        <ids:simpleValue>CompositionType</ids:simpleValue>
      </ids:name>
      <ids:value>
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      </ids:value>
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  <ids:requirements>
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      </ids:name>
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```

```
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CAPÍTULO 7 – CONCLUSÕES GERAIS

Resumo

Neste capítulo são apresentadas as conclusões gerais do trabalho, englobando as principais citadas nos artigos desenvolvidos, as considerações finais e as propostas para futuros trabalhos que poderão ser elaborados na linha de pesquisa considerada.

7.1 Considerações finais

O sistema BIM se destaca como uma inovação aderente a todas as fases do ciclo de vida do projeto e suas aplicações ampliam as potencialidades do contexto simulatório, proporcionando um ambiente favorável ao desenvolvimento de soluções com maior nível de precisão.

A lacuna de pesquisa delineada (Capítulo 3) evidencia uma fragilidade da literatura BIM brasileira publicada até 2024 que, em grande parte, restringe o modelo de ciclo de vida do projeto à fase operacional, limitando as aplicações BIM às ações de monitoramento. As atividades clássicas da fase operacional, como projetos de reformas e reabilitações, são abordadas pela ABNT NBR ISO 19650-1 (2024) no contexto dos "eventos gatilhos". No entanto, essas atividades não são devidamente contempladas no modelo de ciclo de vida amplamente referenciado. Além disso, considerando que mais de 60% das publicações analisadas traduzem ou customizam o modelo norte-americano, há uma demanda por atualização destas publicações, especialmente porque servem como referência para elaboração de planos de execução BIM no Brasil.

O DPL (Capítulo 4) destaca a expressividade da fase operacional, sobretudo pelo aspecto de hospedar, simultaneamente, as fases anteriores. Alinhado ao arcabouço normativo ABNT ISO 12006-2 (2018) e à semântica de cada fase do ciclo, o novo modelo de representação do ciclo de vida é capaz especificar com precisão, IfcProject.Phase. Esse artefato não apenas auxilia, como também suscita a cadeia produtiva a considerar aplicações futuras do modelo, inclusive aquelas voltadas ao encerramento do ciclo, em uma perspectiva semântica inversa às demais fases do ciclo. Neste contexto, os requisitos de informações do projeto tendem a abranger expectativas mais amplas.

Os artefatos desenvolvidos sob o espectro dos arcabouços Identificação, Geométrico e de Unidades (Capítulo 2); Geográfico e Geodésico (Capítulo 5); Elementos construtivos da ponte e suas respectivas partes (Capítulo 6) refletem a estrutura espacial essencial do IFC. A replicabilidade das soluções elaboradas pode ser realizada manualmente, utilizando um simples notepad, independentemente do softwares BIM utilizados pelos profissionais. Essa abordagem destaca um dos pilares da interoperabilidade neutra e aberta, além de reforçar o aspecto sustentável e atemporal do STEP Physical File.

Ainda que a especificação *OpenBIM* tenha evoluído substancialmente, limitações na forma de representar o esquema IFC ainda estão presentes, o que pode representar dificuldades especialmente para os profissionais que não têm um conhecimento básico sobre linguagem de programação orientada a objetos (OOP). Por esta razão, os diagramas de herança desenvolvidos neste trabalho representam artefatos auxiliares. Especialmente, por reduzir a abstração do esquema, favorecer a mitigação de dificuldades de compreensão e elevar do nível de precisão de dados envolvidos na elaboração de planos de trabalho.

A verificação automatizada dos requisitos de informação envolvidos no estudo através do desenvolvimento do IDS (Capítulo 6) foi validada exitosamente, comprovando que o padrão de interoperabilidade aberta representa, claramente, um caminho promissor na direção da automação dos processos de colaboração e interoperabilidade na indústria da construção civil.

Por fim, os artefatos propostos demonstram a performance semântica do IFC e, paralelamente, destacam recursos que podem servir de referência para desenvolvedores de software. Alinhado às atuais demandas da governança brasileira, refletidas neste estudo, um universo mais amplo de dados deveria ser especificado, mesmo que a natureza opcional de alguns dados seja tolerada pelo esquema.

Neste contexto, uma das mais relevantes lições aprendidas durante o pesquisa é que os gestores BIM devem elaborar protocolos criteriosos de modelagem, colaboração e interoperabilidade, alinhados às particularidades de cada projeto. Planos de execução voltados para o controle de qualidade são essenciais, pois a precisão dos processos de tomada de decisão ao longo do ciclo de vida do projeto depende diretamente da qualidade da informação (geométrica e não geométrica) impactando positiva ou negativamente, sua sustentabilidade.

7.2 Recomendações para trabalhos futuros

Nesta tese, o objeto de estudo é um modelo de ponte rodoviária com tipologia estrutural composta por vigas de concreto, escolhida devido à sua ampla representatividade na malha viária brasileira. Consequentemente, outras tipologias estruturais de pontes exigem investigações específicas.

Da mesma forma, adotou-se o Revit como software de modelagem, por ser utilizado pelo gestor (DNIT) e por um número significativo de profissionais BIM. No entanto, diferentes software podem apresentar variações no mapeamento de dados. Assim, uma análise abrangente envolvendo múltiplas ferramentas de modelagem permitiria comparar seu desempenho, configurando uma relevante linha de pesquisa futura.

Dada a diversidade de software BIM, que atendem o viés da isonomia dos processos licitatórios públicos, o atendimento aos requisitos de informação dos projetos licitados pode exigir um conhecimento básico sobre o arquivo neutro adotado no esquema de dados IFC. Neste sentido, a construção de diagramas, não abordados nesta pesquisa, representaria uma contribuição relevante para os profissionais da cadeia produtiva.

Por fim, vale destacar que a informação é a essência do sistema BIM, independente de sua natureza geométrica ou não geométrica, representa o cerne dos processos colaborativos ao longo do ciclo de vida do projeto. Razão pela qual, pesquisas que exploram a interoperabilidade como temática, serão exponencialmente demandadas em resposta à dinâmica tecnológica que a indústria da construção civil vivencia.

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