ARTIGO

INTEROPERABILITY LEVEL FOR BRIDGE STRUCTURAL ANALYSIS FROM THE IFC DATA INTERPRETATION

NÍVEL DE INTEROPERABILIDADE PARA ANÁLISE ESTRUTURAL DE PONTES A PARTIR DA INTERPRETAÇÃO DE DADOS IFC

NIVEL DE INTEROPERABILIDAD PARA EL ANÁLISIS ESTRUCTURAL DE PUENTES BASADO EN LA INTERPRETACIÓN DE DATOS IFC

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ABSTRACT:

Importing IFC (Industry Foundation Classes) data from bridge structural models into structural analysis software is common in the BIM (Building Information Modeling) workflow. However, some software tools still do not import IFC data in the extended version that covers bridge models. In addition, there is a lack of a holistic framework for determining indicators that effectively represent the interoperability level for bridge structural analysis. To prevent data loss in bridge models, this work proposes a tool for interpreting IFC data related to the semantics of bridge elements, geometry, and material properties. A new methodology was developed to quantitatively evaluate an interoperability level for bridges structural analysis, considering the relevance of the imported information by defining numerical weight values. Then, a new framework was proposed for determining each data flow's Interoperability Level for Bridge Structural Analysis (ILBSA). The interoperability level results showed that commercial bridge structural analysis software requires significant advances in interpreting IFC data.

KEYWORDS: Bim; Bridges; Infrastructure; Data exchange.

RESUMO:

Importar dados IFC (Industry Foundation Classes) de modelos estruturais de pontes em um software de análise estrutural é uma tarefa comum no fluxo de trabalho BIM (Building Information Modeling). Entretanto, alguns softwares ainda não importam dados IFC na versão de extensão que engloba modelos de pontes, podendo gerar inconsistências na semântica dos elementos e representações geométricas ineficientes. Para evitar perdas de informações de um modelo de ponte, propõe-se uma ferramenta de interpretação de dados IFC referente à semântica dos elementos de ponte, geometria e propriedades dos materiais. Uma nova metodologia foi desenvolvida para avaliar quantitativamente um índice de interoperabilidade para fins de análise estrutural de pontes (ILBSA), considerando a relevância das informações importadas definindo valores numéricos de pesos. Os resultados dos níveis de interoperabilidade mostraram que os softwares comerciais de análise estrutural de pontes requerem avanços significativos na interpretação de dados IFC.

PALAVRAS-CHAVE: Bim; Pontes; Infraestrutura; Troca de dados.

Conflito de Interesse: Declaramos não haver conflitos de interesse.

Ética em Pesquisa: Não há necessidade.

Submetido em: 27/07/2024
Aceito em: 11/12/2024.

How to cite this article:

TEIXEIRA, G. P. et. al. Interoperability level for bridge structural analysis from the IFC data interpretation. **Gestão & Tecnologia de Projetos**. São Carlos, v19, n3, 2024. https://doi.org/10.11606/gtp.v19i3.227401

RESUMEN:

La importación de datos IFC (Industry Foundation Classes) de modelos estructurales de puentes a software de análisis estructural es una tarea habitual en el flujo de trabajo BIM (Building Information Modeling). Sin embargo, algunos programas informáticos siguen sin importar datos IFC en la versión de ampliación que incluye modelos de puentes, lo que puede provocar incoherencias en la semántica de los elementos y representaciones geométricas ineficaces. Para evitar la pérdida de información de un modelo de puente, se propone una herramienta para interpretar los datos IFC relativos a la semántica de los elementos del puente, la geometría y las propiedades de los materiales. Se ha desarrollado una nueva metodología para evaluar cuantitativamente un índice de interoperabilidad para el análisis estructural de puentes (ILBSA), considerando la relevancia de la información importada mediante la definición de valores numéricos de peso. Los resultados de los niveles de interoperabilidad mostraron que el software comercial de análisis estructural de puentes requiere avances significativos en la interpretación de los datos IFC.

PALABRAS CLAVE: Bim; Puentes; Infraestructuras; Intercambio de datos.

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INTRODUCTION

Using BIM (Building Information Modeling) in multi-story buildings and infrastructure projects can bring some benefits, such as more efficient project management, enhanced collaborative efforts, and reductions in project execution timelines (Kumar *et al*., 2017). To maximize these benefits in the BIM workflow, it is essential to improve data exchange between the different software available (Biswas *et al*., 2024).

For structural analysis purposes, manual generation of the structural model leads to accumulated errors, rework, and high time consumption (Ramaji & Memari, 2018; Khattra *et al*., 2020). On the other hand, the exchange of IFC (Industry Foundation Classes) data between a BIM platform and structural analysis software can lead to semantic losses of BIM elements (Jiang *et al*., 2023) and non-parametric description of their 3D geometry (Ji *et al*., 2011). One of the options for improving this IFC data flow is the use of data interpretation tools during the export of the .ifc file (Ramaji & Memari, 2018; Khattra *et al*., 2020; Chen *et al*., 2005; Hu *et al*., 2016). The data exchange between different applications can be carried out efficiently if BIM platforms and structural analysis software have consistent support for the export/import of IFC data, avoiding loss of information and low semantic level (Ren *et al*., 2018).

The types of structural models for girder bridges vary in relation to the complexity of the geometry of the elements, the simplification level of the analysis model, and the computational effort to be used. In practical applications, the two-dimensional model is the prevailing choice for Finite Element Method (FEM) structural analysis of girder bridges, as it covers the majority of the bridge structural elements and provides force values that can be directly used for design purposes (El Debs, 2021). The two-dimensional model consists of one-dimensional Euler-Bernoulli finite elements, that represent girders, diaphragms, pier cap beams, and columns, in addition to two-dimensional Reissner-Mindlin plate/shell finite elements, that represent the slabs (El Debs, 2021). For example, in a situation where the load-bearing capacity of a girder bridge is assessed using two-dimensional structural analysis, the user needs to be provided with information relating to geometry and materials to reduce rework at the structural modeling stage and, consequently, make structural analysis via FEM more efficient. Since the BIM modeling platform and the structural analysis software may not be compatible, the IFC use as a data exchange standard becomes essential in the workflow.

The available software tools still do not import IFC data in the extended version that includes bridge models (IFC4.3.2.0 schema). Furthermore, the current state-of-the-art lacks a comprehensive framework for determining indicators that effectively represent the interoperability level for bridge structural analysis. To narrow these knowledge gaps in the literature, the present work proposes an innovative tool for interpreting IFC4.3.2.0 data for structural analysis purposes in SAEP, which is a software program under development capable of modeling and performing structural analysis of concrete beam bridges with straight and level axes, as well as importing .ifc files and interpreting IFC data associated with the structural model of some bridge elements. In order to compare the IFC data interpreted in SAEP, a methodology is proposed for determining a numerical indicator that represents the efficiency level of IFC interoperability. The proposed indicator aggregated data related to the semantics of bridge elements, general information, geometry, and materials transferred between Revit (v.2024) and the following bridge modeling and structural analysis software: Allplan Engineering (v. 2024-1-2), Bentley OpenBridge (v. 23.00.00.121), CSi Bridge (v. 23.0.0), Scia Engineer (v. 24.0), and SAEP. The results were analyzed using a case study comprising bridge elements with shapes commonly used in the field of structural modeling.

LITERATURE REVIEW

IFC DATA EXCHANGE BETWEEN BIM PLATFORMS AND STRUCTURAL ANALYSIS SOFTWARE

Generally speaking, IFC (Industry Foundation Classes) interoperability is the ability of systems to exchange information without loss while maintaining its semantic level using a standard construction data model named IFC. The IFC is an extensive data structure standardized in the AEC (Architecture, Engineering, and Construction) industry and organized hierarchically to facilitate the implementation of data exchange between applications. This data structure inherits the concepts of object-oriented programming (OOP) and is described using a modeling language named EXPRESS, defined by ISO 10303-11 (Borrmann *et al*., 2018).

A one-way data exchange using the IFC standard is exemplified using a BIM design platform and structural analysis software. The unidirectional IFC data exchange process is summarized as follows: 1) defining the exchange requirements, i.e. the information the structural analysis software needs to receive; 2) exporting an .ifc file from the BIM platform using a specific model view; 3) optionally using IFC viewers to validate the exported model; 4) importing a validated .ifc file into the structural analysis software; 5) checking the imported data directly in the structural analysis software.

The main problems in exchanging IFC data between BIM platforms and structural analysis software are: a) the exported view model does not cover all the information that the target software needs to receive (Luttun & Krijnen, 2020); b) the various ways of representing geometry, properties, and relationships in IFC can lead to inconsistencies and loss of information (Lai & Deng, 2018). Therefore, IFC interoperability is achieved if the BIM platform and structural analysis software have consistent support for exporting/importing IFC data (Ren *et al*., 2018) by defining data models and standardizing their representation (Hu *et al*., 2016).

Defining the structural analysis scenarios is fundamental in the IFC data exchange process and is related determining the exchange requirements. Structural analysis is divided into three stages (Ren & Zhang, 2020): 1) intrinsic modeling stage, in which the structural analyst depends only on the geometric data of the elements and the materials related to each element; 2) extrinsic modeling stage, in which the analyst also depends on the data of boundary conditions and loads acting on each element; and 3) analysis stage, which is the stage of processing the data from stages 1 and 2, obtaining the results of the analysis. The exchange of IFC data between structural analysis software is compromised when the information is related to the analysis stage (Ren & Zhang, 2020). However, if IFC data is imported into structural analysis software from the export of IFC data on a BIM modeling platform, at least information related to cross-sections, elements, and materials is expected since data on connections and acting loads are not exported via coordination or reference models view (Ramaji & Memari, 2018).

The automatic extraction of IFC data, such as element geometry and materials, speeds up the process of generating structural models, reducing errors, avoiding rework, and improving coordination between architects and structural engineers (Khattra *et al*., 2020; Chen *et al*., 2005; Liu *et al*., 2010; Hu *et al*., 2016). Chen *et al*. (2005) implemented an information web server based on IFC to automatically transform information from the architectural domain to the structural domain. Deng and Cheng (2006) developed an interpretation mechanism between architectural models based on IFC and structural models based on XML files. Liu *et al*. (2010) proposed a computational tool that interprets IFC data from architectural models into structural model data, following the data structure of PKPM software, which is widely used in engineering offices in China. Qin *et al*. (2011) proposed a unified XML-based core model for converting architectural models between various commercial CAE software. Khattra *et al*. (2020) developed an algorithm using Python's IfcOpenShell library to interpret information from the architectural BIM model to the structural model by implementing an integrated workflow.

The architectural or structural model can be directly interpreted into its respective analytical model, considering the connections between the elements. Wang *et al*. (2015) developed an IFC data interpreter from structural models to analytical models. Hu *et al*. (2016) proposed a dual-track data interpretation algorithm based on element mapping, conflict resolution between architectural and structural elements, web-based integration, structural analysis, and continuous updating. Liu *et al*. (2016) developed a tool for interpreting IFC data from architectural models into structural and analytical models using MIDAS, ETABS, and ABAQUS software. Ramaji and Memari (2018) proposed a method that is applied to MVD Coordination View (CV) v.2.0 (IFC2x3) data, dividing the information into direct exchange units and interpretation units to determine the analytical model. To avoid manual editing when interpreting information related to the connections between elements in MVD CV v.2.0, Ramaji and Memari (2018) developed connectivity adjustments using an algorithm considering the distances between point-to-point and point-to-line.

For structural analysis of bridges, researchers enabled the interpretation of IFC data by proposing new IFC entities for bridges, sets of properties, characteristics for finite element analysis, and mesh-free analysis. In this context, the IFC4.3.2.0 scheme was officially published in 2023 by buildingSMART International (bSI). Hassanien Serror *et al*. (2008) developed a data transfer technology called Shared Computer-Aided Structural Design (sCAsD) and proposed IFC entities for finite element analysis of buildings and bridges. Xu *et al*. (2019) proposed a method based on the interpretation of IFC entities from the Brep geometry of bridge elements to perform finite element analysis. Pukl *et al*. (2016) converted bridge IFC data into structural analysis models in the input format of the ATENA software, which is used for non-linear finite element analysis of concrete structures. Park *et al*. (2020) proposed an extension of IFC for bridge elements and a methodology that interprets bridge model data to perform structural analysis without the need for meshing.

Currently, some certified BIM software offers a trial version for exporting IFC data at a higher version than IFC4, but it does not have implemented Model View Definition (MVD). This makes it difficult to carry out tasks that require interpreting bridge IFC data for information related to the analytical model. Therefore, the export of bridge IFC data for structural analysis purposes must cover the correct semantics of the elements, efficient geometric representation, and relationships between bridge elements and materials, among other factors that can not be identified when exporting view models in IFC4.

BRIDGE INFORMATION MODELING

IFC EXTENSION FOR BRIDGES

To meet the global demand for infrastructure projects such as bridges, railways, roads, and tunnels, an extension project of IFC was developed, covering not only building modeling. The final version of the schema, IFC4.3.2.0 (IFC4x3_ADD2), was officially published in 2023 by bSI.

Considering the various domains in construction modeling, previous studies presented proposals for extensions to IFC4 aimed at infrastructure works before the official publication by the bSI, with the main objective of improving interoperability between software (Yu *et al*., 2023). Yabuki and Shitani (2003) developed a data model for reinforced and prestressed concrete bridges, proposing new entities for slabs, prestressing strands, sheaths, reinforcement, and anchoring devices. Lee and Kim (2011) considered adding IFC entities to define spatial elements in road structures. Ji *et al*. (2011) proposed an IFC data structure considering the parameterization of physical bridge elements. Amann *et al*. (2014) integrated new entities to describe transition curves for the IFCAlignment project. Amann *et al*. (2015) proposed an extension for cross-sections in road design based on the IFCAlignment project. Tanaka *et al*. (2017) developed an IFC-based information model to meet the requirements of bridge inspection processes. Park *et al*. (2020) integrated the mesh-free analysis method into the extended bridge model based on IFC. Lee *et al*. (2014), Gao *et al*. (2016), and Kwon *et al*. (2020) developed IFC entities to semantically define railroad design. Therefore, even with the efforts of several authors in contributing extensions to IFC4 and the official publication of the IFC4.3.2.0 schema in 2023, there may be a considerable delay in implementing a new schema in BIM software (Cerovsek, 2011).

The first stage of the IFC4 extension project was dedicated to the development of the first data schema, IFC4.1, proposed by the internal committee of bSI, titled IFCAlignment (Borrmann *et al*., 2019), officially published in 2018. This schema defined the characteristics for describing the alignment of infrastructure projects, such as the reference line that delineates the layout of a bridge. In addition to defining the alignment, the new IFC geometric representation entity *IfcSectionedSolidHorizontal* was introduced, which allows sweeps along a directrix defined in the project (Borrmann *et al*., 2019). The IFCAlignment project has enabled a) the ability to exchange alignment information in the planning, design, construction, and management phase; b) the linking of alignment information, cross-sections, and three-dimensional geometry of elements; c) the consultation of linear referencing and positioning information; among other achievements (Amann *et al*., 2015). The IFCBridge project was officially launched in 2016 based on the IFCAlignment project and previous IFC extension projects (Markic, 2017).

The second part of the project, IFC4.2, officially published in 2019, defined the spatial hierarchy of the project, expanding specifically for bridges and considering future infrastructure works through the *IfcFacility* subtypes and *IfcFacilityPart* entities (Borrmann *et al*. 2019). The *IfcBridge* entity, as one of the subtypes of *IfcFacility*, has the *PredefinedType* attribute, encompassing various types of bridge structural systems (e.g., girder, cable-stayed, arch, etc.). Another important IFC entity is called *IfcBridgePart*, a subtype of *IfcFacilityPart*, which defines the different parts of the bridge (e.g., foundation, substructure, superstructure, etc.). In addition, the IFC4.2 schema has defined new entities that are *IfcBuildingElement* subtypes, such as the support elements (*IfcBearing*) and the deep foundation (*IfcDeepFoundation*). Some elements have been described by expanding the predefined types of entities already defined in IFC4, such as girders (GIRDER_SEGMENT), diaphragms (DIAPHRAGM), and pier cap beams (PIERCAP) of bridges, which are predefined types of *IfcBeam*. As with the IFC4 schema, objects not identified in a given schema are defined by the *IfcBuildingElementProxy* entity.

IFC4.3 was published in 2021, with the possibility of updates, taking into account rail (*IfcRailway*), road (*IfcRoad*), and waterway (*IfcMarineFacility*) projects, along with bridge (*IfcBridge*) and building (*IfcBuilding*) projects. New elements were also defined as IfcBuiltElement subtypes to replace the *IfcBuildingElement* entity, such as pavement (*IfcPavement*) and rail (*IfcRail*). The first candidate for updates was called IFC4.3.1.0 (IFC4x3_ADD1), with superelevation definitions, advanced geometric representations, and a spatial structure that promotes greater collaboration. IFC4.3.2.0 (IFC4x3_ADD2) was officially published in 2023 with a better definition for the linear positioning of objects using the *IfcAxis2PlacementLinear* and *IfcPointByDistanceExpression* entities (Jaud *et al*., 2021).

IFC GEOMETRIC REPRESENTATION

The geometric representation of BIM objects is one of the most relevant information when exchanging data between software. Geometry resources are one of the most extensive and complex IFC subprocedures, requiring a significant computational effort for being implemented in BIM software (Krijnen *et al*., 2020). Consequently, Wagner *et al*. (2020) carried out an extensive literature review to analyze geometric descriptions in relation to the requirements established in each domain. The authors recommended choosing the most suitable geometric description individually, considering the domain and the type of project.

Wagner *et al*. (2020) classified geometric representations as follows: 1) point cloud; 2) tessellated (triangulated or polygonal surfaces, analogous to a mesh); 3) boundary representation (Brep); 4) Constructive Solid Geometry (CSG); and 5) sweeps and rotations. The IFC does not semantically define solids formed by point clouds; however, some studies already presented the interpretation of sets of points in the IFC geometric representation of bridge elements (Lu & Brilakis, 2019; Justo *et al*., 2023). The geometric representations for items 1-3 and 4-5 have explicit and implicit modeling approaches, respectively (Borrmann *et al*., 2018).

A solid defined by implicit modeling stores the creation history as information is defined (Borrmann *et al*., 2018). For example, a prismatic solid generated by extrusion of a cross-section (*IfcExtrudedAreaSolid*) requires the following sequence of information: 1) definition of the cross-section; 2) position of the cross-section; 3) extrusion direction; and 4) extrusion depth. Each piece of information is stored, and the solid is generated only when all the information is defined. In IFC4.3.2.0, the subtypes of *IfcSweptAreaSolid*, *IfcSweptDiskSolid*, *IfcSectionedSolid*, and *IfcCsgSolid* represent solids modeled implicitly.

Explicit modeling represents solids generated by Brep and tessellated surface representation (Borrmann *et al*., 2018). A Brep solid is defined by the sequence body - faces - edges - vertices. A body is composed of a set of faces, a set of edges defines each face, and each edge is defined by its vertices. Subtypes of *IfcManifoldSolidBrep* are used to define solids by boundary representation. Additionally, solids modeled explicitly can be composed of triangles or polygons that define their entire surface through a set of cartesian points, using the subtypes of *IfcTessellatedItem*.

In the geometry context of bridge elements, modifying the road axis implies an automatic update of the other bridge elements (Ji *et al*., 2012; Hu *et al*., 2014), making the alignment's parameterization and bridge elements a fundamental step in the design phase. The studies by Sampaio (2003), Ji *et al*. (2012), Lee *et al*. (2012), Karaman *et al*. (2013), and Girardet and Boton (2021) have shown the importance of parameterizing bridge elements. Therefore, implicit methods are considered the most efficient geometric representations, as they involve fewer parameters to interpret, resulting in smaller files capable of being read by a computer, improving accuracy and allowing for a better fit in the structural analysis domain (Markic, 2017).

METHODOLOGY

SAEP'S GENERAL FEATURES

SAEP is based on a methodology for modeling bridges based on parametric data. It also comprises a computer system implementation for two-dimensional structural analysis of the load capacity of bridges in its stand-alone version. SAEP only considers concrete bridges with a straight longitudinal axis, as this type of bridge is widely used in Brazil. The data structure was developed in the Delphi language, using the concepts of classes and objects, and the advantages of OOP. As for the software interface, it was decided to use OpenGL linked to the Delphi programming environment. This, SAEP was able to generate the following results: a) envelopes of nodal displacements based on the degrees of freedom considered for each element type; b) influence lines/surfaces for each force using the Jepsen & Damkilde (2016) methodology; c) envelopes of maximum and minimum forces due to the combination of dead and live loads; d) Rating Factor (RF) of the bridge, considering its deterioration condition and the application of loads from vehicles.

It is important to note that SAEP has some limitations compared to the commercial software evaluated in this research. SAEP models and interprets IFC4.3.2.0 data for concrete girder bridges with straight-axis and at level, but some types of bridges were not considered, such as steel-concrete, box girder, or cable-stayed bridges. Another limitation is importing a coordination, reference, or design view model in the IFC4 schema. SAEP does not interpret bridge elements without the correct definitions, i.e., in this case, the user will not visualize the structural model.

To read the bridge's structural model, an IFC4.3.2.0 data interpreter was implemented in SAEP, considering four stages: 1) implementation of IFC entities in the programming environment, i.e. creation of a library of IFC classes for modeling the bridge in SAEP; 2) development of an algorithm for reading an .ifc file; 3) development of IFC data interpreter; 4) validation of the IFC data interpretation tool. Since SAEP was developed in the Delphi language, the IFC class library and the .ifc file reader were also written in this language, facilitating the integration of SAEP with the IFC4.3.2.0 data interpretation tool.

Figure 1 shows the workflow for IFC4.3.2.0 data interpretation by SAEP. In addition, SAEP enables the exporting of native files with all the structured information, facilitating user readability.

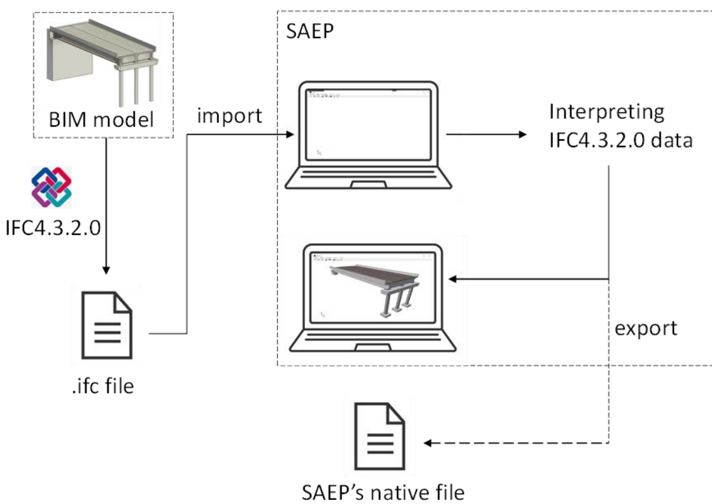

Figure 1. Workflow for IFC4.3.2.0 data interpretation by SAEP

Source: Authors

FRAMEWORK FOR OBTAINING THE ILBSA (INTEROPERABILITY LEVEL FOR BRIDGE STRUCTURAL ANALYSIS)

Figure 2 shows the proposed framework for determining each data flow's Interoperability Level for Bridge Structural Analysis (ILBSA). The Revit v. 2025 platform was chosen to export the IFC data for the model, known as the Standard Model. A model named Standard Model was created on the Revit v.2025 platform. Revit was chosen because it is a widely used BIM platform for modeling straight-axis girder bridges, and it allows exporting data in the IFC4x3 schema using a trial version. After defining the Standard Model, the exported IFC instances were checked using the trial version view model in the IFC4x3 schema available in Revit. The IFC validation consisted of three filters: 1) use of buildingSMART IFC Validation Service (v.0.6.2); 2) use of the following IFC viewers: BIMcollab Zoom (v.8.1), usBIM.viewer+ (v.9.00), and BIMvision (v.2.28.0); and 3) visual inspection directly on the exported .ifc file. These viewers were selected because they can import .ifc files in a schema superior of IFC4. All the information presented by the viewers or the data mapping tool was checked in the .ifc file through visual inspection.

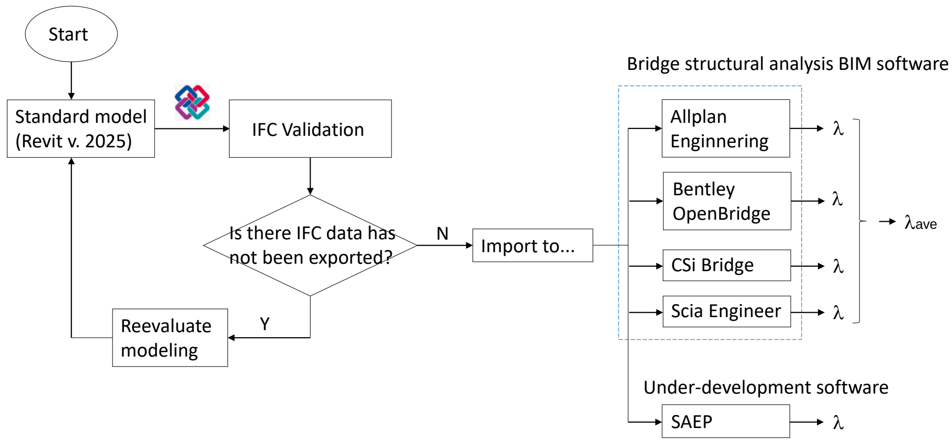

Figure 2. Proposed framework for determining each data flow's ILBSA

Source: Authors

The information checked refers to the minimum necessary for structural modeling, i.e., without considering the links between the elements and the application of the load acting on the structure. Therefore, the following information was considered in this work: 1) identification of elements; 2) general information, such as the name and global identity; 3) geometry, not only encompassing the visualization of the 3D solid but also the cross-section information, position of the element and the element × material relationship; 4) materials, such as the name of the property sets that encompass the material, category, name of the properties as specified by bSI, values of the properties and the units. The commercial software chosen does not support the import of .ifc files in the IFC4.3.2.0 schema. For these cases, we opted to export the Design Transfer View (DTV, IFC4 schema) model unofficially available in Revit v.2025. This version of the view model is suitable for structural modeling, allowing the receiving software to modify the information (Trzeciak & Borrmann, 2018). Finally, the IFC data was imported into the software, and the value of the ILBSA (represented by the symbol λ) was determined.

The results were evaluated using the λ values for each case, quantitatively comparing the unidirectional flow of information between Revit and commercial software for bridge modeling and structural analysis, using an average value (λ_{ave}), and between Revit and SAEP.

STANDARD MODEL'S FEATURES

Figure 3 shows a 3D view of the Standard Model, used as a case study and created by parameterizing the different elements in Revit. The girders were parameterized considering the cross-section extruded along its length, in addition to the enlargement at the ends as a second element, dependent on the dimensions of the cross-section and the total length. The pier cap beam was parameterized similarly, considering an extruded cross-section in addition to the chamfered sections at the ends as dependent elements. The parameterization of these elements is justified to reduce the density of information related to the geometric representation and to associate the material with the cross-sections of the extruded sections, making it easier to interpret the data. Slabs, pavements, and barriers were considered as elements generated by extruding an arbitrary profile in the longitudinal direction of the bridge.

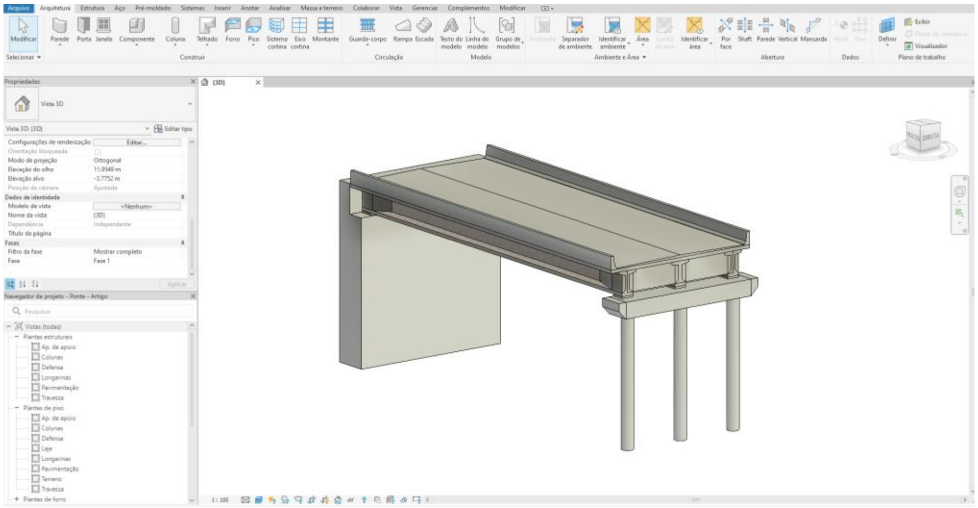

Figure 3. 3D view of the Standard Model

Source: Authors

The materials were associated with the typified elements, i.e., all bridge elements of the same type had the same properties as the user-defined materials. The import of information related to the bearings and the bridge abutment was not evaluated.

INTEROPERABILITY LEVEL FOR BRIDGE STRUCTURAL ANALYSIS (ILBSA)

Each bridge structural analysis software considered has an IFC data interpreter for the native data structure; however, some errors in data exchange can occur. The ILBSA indicator proposed in this work is defined as the percentage of information related to the structural analysis of concrete girder bridges with straight-axis, and this information was interpreted by bridge structural analysis software from an .ifc file exported by Revit. The information was analyzed and classified based on authors' expertise with data exchange between a BIM platform and structural analysis software. In addition, challenges of locating information within the structural analysis software and the rework time required to enter uninterpreted information were considered. To define the numerical value of the ILBSA, the information sets (Iset), the weights of each Iset, and the weights of each information were established, as shown in Table 1.

Table 1. Information sets (Iset) considered for each type of bridge element

Source: Authors

i. **Iset**	***i.j*** **Information name**	**δ_{ij} (%)**	**weight (ω_i)**
1. Iset_Semantics	1.1 *Predefined type*	100	0.25
2. Iset_GeneralInformation	2.1 *Name*	50	0.05
	2.2 *Global ID*	50	
3. Iset_Geometry	3.1 *Solid 3D*	10	0.50
	3.2 *Profile*	40	
	3.3 *Positioning*	30	
	3.4 *Material relationship*	20	
4. Iset_Material	4.1 *Material name*	5	0.20
	4.2 *Category*	5	
	4.3 *Properties name*	40	
	4.4 *Properties value*	25	
	4.5 *Unity*	25	

Table 1 indicates that the sets of information have been numbered from 1 to 4, and the weights of each Iset add up to a value of 1. These recommended weights values indicate the relevance of each Iset for the user who will receive this information. For example, the Iset related to materials (Iset_Material) has 20% relevance ($\omega 4$ = 0.20) about the sets of information analyzed. Each piece of information has a percentage transfer value to the structural analysis software. For example, the cross-section information (3.2 Profile) has 40% relevance to the information contained in the geometry-related Iset (Iset_Geometry) of a bridge element.

The information from the four sets is checked for each type of bridge element: 1) Girders; 2) Diaphragms; 3) Pier cap beams; 4) Columns; 5) Barriers; 6) Pavement; and 7) Slabs. Therefore, the ILBSA value for each data flow, represented by the symbol λ, is given by equation (1):

$$\lambda = \frac{\sum_{i=1}^{N}\left[\omega_i \cdot \sum_{k=1}^{n}\sum_{j=1}^{m}\left(\delta_{ij}\right)_k\right]}{n \cdot \sum_{i=1}^{N}\omega_i}$$

Equation 1. ILBSA - λ

Source: Authors

where i = 1, …, N is the index of each Iset; N is the number of Iset; k = 1, ..., n is the index of each type of bridge element; n is the number of bridge elements; j = 1, ..., m is the index of each information contained in the Iset; m is the number of information contained in each Iset; $(\delta_{ij})_k$ is the percentage value of the transfer of the *j-th* information contained in the *i-th* Iset, referring to the *k-th* type of bridge element; and ω_i is the weight of the *i-th* Iset.

The semantics of a bridge element are identified through the *PredefinedType* attribute of some subtype of *IfcBuiltElement*. Some BIM platforms export an unofficial model view that follows the IFC4x3 schema and covers the predefined types of bridge elements, such as Revit v.2025. For the structural analysis of a bridge from a model imported using an .ifc file, the exact identification of the elements is important for the association of the information in each of them and the automatic generation of the finite element mesh. Therefore, the 25% weight ($\omega 1$ = 0.25) considers the relevance of information as a requirement for identifying the bridge element. In addition, the weight value is higher than geometry Iset (50%) due to the ease of implementing the semantics' interpretation in structural analysis software.

The general information considered in this study was the name and the global identity, determined by the *Name* and *GlobalID* attributes of the *IfcRoot* abstract entity. Both parameters were considered in Iset_GeneralInformation, with 50% weight for each, and Iset with 5% total weight ($\omega 2$ = 0.05). The low weight of this information is justified by the ease with which it can be transferred to analysis software, without considerable computational effort in interpreting this IFC data. In addition, the user can edit the names of the bridge elements, reducing the relevance of this information.

The geometric representation of the bridge (Iset_Geometry) is the most relevant information set to be analyzed, with 50% weight ($\omega 3$ = 0.50). This can be explained by the wide coverage of IFC geometric representations, which makes data interpretation difficult for structural analysis software when there is a loss and inefficiency of geometric information. Geometric information with a low semantic level for structural analysis can lead to more rework than the rework to enter the other information. Therefore, considering both the relevance and amount of information, geometry has the highest weight value.

Geometry-related semantics cover not only the visualization of the 3D solid but also how the geometric representation has been considered in the structural model. The two-dimensional structural bridge analysis requires implicit geometric modeling information, such as cross-section information and element positioning, which is not easily found in Brep or tessellated solids. Parameterized geometric results in the use of more efficient finite elements and, consequently, generates less computational effort in the analysis. The relationship information that associates the material with the bridge element or cross-section is also considered.

Material properties must be interpreted, especially in cases where the strength of bridge elements needs to be determined and the user does not know these property values. The lack of this information may lead to destructive or non-destructive tests or even more costly solutions. Therefore, the information related to materials (Iset_Material) weighs 20% ($\omega 4$ = 0.20). The names of the properties associated with the material were given higher weight values than the weights relating to the values of the properties and their units since the Name attribute of the *IfcPropertySingleValue* entity must be equal to the name of the property defined by bSI. The following properties were considered for interpreting the IFC data: longitudinal modulus of elasticity and Poisson's ratio, contained in *Pset_MaterialMechanical* under the names *YoungModulus* and *PoissonRatio*, respectively; and material density, contained in *Pset_MaterialCommon* under the name *MassDensity*.

RESULTS

DETAILS OF ERRORS

Tables 2 to 5 show the main errors observed during the data exchange between Revit and the Allplan, Bentley, CSi Bridge, and Scia Engineer software. Semantic errors of the bridge elements result from the software's limited support for importing and exporting the IFC4x3 schema. Geometry errors include the misinterpretation of cross-sections and the incorrect positioning of the bridge elements. Regarding the interpretation of material information, only CSi Bridge performed well.

Information	Details of errors – Allplan
Semantics	Girders, diaphragms, pier cap beams, and pavement were not identified
General information	No errors were identified
Geometry	Elements with non-parametric cross-sections were not identified
Material	No material properties were identified

Table 2. Details of errors – Allplan

Source: Authors

Information	Details of errors – Bentley
Semantics	Girders, diaphragms, pier cap beams, and pavement were not identified
General information	No errors were identified
Geometry	Cross-section information and elements positioning were not identified
Material	No material properties were identified

Table 3. Details of errors – Bentley

Source: Authors

Information	Details of errors – CSi Bridge
Semantics	Girders, diaphragms, pier cap beams, pavement, and barriers were not identified
General information	No errors were identified
Geometry	Cross-section information for girders, barriers, and pavement were not identified
Material	Mass density and Young modulus not identified

Table 4. Details of errors – CSi Bridge

Source: Authors

Information	Details of errors – Scia Engineer
Semantics	Girders, diaphragms, pier cap beams, pavement, barriers, and slabs were not identified
General information	No errors were identified
Geometry	Relationship between material and bridge elements were not identified
Material	No material properties were identified

Table 5. Details of errors – Scia Engineer

Source: Authors

ILBSA VALUES

Figure 4 shows the ILBSA results for each flow, as well as the average ILBSA results for the unidirectional flow for each commercial structural analysis software. The ILBSA value for the Revit - SAEP flow was considerably higher than the average obtained for the Revit - commercial software workflow due to some advantages of SAEP over the other software.

All the software interpreted the name and global identity (*GlobalID*). This information is easily interpreted, requires minimal implementation effort, and is useful for correctly identifying bridge elements and structural analysis elements.

SAEP allows for the concrete girder bridge modeling by importing an .ifc file in the IFC4.3.2.0 schema, as well as modeling through the user's own data input. The modeling and structural analysis software analyzed cannot interpret the semantics of bridge elements, since it does not yet import .ifc files in the IFC4.3.2.0 schema, so the import was completed in the design model view in the IFC4 schema. Therefore, little can be gained from the imported model to carry out the structural analysis in each software, represented by the λ value of each flow.

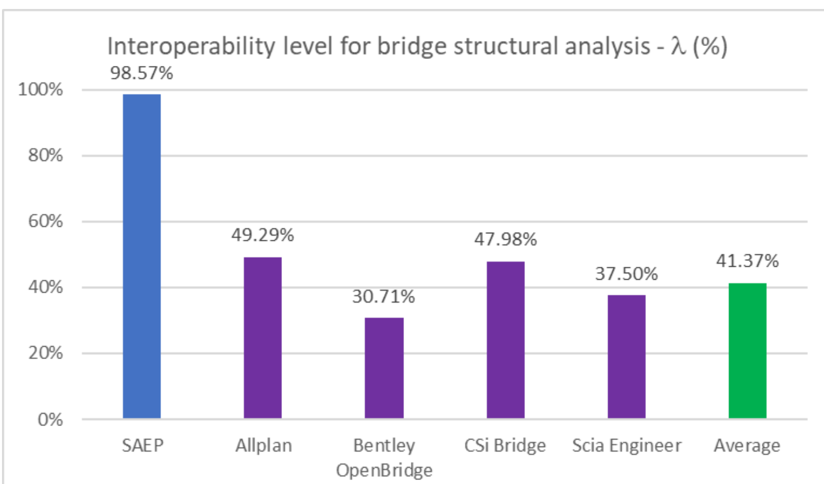

Figure 4. λ values (ILBSA) for each unidirectional workflow. The percentage values refer to the interoperability level for bridge structural analysis

Source: Authors

Figure 5 shows the percentage of geometry-related information (Table 1) that was interpreted by each software. The 51.16% value obtained for the average geometric information interpreted by the commercial software, compared to the 97.14% value obtained for the geometric information interpreted by SAEP, is justified by the low semantic level of geometry for structural analysis purposes interpreted by the commercial software. Determining the cross-section was the main information not interpreted by commercial software, especially in cases where the cross-sections of extruded elements were represented arbitrarily, using the *IfcArbitraryClosedProfileDef* entity. The information on the positioning of the cross-section of each bridge element, or the coordinates of the vertices of the elements about the global axis of the project, was only interpreted by the Scia Engineer. Elements with parametric cross-sections, represented by *IfcParameterizedProfileDef* subtypes, were interpreted correctly. SAEP can only visually represent elements extruded in a given direction, so sections with variable cross-sections are ignored for visualization purposes, which explains the 97.14% percentage of interpreted geometric information. Figure 6 shows the 3D view of the geometry of the standard model in each software.

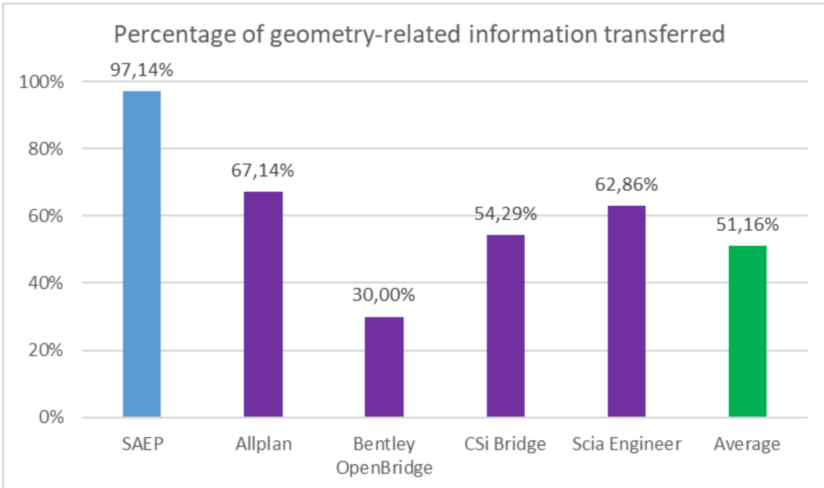

Figure 5. Percentage of geometry-related information that was interpreted in each software

Source: Authors

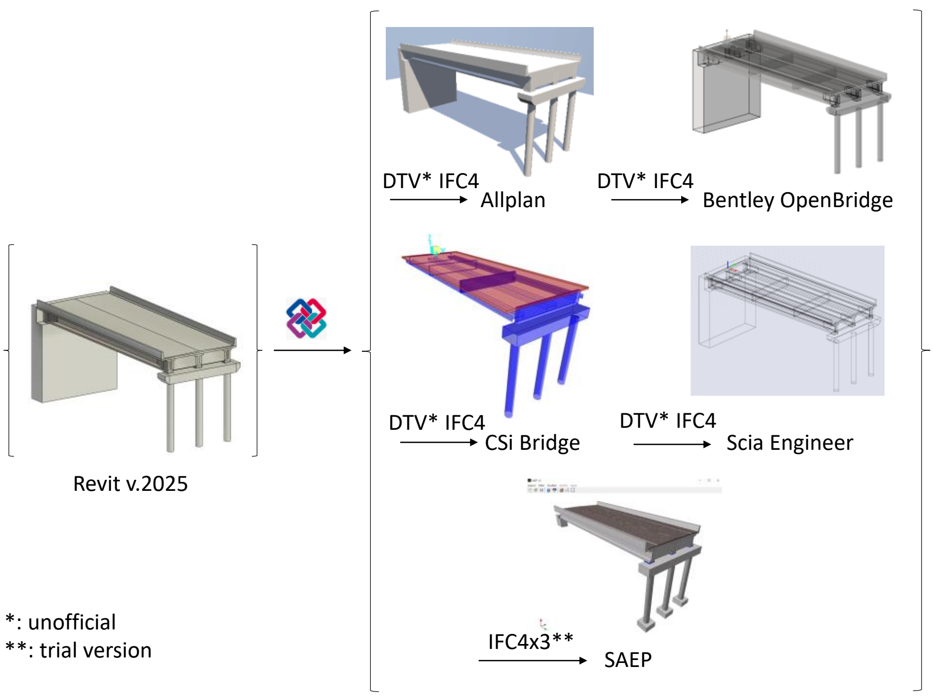

Figure 6. 3D view of the Standard Model in each software

Source: Authors

The association relationship between the material and the element, through the entity *IfcRelAssociatesMaterial*, was interpreted correctly in most of the elements analyzed. Apart from SAEP, only CSi Bridge identified the material category and the name of the properties, but with incorrect values. The Allplan, Bentley OpenBridge, and Scia Engineer software did not interpret the information related to material properties. The reason is that the *IfcMaterialProperties* entity, which is responsible for defining the properties of the materials associated with an instance of *IfcMaterial*, has not been interpreted.

CONCLUSION

This paper presents a methodology for quantitatively determining the interoperability level for structural analysis of concrete bridges with straight beams (ILBSA, mathematically represented by λ), defining the relevance of the information using weights. In addition, a novel IFC4.3.2.0 data interpreter was implemented in the SAEP to achieve a high level of interoperability for two-dimensional structural analysis of bridges.

Based on the results presented in this work, the following contributions can be highlighted:

- Definition of the ILBSA indicator: the ILBSA was developed for the subdomain of structural bridge modeling and analysis, and the methodology applied for its determination can be applied to other subdomains by defining weights, taking into account the relevance of the imported information;
- SAEP interpreted IFC data in the IFC4.3.2.0 schema: this functionality of SAEP represents an evolution over the commercial software evaluated in this study, which did not import .ifc files in the IFC4.3.2.0 schema and did not interpret bridge elements semantically;
- In addition to interpreting design view models in the IFC4.3.2.0 schema, SAEP allowed the interoperability from the import of reference view models: the commercial software evaluated in this work only allowed the import of design view models in the IFC4 schema, containing few information for structural analysis, according to the ⍰ values shown in Figure 2;
- Interpretation of Brep geometry and arbitrary cross-sections for structural analysis: SAEP interpreted Brep geometry, determining information related to the cross-section and positioning in the global axis. Arbitrary cross-sections, defined by *IfcArbitraryClosedProfileDef*, were interpreted and parameterized. The commercial software analyzed in this study did not parameterize an explicit geometric representation, which can lead to the consideration of three-dimensional finite elements, resulting in increased processing time in the analysis;
- Interpretation of material properties: SAEP interpreted the association relationship between the material and element, as well as material properties with names, values, and units. In general, the results showed that material properties were not interpreted by the commercial software investigated in this research.

The λ values showed that SAEP interpreted IFC4.3.2.0 data with a high semantic level. The conclusion that the amount of information that the user has to insert into the structural model to generate the analytical model is considerably less compared to other software.

The interpretation of design view models by the commercial software evaluated in this work still needs to be adjusted. Much of the relevant information is lost, and many parameters are not correctly defined. The ILBSA average value (λ_{ave}) showed that a few data can be used for structural analysis, requiring structural remodeling by the user. It can be concluded that there is an urgent need for structural bridge analysis BIM software developers to implement the reading and interpretation of design view models in the IFC4.3.2.0 schema, to make the workflow as effective as possible.

A suggestion for future research is the methodology to evaluate an interoperability level for interpretation of IFC4.3.2.0 data associated with concrete and steel-concrete bridge models with curved axes into the format corresponding to the analysis model, considering the native data structure of the receiving software and IFC.

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