INL/CON-23-75955-Revision-0

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March 2024

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division XI

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ABSTRACT

There is a growing need in the AEC industry for the digitalization of model-based data exchange in BIM workflows. However, users continue to face difficulties exchanging data between BIM-based computer-aided design (CAD) and computer-aided engineering (CAE) software, even with the open, non-proprietary data exchange format called Industry Foundation Classes (IFC). Proposed solutions in academic research focus primarily on building systems, with comparatively little attention to piping models. Therefore, this paper introduces an interoperability tool for enabling piping model data exchange between architectural and structural analysis domains. The tool is tested using a piping model created in Autodesk Revit and shows marked improvement for IFC-based CAD-to-CAE interoperability over existing practice.

INTRODUCTION

Projects in the architectural, engineering, and construction (AEC) industry often experience cost overruns and are not finished according to schedule (Agarwal et al., 2016). For example, in the cases of the Vogtle nuclear facility and the V.C. Summer site, Adams (2014) describes how redesigns requiring regulatory approval led to schedule delays and increased expenses. The greatest potential for overcoming these challenges lies in the industry's digital transformation, spearheaded by the growing adoption of BIM-based methods and technologies (Construction, 2014; Holzer, 2016; Ramaji and Memari, 2018). In particular, a fully integrated, digitalized design environment involving architects and structural engineers necessitates the ability for data exchange between computer-aided design (CAD) and computer-aided engineering (CAE) software. Using BIM for such engineering analysis purposes has the potential to save time and cost through automation and to achieve higher quality and better performance in buildings (Alwisy et al., 2012; Gane and Haymaker, 2007; Sacks and Barak, 2008; Sandhu et al., 2023a, 2022, 2023b). However, according to a McGraw Hill industry survey (Construction, 2014), despite having the highest frequency index, which measures the frequency with which BIM is used for a process, structural analysis had the second-lowest value/difficulty ratio among industrial professionals. In other words, there is a high demand for BIM interoperability for structural analysis, but this particular BIM use is currently inefficient for industry practice. Improving BIM interoperability for structural analysis is key to achieving an integrated design-construction environment that enables risk-informed decision-making for project deviations.

Sibenik and Kovacic (2020) conduct a literature review and comparative software study to assess the performance of CAD-to-CAE interoperability for BIM-based software. Their literature review found that the majority of the research efforts of the academic community have focused on improving BIM-based data exchange via the IFC open file format (Hassanien Serror et al., 2008; J. Ramaji and Memari, 2016; McCarn, 2020; Oh et al., 2015; Qin et al., 2011; Ramaji and Memari, 2018; Wan et al., 2004; Weise et al., 2003). Industry Foundation Classes (IFC) is the standard format for open and non-proprietary BIM model-based data exchange. IFC characterizes objects, their properties, and their relationships, and over 150 software tools claim to support the IFC schema, either for import and/or export of IFC data models, including leading CAD and CAE software applications. IFC is developed by building SMART International (bSI) and is ISO certified (ISO 16739-1:2018) (ISO, 2018).

There is a substantial body of research offering proposals for improving BIM CAD-to-CAE software interoperability using IFC for architectural designs of buildings, as discussed in Sibenik and Kovacic (2020). However, there are comparatively far fewer studies regarding improving BIM interoperability for piping designs. Perrone and Filiatrault (2017) presents an Excel-based application for the automatic seismic analysis of piping systems utilizing IFC-imported BIM data. However, the procedure only imports geometric properties of piping, requiring users to manually submit other necessary parameters, such as section properties. Crowder et al. (2022) presents a tool for transforming IFC files of piping models exported from the CAD software Revit into structural analysis models for the CAE software ANSYS. However, the scope of that study is limited to improving bilateral data exchange between Revit IFC files and ANSYS, which does not satisfy the need for a generalized solution for BIM interoperability for piping.

To address the need for BIM interoperability of piping models between the architectural and structural analysis domains, this paper presents a BIM interoperability tool for converting architectural IFC files of piping into automatically generated structural analysis models. The essential functionality of the tool is to convert IFC4 files from the original architectural sub-schema representation, known as IFC4 Reference View (RV), into the equivalent structural analysis sub-schema representation, known as an IFC4 Structural Analysis View (SAV). By keeping the piping model data in the IFC data model format, the resulting structural analysis representations can be more readily imported and tested in a number of IFC-compliant software. The BIM interoperability tool for piping is tested on a number of CAD and CAE software in order to showcase the practical implications and improvement over existing model data exchange practices.

BIM-BASED SOFTWARE AND DESCRIPTION OF PIPING MODEL USED IN THIS STUDY

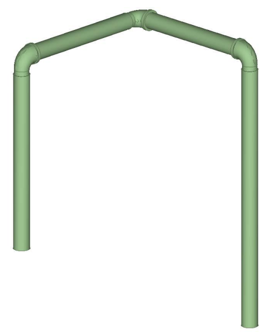
This study assesses the one-way interoperability from one BIM-based CAD to three CAE software. Table 1 details these commonly used BIM-based software, their parent companies, their versions, and a link to the respective companies' websites. To assess the current IFC capabilities of the software under consideration, the author employs the most recent versions available at the time of writing in August 2023. Revit is capable of exporting and importing IFC4 RV but not IFC4 SAV. SAP2000 and RFEM are capable of exporting and importing IFC4 RV and IFC4 SAV. ANSYS has no IFC export or import capabilities.

One commercial piping model from Autodesk Revit is considered in the CAD-to-CAE interoperability tests in this study. The piping model is hereby referred to as the "SimplePiping" model. Figure 1a shows the original SimplePiping model created in Revit, and Figure 1b shows the exported IFC4 RV file. The IFC4 RV file contains seven IFC entities: four IfcPipeSegment of steel material with a Schedule 40 NPS 2 designation and three IfcPipeFitting elbows of steel material with an unspecified designation.

Table 1: List of BIM-based Software Adopted for Piping Interoperability Tests

Platform	Company	Software	Version	Website
CAD	Autodesk	Revit	2024	www.autodesk.com
CAE	CSI	SAP2000	23.0.0	www.csiamerica.com
	Dlubal	RFEM	6.02	www.dlubal.com
	ANSYS	Mechanical APDL	2022 R2	www.ansys.com

(a) Original Revit Model



(b) Exported IFC4 RV

Figure 1. Revit SimplePiping Model

ASSESSMENT OF IFC IMPORT INTO STRUCTURAL ANALYSIS SOFTWARE USING EXISTING PRACTICE

This section presents an assessment of one-way IFC-based BIM interoperability for piping between the CAD software Revit and the CAE software RFEM and SAP2000. The purpose of this assessment is to emphasize the deficiencies in IFC-based model data exchange for simple piping between Revit and the CAE software of interest. This assessment is not a comparative study for generalizing the IFC-based interoperability performance of CAD and CAE writ large. ANSYS Mechanical APDL is not considered for this evaluation because it lacks IFC support. The assessment is performed by importing the IFC4 RV file of the Revit SimplePiping model into SAP2000 and RFEM, as shown in Figure 2. For the IFC4 RV import into SAP2000, the following observations are made:

- SAP2000 does not recognize IFC piping elements, therefore all of the IfcPipeSegment and IfcPipeFitting objects fail to import.
- Due to the complete failure to import the model, the piping model would need to be wholly reconstructed.

For the IFC4 RV import into RFEM, the following observations are made:

- After converting the raw imported geometry to RFEM native objects, the geometry of the elbows is incorrect, and no section or material data is recognized.
- Due to the missing information and incorrect geometry for elbows, the imported model requires substantial rework before it can be used for structural analysis.

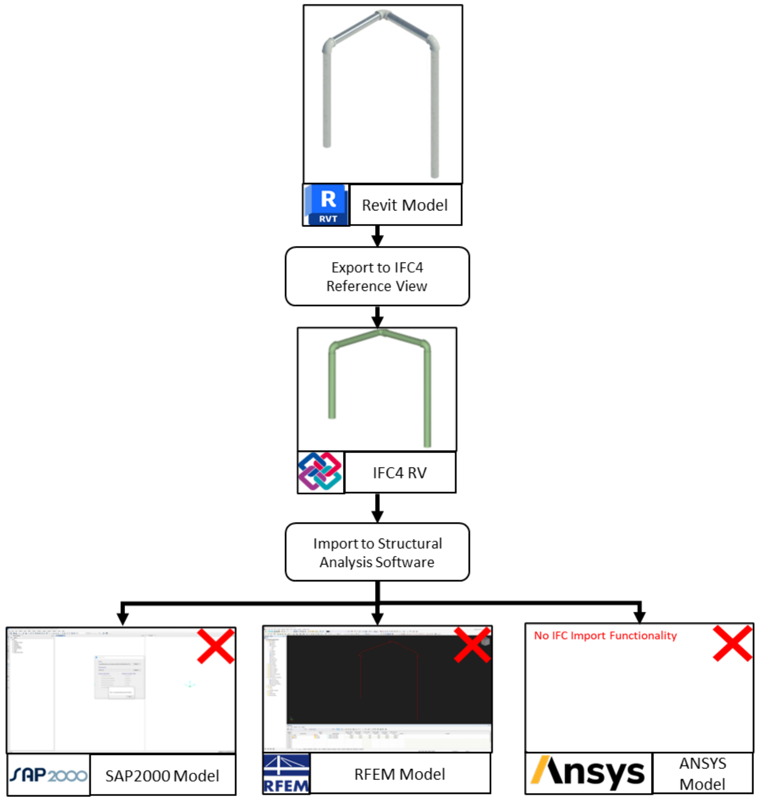


Figure 2. Assessment of IFC Import Using Existing Practice

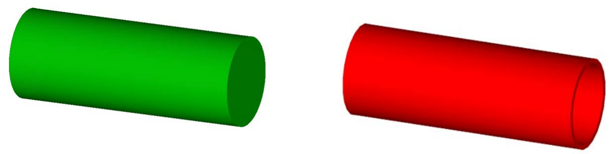
For both CAE software, the imported piping model data from Revit is either unusable or requires substantial rework.

METHODOLOGY OF BIM INTEROPERABILITY TOOL FOR PIPING ENTITIES

This section briefly describes the methodology for the interpretation mechanisms of the developed BIM interoperability tool that concerns the conversion of IFC4 RV architectural entities for piping, namely IfcPipeSegment and IfcPipeFitting, to their IFC4 SAV structural analysis element counterparts, namely IfcStructuralCurveMember. The scope of discussion for the conversion mechanisms is limited to linear piping elements. Therefore, only straight IfcPipeSegments and IfcPipeFittings that represent coupling elements and tee joints are discussed, but curved elements such as elbows are not.

IfcPipeSegment - Conversion from IFC4 RV to IFC4 SAV

This subsection briefly describes the interpretation mechanism used to convert the IFC4 RV representation of pipe segments (i.e., IfcPipeSegment) to the equivalent IFC4 SAV representation (i.e., IfcStructuralCurveMember). The interpretation mechanism follows a similar conversion procedure for structural frame members (i.e., IfcBeam, IfcColumn, IfcMember), introduced in Crowder et al. (2022) and refined in Crowder (2023), but with one modification. If the pipe wall thickness of the IfcPipeSegment cannot be determined by the solid body representation provided in the IFC4 RV file, as is often the case where IfcPipeSegments are represented only as solid cylindrical bodies, then the missing thickness parameter must be accounted for. The measured outer diameter of the IfcPipeSegment is matched to the closest outer diameter of a standard Schedule 40 steel pipe. Then, the outer diameter and the thickness of



(a) Original IFC4 RV (b) New IFC4 SAV[a]

Figure 3. IfcPipeSegment - Conversion from IFC4 RV to IFC4 SAV

[a] 3D Sweptsolid representation overlaid the actual wireframe representation for visual clarity

the converted IfcPipeSegment take on the values of that particular Schedule 40 pipe. Figure 3 and Table 2 summarize the conversion of a typical IfcPipeSegment from an IFC4 RV file. Note that the outer diameter and thickness of the resulting hollow circular IfcStructuralCurveMember is based on an assumed pipe size of Schedule 40 NPS 4.

Table 2: IfcPipeSegment - Conversion from IFC4 RV to IFC4 SAV

Property	Original IFC4 RV Representation	Converted IFC4 SAV Representation
IFC Class	IfcPipeSegment	IfcStructuralCurveMember
RepresentationType	SweptSolid	Edge
Designation	Unspecified	Sch. 40 NPS 4[a]
Outer Diameter (mm)	114.3	114[b]
Thickness (mm)	Unspecified	6[b]
Material	Steel	S355 Steel
No. of Elements	1	1

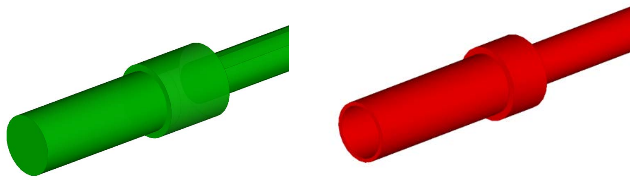
[a] Assumed based on best match
[b] Based on assumed pipe schedule

IfcPipeFitting - Conversion from IFC4 RV to IFC4 SAV

This subsection briefly describes the interpretation mechanism used to convert the IFC4 RV representation of pipe fittings (i.e., IfcPipeFitting) to the equivalent IFC4 SAV representation (i.e., IfcStructuralCurveMember). IfcPipeFittings are a general IFC class that can represent a number of different pipe fittings such as couplings, tee joints, elbows, closures, flanges, and others. Developing a general interpretation mechanism for pipe fittings capable of directly analyzing all the diverse geometry and types of such components can be impractical. Therefore, an implicit interpretation mechanism is utilized whereby the spatial locations and section properties of pipe fittings are inferred based on the properties and arrangement of adjoining pipe segments.

Evaluating IfcPipeFitting as a Coupling

If the number of neighboring IfcPipeSegments is two and the angle between the two neighboring IfcPipeSegments is 0°, then the IfcPipeFitting is classified as a coupling. The geometry of the IfcPipeFitting is assumed to be a line whose starting and ending points are determined by the adjacent nodes of two neighboring converted IfcPipeSegments, resulting in one IfcStructuralCurveMember. For the section data of the IfcPipeFitting coupling, the outer diameter is taken as the maximum dimension of the two end surfaces of the coupling, and the inner diameter is taken as the average of the inner diameters of the two neighboring IfcPipeSegments. Figure 4 and Table 3 summarize the conversion of a typical IfcPipeFitting classified as a coupling.



(a) Original IFC4 RV (b) New IFC4 SAV[a]

Figure 4. IfcPipeFitting (Coupling) - Conversion from IFC4 RV to IFC4 SAV

[a] 3D Sweptsolid representation overlaid the actual wireframe representation for visual clarity

Table 3: IfcPipeFitting (Coupling) - Conversion from IFC4 RV to IFC4 SAV

Property	Original IFC4 RV Representation	Converted IFC4 SAV Representation
IFC Class	IfcPipeFitting	IfcStructuralCurveMember
RepresentationType	SweptSolid	Edge
Designation	Unspecified	-
Outer Diameter (mm)	108	108
Thickness (mm)	Unspecified	21.5[a]
Material	Steel	S355 Steel
No. of Elements	1	1

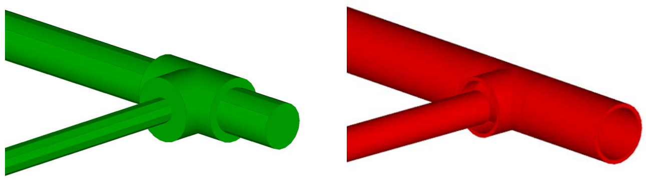
[a] Based on average inner diameter of neighboring pipe segments

Evaluating IfcPipeFitting as a Tee Joint

If the number of neighboring IfcPipeSegments is three, then the IfcPipeFitting is classified as a tee joint. The geometry of the IfcPipeFitting is assumed to consist of three lines whose geometry is determined by the spatial arrangement of the three neighboring IfcPipeSegments. The three lines share a common starting point at the geometric center of the IfcPipeFitting, while their independent endpoints coincide with the endpoints of their respective closest adjacent IfcPipeSegment. The section data of the IfcPipeFitting tee is assumed to match the section data of the largest neighboring IfcPipeSegment. Figure 5 and Table 4 summarize the conversion of a typical IfcPipeFitting classified as a tee joint.

Evaluating IfcPipeFitting as an Elbow

If the number of neighboring IfcPipeSegments is two and the angle between the two neighboring IfcPipeSegments is greater than 0° and less than 180°, then the IfcPipeFitting is classified as an elbow. The conversion procedure for an elbow is beyond the scope of discussion for this paper.



(a) Original IFC4 RV (b) New IFC4 SAV[a]

Figure 5. IfcPipeFitting (Tee) - Conversion from IFC4 RV to IFC4 SAV

[a] 3D Sweptsolid representation overlaid the actual wireframe representation for visual clarity

Table 4: IfcPipeFitting (Tee) - Conversion from IFC4 RV to IFC4 SAV

Property	Original IFC4 RV Representation	Converted IFC4 SAV Representation
IFC Class	IfcPipeFitting	IfcStructuralCurveMember
RepresentationType	SweptSolid	Edge
Designation	Unspecified	Sch. 40 NPS 2[a]
Outer Diameter (mm)	84	60.1[b]
Thickness (mm)	Unspecified	3.9[b]
Material	Steel	S355 Steel
No. of Elements	1	3

[a] Assumed based on neighboring pipe segments
[b] Based on assumed pipe schedule

ASSESSMENT OF IFC IMPORT INTO STRUCTURAL ANALYSIS SOFTWARE USING INTEROPERABILITY TOOL

This section presents an assessment of one-way IFC-based BIM interoperability for piping between the CAD software Revit and the CAE software RFEM and SAP2000 using the author's BIM interoperability tool for converting IFC4 RV files into IFC4 SAV files. The purpose of this assessment is to showcase the application of the interoperability tool and discuss how the results show improvement over existing practice.

The assessment is performed by converting the IFC4 RV file of the Revit SimplePiping model into an IFC4 SAV file and then importing the IFC4 SAV file into SAP2000 and RFEM, as shown in Figure 6. The yellow and red coloring of the IFC4 SAV pipe segment and elbow elements are visual indicators for the end user that signify missing material data. Yellow indicates that the material grade of the element is assumed, while red indicates that the material grade and type of the element are assumed. A post-processing function of the interoperability tool also translates the IFC4 SAV file into a text file containing macro commands for generating a structural model within ANSYS. For the IFC4 SAV import into SAP2000, RFEM, and ANSYS,

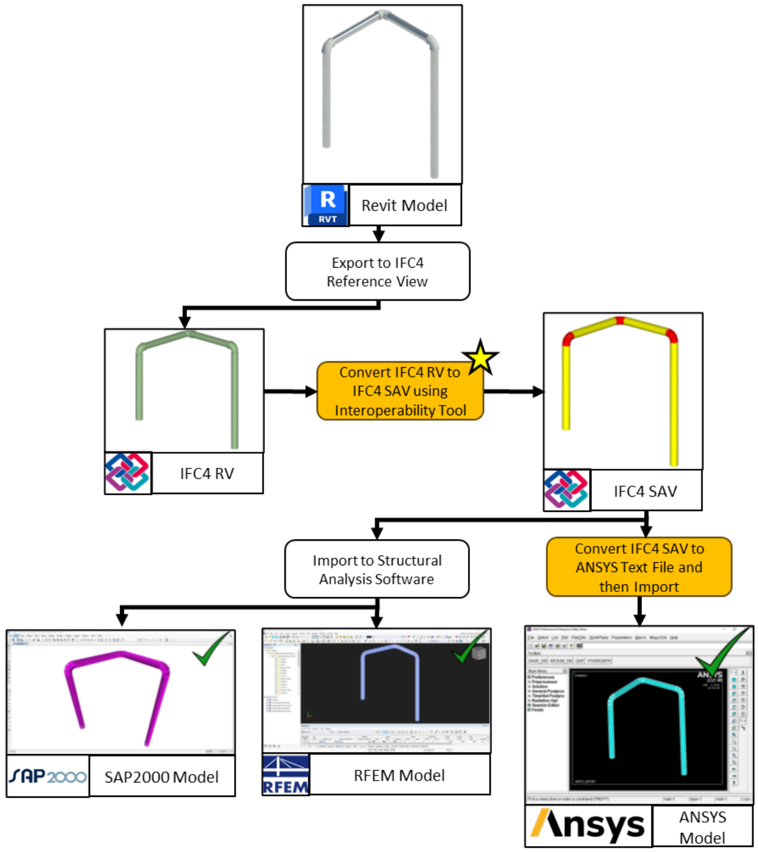


Figure 6. Assessment of IFC Import Using Interoperability Tool

the following observations are made:

- Nearly all the structural information is accurately represented in the IFC4 SAV file, but missing material information must be compensated for and the elbow sizes should be checked.
- The CAE software recognize and properly represents all structural element information present in the IFC4 SAV file, and the elements are properly connected.
- Correcting the material properties and checking the elbow sizes requires minimal rework before the model is ready for structural analysis.

SUMMARY AND CONCLUSIONS

There is a growing need in the AEC industry for the digitalization of model-based data exchange in BIM workflows. However, users continue to face difficulties exchanging data between BIM-based computer-aided design (CAD) and computer-aided engineering (CAE) software, even with the open, non-proprietary data exchange IFC format. Proposed solutions in academic research focus primarily on building systems, with comparatively little attention to piping models. Therefore, this paper introduces an interoperability tool for enabling piping model data exchange between architectural and structural analysis domains. The essential functionality of the tool is to convert architectural IFC4 Reference View (RV) files to the analytical IFC4 Structural Analysis View (SAV) file format. The tool is tested using a piping model created in the

CAD software Autodesk Revit. The Revit piping model is exported to the IFC4 RV file format, converted into the IFC4 SAV file format using the author's interoperability tool, and then the converted model is imported into the CAE software SAP2000, RFEM, and ANSYS. The automatically generated structural analysis models require minimal rework before use, which shows marked improvement in IFC-based CAD-to-CAE interoperability over existing practice. The interoperability tool has certain limitations, namely that it does not cover the breadth of IFC classes for other pipe components, such as IfcValve for valves. The tool also must oftentimes assume missing object information, such as pipe sizes and material data, in order to generate workable structural analysis models. Future work and publications will showcase interpretation mechanisms for elbows and valves and will test more complex piping models from other BIM software, such as AVEVA E3D.

REFERENCES

Adams, R. (2014). "Root Cause of Vogtle and VC Summer Delays." https://www.ans.org/news/article-1646/root-cause-of-vogtle-and-vc-summer-delays/.

Agarwal, R., Chandrasekaran, S. and Sridhar, M. (2016). "Imagining construction's digital future." *Capital Projects and Infrastructure*.

Alwisy, A., Al-Hussein, M. and Al-Jibouri, S. H. (2012). *BIM Approach for Automated Drafting and Design for Modular Construction Manufacturing*, pp. 221–228.

Construction, M. H. (2014). "The business value of BIM for construction in major global markets: How contractors around the world are driving innovation with building information modeling." *Smart MarketReport*, pp. 1–60.

Crowder, N., Lee, J., Gupta, A., Han, K., Bodda, S. and Ritter, C. (2022). "Digital Engineering for Integrated Modeling and Simulation for Building-Piping Systems Through Interoperability Solutions." *Nuclear Science and Engineering*, 196(sup1), pp. 260–277.

Crowder, N. C. (2023). *Improving Digital Engineering Workflows by Enabling BIM Interoperability for Structural Analysis and Facilitating Accurate Modeling of Building, Equipment, and Piping Systems*. Ph.D. thesis, North Carolina State University.

Gane, V. and Haymaker, J. (2007). "Conceptual design of high-rises with parametric methods." In *Predicting the Future, 25th eCAADe Conference Proceedings*, pp. 293–301, Citeseer.

Hassanien Serror, M., Inoue, J., Adachi, Y. and Fujino, Y. (2008). "Shared computer-aided structural design model for construction industry (infrastructure)." *Computer-Aided Design*, 40(7), pp. 778–788, ISSN 0010-4485, current State and Future of Product Data Technologies (PDT).

Holzer, D. (2016). *The BIM Manager's Handbook: Guidance for Professionals in Architecture, Engineering, and Construction*. Wiley, ISBN 9781118982341.

ISO (2018). "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries (ISO 16739-1:2018)." https://www.iso.org/standard/70303.html.

J. Ramaji, I. and Memari, A. (2016). "Interpreted Information Exchange: Systematic Approach for BIM to Engineering Analysis Information Transformations." *Journal of Computing in Civil Engineering*, 30, p. 04016028.

McCarn, S. A. (2020). “Integrated Approach to Design and Construction using Building Information Modeling.”

Oh, M., Lee, J., Hong, S. W. and Jeong, Y. (2015). “Integrated system for BIM-based collaborative design.” *Automation in Construction*, 58, pp. 196–206, ISSN 0926-5805.

Perrone, D. and Filiatrault, A. (2017). “Automated seismic design of non-structural elements with Building Information Modelling.” *Automation in Construction*, 84, pp. 166–175.

Qin, L., Deng, X.-Y. and Liu, X.-L. (2011). “Industry foundation classes based integration of architectural design and structural analysis.” *J. Shanghai Jiaot. Univ.*

Ramaji, I. J. and Memari, A. M. (2018). “Interpretation of structural analytical models from the coordination view in building information models.” *Automation in Construction*, 90, pp. 117–133, ISSN 0926-5805.

Sacks, R. and Barak, R. (2008). “Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice.” *Automation in Construction*, 17(4), pp. 439–449, ISSN 0926-5805.

Sandhu, H. K., Bodda, S., Sauers, S. and Gupta, A. (2023a). “Condition Monitoring of Nuclear Equipment-piping Systems Subjected to Normal Operating Loads Using Deep Neural Networks.” *Journal of Pressure Vessel Technology*, pp. 1–35.

Sandhu, H. K., Bodda, S. S. and Gupta, A. (2022). “Post-hazard condition assessment of nuclear piping-equipment systems: Novel approach to feature extraction and deep learning.” *International Journal of Pressure Vessels and Piping*, p. 104849.

Sandhu, H. K., Bodda, S. S. and Gupta, A. (2023b). “A Future with Machine Learning: Review of Condition Assessment of Structures and Mechanical Systems in Nuclear Facilities.” *Energies*, 16(6), ISSN 1996-1073, doi:10.3390/en16062628.

Sibenik, G. and Kovacic, I. (2020). “Assessment of model-based data exchange between architectural design and structural analysis.” *Journal of Building Engineering*, 32, p. 101589, ISSN 2352-7102.

Wan, C., Chen, P. H. and Tiong, R. L. K. (2004). “Assessment of IFCs for structural analysis domain.” *ITcon*, 9, pp. 75–95.

Weise, M., Katranuschkov, P., Liebich, T. and Scherer, R. J. (2003). “Structural analysis extension of the IFC modelling framework.” *ITcon*, 8, pp. 181–200.