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# BIM Interoperability for Structure Analysis

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## ABSTRACT

Building Information Modeling (BIM) is facilitating a procedural change for the architecture, engineering, and construction (AEC) industry to share information in all the phases of the life cycle of a building. It possesses great advantages in designing, analyzing, and documenting all physical and functional information of a building and construction project. Structural analysis is an integral part of the life cycle phases of building construction projects. The information needed for structural analysis originates from the architectural model, but the architectural model can be created without much consideration of structural analysis. Software tools used by architects and structural engineers are usually different and sustain information inconsistency and or missing information leading to software interoperability problems. As the first step towards addressing this issue, in this paper, the authors conducted a preliminary literature review in order to identify topics and trends on the BIM interoperability problem with a focus on the structural analysis domain, from both the theoretic perspective and the application perspective. Structural analysis is performed and discussed in the following sections to demonstrate interoperability problems and propose possible solutions.

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## INTRODUCTION

"Interoperability means the ability of information and communication technology (ICT) systems and of the business processes they support to exchange data and to enable the sharing of information and knowledge" (EIF 2004). This definition by the European Interoperability Framework (EIF) is readily applicable in the architecture, engineering, and construction (AEC) domain (EIF 2004). Traditionally, project information is shared through exchanging files in different formats, such as .dwg, .dxf, and .pdf, but appropriate levels of information cannot be transferred from one model to another in a straightforward way through such file exchange (Howell and Batcheler 2005). In order to better exchange and represent data in the AEC domain, the International Alliance for Interoperability (IAI) (former name of buildingSMART) developed a set of building product models including industry foundation classes (IFC). The IFC standard was first specified in 1996 (BuildingSMART 2007). It was constantly being developed and was registered as ISO 16739. IFC is currently the most widely used non-proprietary exchangeable format to represent building information and accelerate information exchange between AEC software (Volk et al. 2014). IFC-based BIM models are designed to be more interoperable than traditional CAD; and IFC has been used in information exchange in many scenarios (Volk et al.

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2014). This short review paper focuses on existing work and related background using IFC-based BIM models for information exchange between architectural and structural models, and identifying research gaps on this topic.

After years of development, the three main stages of which are shown in Table 1, IFC has helped simplify information flow in the AEC domain.

**Table 1. The Three Main Development Stages of IFC**

| Stages | Time | Development |
|---|---|---|
| First – Preliminary Stage | 1994-1999 | 1994.08 - An open standard (the precursor of IFC) for information exchange in the AEC industry was published.<br>1997.01 - IFC 1.0 was established with limited scope of information coverage.<br>1999.04 - IFC 2.0 was published with a focus on building services, cost estimation, and construction planning (Kiviniemi 2006). |
| Second – Improved Information Coverage of AEC Domain | 2000-2005 | 2000 - IFC 2X was published with more focus on underlying technical architecture.<br>2003.05 - IFC2X2 was released with a focus on 2D model support for facility management and building codes verification (Liebich 2010).<br>IFC 2X and IFC 2X2 cover 6 AEC subdomains: heating, ventilation and air-conditioning (HVAC), engineering, architecture, codes standards, cost estimating, facilities management, and simulation (Chen et al. 2005). |
| Third – Refinement Stage | 2006-now | 2006 - IFC3 was published (Kiviniemi 2006).<br>2010 - IFC4 was published and it keeps developing (Liebich 2010).<br>IFC3 and onward emphasizes integrated design and construction process |

## BIM INTEROERABILITY

The Knowledge Industry Survival Strategy (KISS) classification of BIM interoperability levels is used for modeling language check, information storage and exportation. KISS has five different levels: file and syntax level, visualization level, semantic level, alternative representations level, and parametric modeling level (Steel et al. 2012). The file and syntax level controls the media of exchange between different software tools and checks representations of model information in the files to ensure the model can run without errors in the different software tools (Steel et al. 2012). The visualization level is vital in BIM interoperability, given the multiple dimensions and the high level of complexity of BIM data. Visualization of BIM models can help identify such missing or inconsistent information, but the large size of a BIM model causes certain difficulty in its visualization in a comprehensive, detailed, and organized manner, especially when checking information consistency from model to model is taken into consideration. The semantic level addresses the exchange of real meanings between models. Alternative representations level explains that different simulations have different focus areas out of research needs or application

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needs, such as energy simulation and fire emergency exit simulation. Parametric modeling level defines parametric properties of models. An ultimate BIM interoperability needs to have successful and smooth information exchange at all these five levels.

IFC interoperability defines five layers to support deployable results in AEC projects (Figure 1), namely, IFC model specification, IFC model view definitions (MVDs), IFC implementations, exchange requirements, and process map. The relationships between these five layers can be represented as a pyramid shape, with each layer having a direct relationship with its neighbors. In addition, an information delivery manual (IDM) decides what information need to be delivered from one party to another at any given time for a successful communication process and affects several layers (Volk et al. 2014).

The lower level layers provide information requests to the upper level layers. The upper level layers respond to the requests through technological innovations and deployment. The lower level layers need to be aware of the feasibility of their requests' being accepted by the upper level layers to implement. Any noted limitations based on IFC data exchange requirements should be conveyed to software developers whose development and implementation rely on information provided by the upper level layers.

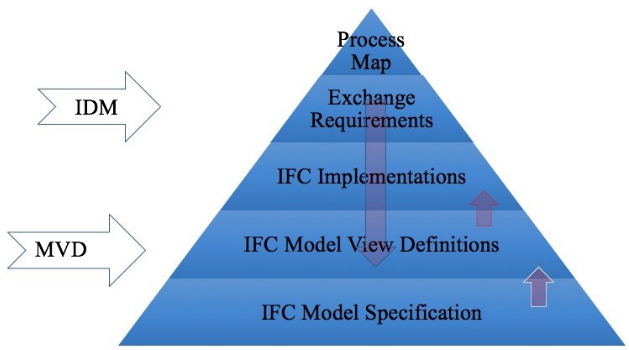


**Figure 1. IFC interoperability layers (Kiviniemi 2006)**

## RESEARCH GAP ANALYSIS IN ARCHITECTURAL/STRUCTURAL INTEROPERBILITY

Interoperability is the core of BIM information exchange in the AEC domain. In this paper, the authors focus on gap analysis of using IFC between architectural design and structural analysis, mainly from the standpoints of IFC extension and IFC file importation/exportation.

The IFC extension has two main levels: IFC concepts extension and IFC domain extension. In IFC concepts extension considerations, concepts can be classified into three main categories: concepts in an IFC model, concepts not in an IFC model, and newly introduced concepts (Wan et al. 2004). For example, in structural analysis, boundary conditions (e.g., restraints and release of frame elements) are usually manually added to an existing IFC model, and they must be compatible with existing information in this IFC model. How to add new concepts into an existing IFC model without causing conflicts with the existing information in the IFC model is an important consideration in such efforts. Lee and Kim (2011) proposed to add "IfcSpatialElement" for representing spatial elements in bridge structures. They added the "IfcSpatialElement" as a subconcept of "IfcElement". This addition allows representing spatial elements in a bridge model

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with enhanced clarity, while at the same time being compatible with existing parts of the bridge model. Markova, Dieckmann and Russell (2013) extended the IFC schema by adding the concepts "simulation and documentation," and "optimization" into the material section to enable material reuse feedback in order to reduce waste. Amann et al. (2015) added "IfcReferenceCurveAlignment2D" element into the IFC schema about a horizontal and a vertical alignment curve for road design applications.

IFC domain extension requires users' understanding in: (1) what input information is needed in this domain; and (2) how to minimize potential conflicts between the extension and similar definitions that already existed. How to apply IFC domain extension to AEC subdomains to better support information exchange between different BIM applications in those subdomains is an important problem that needs solving (Santos et al. 2017). For example, Sacks and his colleagues conducted the Rosewood experiment which improved the precasting workflow by extending IFC support from architectural design to construction applications. They also developed an Information Delivery Manual for both design and construction domains (Sacks et al. 2010). Zhang and El-Gohary (2016), on the other hand, extended IFC support from architectural design to building codes compliance checking through semi-automated IFC extension methods. For the problem of limited coverage of the IFC schema in supporting BIM interoperability (Eastman 1992), early work developed customized building models, but they did not integrate all the domains, e.g., the full interoperability from architectural design to structural analysis and beyond is yet to be achieved. IFC Extension and data exchange requirement standardization may solve this problem for BIM interoperability. Well-analyzed IFC files as well as their needed extensions could help broaden BIM information coverage to improve BIM interoperability.

From the software point of view, different software have different information coverage and different usage in the AEC industry. How to import an IFC file and export it for further analysis successfully is another important consideration for interoperability. Table 2 summarizes different BIM software and their information coverage related to structural analysis (Zeng et al. 2014).

**Table 2. Different BIM Software and Their Information Coverage (Zeng et al. 2014)**

| Software / Properties | Tekla Sturctures 18.1 | Etabs 9 | ArchiCAD 16 | SAP 2000 v15 | Revit Structure 2013 | IFC 4 |
|---|---|---|---|---|---|---|
| Geometric property | Yes | Yes | Yes | Yes | Yes | Yes |
| Material property | Yes | No | Yes | No | Yes | Yes |
| Structure analysis modeling | No | Yes | No | No | No | Yes |
| Load | No | No | No | No | No | Yes |
| Reinforcement information | Yes | No | No | No | No | Yes |
| Support restraint | No | No | No | No | No | Yes |

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From Table 2, we can see that different software cover different properties in their modeling. Therefore, when an IFC model is exported from one software and imported into another, certain information may miss or become untraceable. Redefining information manually is time-consuming and human error-prone. But without a full interoperability these manual input cannot be avoided. In the structural analysis domain, for example, when a shell element is being analyzed, the following information are needed but may not be successfully transferred using IFC models: new classes of load setting, combined material definition, different forces and moments (Wan et al. 2004). This requires direct support for IFC files and their processing in structural analysis software applications.

Even with direct IFC file support, missing information can still be a big problem in the importation/exportation of IFC files, especially those that are undetected (Kiviniemi 2008). To address this, developers have to manually check potential information loss before file exchange, or semi-automatically check it in order to avoid/reduce unknown information missing during the file exchange. Human-induced errors also need to be considered in such checking. The sizes and complexities of IFC models affect the importation/exportation process as well. Large models developed in more powerful platforms may contain information that is not directly interpretable in smaller platforms. One way to address this problem is to follow strict information requirements and MVDs to ensure the consistency of models across different platforms.

## BIM INTEROPERABILITY WITH STRUCTURAL ENGINEERING APPLICATIONS

To empirically test the interoperability of BIM for structural analysis, the authors conducted simple experiments using several structural analysis software as described in details below.

ETABS is a software that conducts linear structural analysis involving both static loads and dynamic loads (Kalny 2013). AutoCAD drawings can be imported directly into the ETABS software. Analysis in the ETABS software is based on spatial FEA and focuses on spatial features of the structure such as different earthquake zones for slabs. Objects are simulated by targeted geometric representations. Structural models can be transferred from IFC-based BIM to PKPM or YJK software, and further transferred to the ETABS software (Liu and Zhang 2015).

ABAQUS is a multi-function finite element software, especially suitable for non-linear analysis. It has a different type of database of material modeling comparing to other tools such as ETABS (with .e2k file) and SAP2000 (with .s2k file). For example, in ABAQUS, a structural model can be created directly by selecting material parameters in the GUI. Then processes affecting the structure such as welding and post weld heat treatment of the structure can be automatically simulated and analyzed. It supports both modeling and structural analysis. Model upload from other software (e.g., Pro-Engineer, NX, and Solidworks) is also supported. IFC data exchange to ABAQUS software is possible by using PKPM or YJK as an intermediary platform (Liu and Zhang 2015). Input files for ABAQUS can be manually written to do structural analysis. For example, ABAQUS reads material properties from input files using the following format: **MATERIAL, NAME=STEEL *ELASTIC 200. E9, 0.3*, meaning that this steel element has a Young's modulus of $200*10^9$ and a Poisson ration of 0.3.

SAP 2000 is designed by Computer and Structures Inc. in 2011. It is a civil engineering software used for designing and analyzing structural systems. It has buit-in model templates, and advanced analysis options, especially for 3D complex space structures. SAP 2000 can also be used

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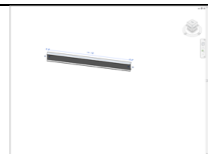
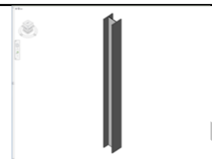
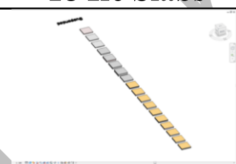
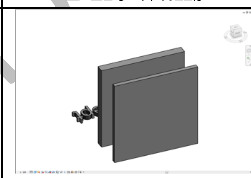
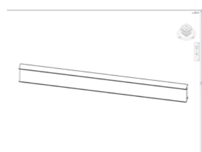
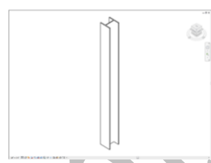
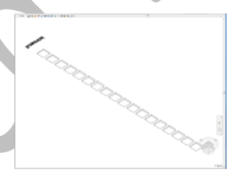
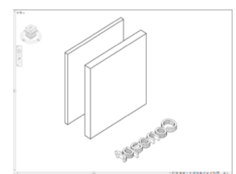
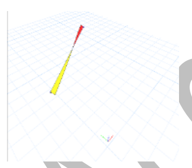
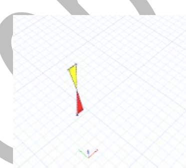
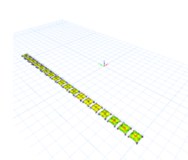
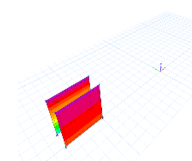
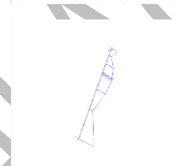
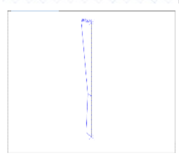
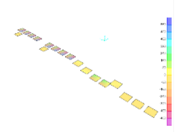
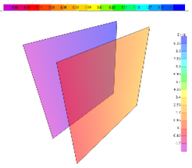
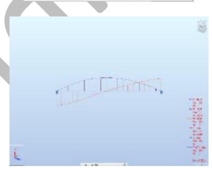
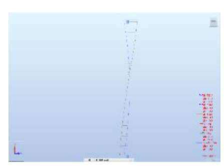
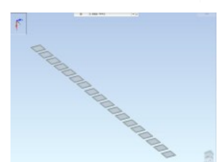
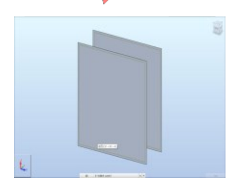
as a solver of other software, such as Tekla Structure software. Wind, wave, bridge and seismic loads can be automatically generated by integrated design code features (Fu 2015).

Autodesk Revit is part of the BIM software developed by Autodesk in 2014. It integrates many parts of different functions, such as architectural design, structural analysis, MEP engineering analysis, sustainability assessment and construction management support. Autodesk Revit Structure has many built-in architectural and structural templates. Models can be created from existing templates or by designing from scratch. In this paper, Autodesk Revit Structure software was used to create beam and column models for testing. Table 3 shows different types of files used in different software for the preliminary interoperability experiment, and their results of structural analysis.

**Table 3. Different Types of Files in Different Software Representation**

| Entities | 1 Ifc Beam | 1 Ifc Column | 18 Ifc Slabs | 2 Ifc walls |
|---|---|---|---|---|
| Original file in Autodesk Revit 2018 |  |  |  |  |
| IFC file exported |  |  |  |  |
| Structural analysis results in ETABS |  |  |  |  |
| Structural analysis results in SAP2000 |  |  |  |  |
| Structural analysis results in Autodesk Robot |  |  |  |  |

In this experiment, Revit files were imported into Autodesk Revit, and exported as IFC files. The IFC files were imported into different software, such as ETABS, SAP 2000, and Autodesk Robot to conduct structural analysis. Four types of objects were used, namely, beam, column, slab, and wall. Beam and column models were created in Autodesk Revit Structure software directly, whereas slabs and walls models were downloaded from online sources. Table 4 shows the property representations of the models in different software for structural analysis,

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including material properties, section properties, degree of freedom, and load description.

IFC file was used as the standard file to test the interoperability between architectural design and structural analysis. During this import/export process, a few problems occurred that caused unsuccessful import/export results. For example, when IFC files were created in the Autodesk Revit Structure and imported into Autodesk Robot for structural analysis, material property was missing and loads information could not be loaded. Autodesk Revit Structure is good for processing large building models, but for simple models, such as a beam or column, boundary conditions such as a pin on certain point/node/element cannot be directly loaded. Secondly, when IFC files were imported, Autodesk Robot could not read material information from the IFC files. It caused information missing when IFC files were imported into Autodesk Robot. That was the reason why we had no structural analysis results for slabs and walls (Table 3) when using Autodesk Robot. If Autodesk Robot can read IFC input files directly like ABAQUS as we explained above, the problem in loading forces information for the created models could be solved.

**Table 4. Properties Representations in Different Software**

| Software | Entities | Material properties | Section properties | Degree of freedom | Load |
|---|---|---|---|---|---|
| ETABS | 1Ifcbeam | Steel ASTM A992 | Frame W12*26 | UX UY RX RY | Trapezoidal |
| | 1Ifccolumn | Steel ASTM A992 | Frame W10*49 | UZ RZ | Trapezoidal |
| | 18Ifcslabs | nbl_DeckBeamAndBlock150 | Slab nbl_DeckBeamAndBlock150 | UZ RZ | Uniform $2kN/mm^2$ |
| | 2Ifcwalls | nbl_concept | Wall nbl_concept150.000 | UY UZ RY RZ | Uniform $2kN/mm^2$ |
| SAP2000 | 1Ifcbeam | Steel ASTM A992 | Frame W12*26 | UX UY RX RY | Trapezoidal |
| | 1Ifccolumn | Steel ASTM A992 | Frame W10*49 | UZ RZ | Trapezoidal |
| | 18Ifcslabs | nbl_DeckBeamAndBlock150 | Slab nbl_DeckBeamAndBlock150 | UZ RZ | Uniform $2kN/mm^2$ |
| | 2Ifcwalls | nbl_concept | Wall nbl_concept150.000 | UY UZ RY RZ | Uniform $2kN/mm^2$ |

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| | | | | | |
|---|---|---|---|---|---|
| Autodesk Robot | 1Ifcbeam | Steel ASTM A992 | Frame W12*26 | UX UY RX RY | Trapezoidal |
| | 1Ifcolumn | Steel ASTM A992 | Frame W10*49 | UZ RZ | Trapezoidal |

Table 5 compares different software from a user's perspective through a small comparative experiment. ETABS and SAP 2000 turned out to be easier to learn and use, whereas Autodesk Robot is more complex but more powerful.

**Table 5. Advantages and Disadvantages of Different Software**

| Software | IFC Import | Time Consumed | Feasibility | Common |
|---|---|---|---|---|
| ETABS | Yes | 10 minutes | Properties need to be set manually, it may cause human error | Autodesk Robot is more complicated to use than ETABS and SAP 2000, it is not an analysis solver, but it has good compatibility with design software to import model structure quickly |
| SAP 2000 | Yes | 10 minutes | Properties need to be set manually, it may cause human error | |
| Autodesk Robot | Yes | 20 minutes | Material properties may be missing when importing IFC models | |

In addition, further gaps were identified in using IFC to support BIM interoperability with structural analysis. One such gap is reflected in the use of a "top-down" approach in representing model elements and tracking semantic changes of elements between different models. This "top-down" approach yields complex data representations and large file sizes, which is hard to program and implement in a software. IFC uses the "top-down" and relational approach to track all the semantic changes when one parameter in the schema changed. This keeps data integrity automatically but can become an obstacle to processing large data file (Lam et al. 2012). In comparison, gbXML uses the "bottom-up" approach, which is more flexible and less complex. A second gap identified is the lack of tools and methods in addressing model information distortion and geometric precision lost problems (Lam et al. 2012). Future research is needed to address these research gaps to improve IFC-based BIM interoperability for structural analysis, through efforts in, for instance, reducing misinterpretation of modeling information passed to structural analysis by establishing data exchange criteria, interfaces, and standard tools.

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## CONCLUSION

Interoperable data exchange is important in the architecture, engineering, and construction (AEC) domain because of: (1) the collaborative nature of the domain; and (2) the many differences in the tools and data formats used by different stakeholders. In this paper, the authors conducted a preliminary literature review about BIM interoperability trying to identify topics and trends on the BIM interoperability problem with a focus on the structural analysis domain, from both the theoretic perspective and the application perspective. Based on the review and preliminary experimental analysis, research gaps were identified in the BIM interoperability with structural analysis area where future researches are recommended: (1) the need of better information coverage in the IFC schema; (2) the need of stronger IFC importation/exportation support in structural analysis software; (3) the lack of methods other than the "top-down" approach in representing model elements and tracking semantic changes of elements between different models; and (4) the lack of tools and methods in addressing model information distortion and geometric precision lost problems. Addressing these research gaps can improve interoperability of IFC-based BIM, and therefore facilitate information flow between different parties in the AEC domain with a central model/database, resulting in a simpler information flow pattern and less interoperability problems.

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