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INTEGRATED APPROACH TO DESIGN AND CONSTRUCTION OF A NUCLEAR FACILITY USING BUILDING INFORMATION MODELING

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ABSTRACT

There is no established pipeline that integrates various advanced modeling and simulation (M&S) tools. Therefore, a common challenge for a complex structure is to deal with multiple models that are authored by different designers. For instance, there are many M&S tools, each having 2D/3D models of different reactor components. When a change is made to one component that affects others, this change has to be communicated to other parties for making corresponding changes. As more changes accumulate, controlling different versions becomes a major challenge. The consequence of poor version controls is the increased number of discrepancies among drawings that are managed by different parties, leading to miscommunication, rework, and, therefore, significant delays and cost overruns.
Building Information Modeling (BIM) is capable of merging multiple models as one federated model, bringing multiple disciplines into a shared platform. If strategically managed and properly controlled, BIM will be a great solution for dealing with the version control challenge. This paper identifies commonly used M&S tools for a nuclear power plant and presents challenges, potential solutions, and a software development plan and guidelines for integrating them with existing BIM solutions. Furthermore, this paper presents case studies that demonstrate how this M&S tool is integrated with an existing BIM software. The proposed approach will enhance the flow of digital information while preventing inconsistencies among different designers and engineers during the design and construction phases in an environment where many changes in design happen.

INTRODUCTION

The design of highly specialized facilities, such as a nuclear power plant, requires multiphyiscs simulations using advanced modeling and simulation (M&S) tools. These M&S tools are highly specialized tools that often require modeling of a structure in new forms (2D, 3D, abstract graphics, etc.) from scratch, instead of importing a 3D model of the structure. Consequently, these tools cannot exchange digital information between each other.

This lack of interoperability can cause design flaws through processes of conversion or recreation. In addition, communication between different parties during the design, analysis and construction phase is not always achieved. To illustrate a potential problem, Figure 1a shows the current, best practice of how digital information should be exchanged among design engineers and construction teams when a change to design is made. As shown in Figure 1a, there is no “main” model that allows pulling of the latest model. For example, if three types of analysis are needed to take place using different M&S tools, changes between parties needs to be communicated. If a change is made in M&S tool 1, this change needs to be communicated to other parties if that change is to influence their analyses. However, if the change is not properly communicated to and confirmed by all design engineers, there could be discrepancies and confusion during construction, leading to time and cost increases and further leading to more changes. The proposed solution (as illustrated in Figure 1b) is to have a data hub for BIM models where all engineers can pull the latest design model, make changes, and push the changes that are made. This data hub allows for exchange of the latest building information without having engineers directly communicating changes with others, which does not always happen in practice. It will ultimately serve as the mediator between design, analysis and construction of a project. In essence, this simulates a type of version control that is about a team maintaining a "main copy" and "working copies" of a design while developing a software program (Louridas 2006). In a similar manner, M&S tools would act as "working copies" to the "master copy" of the main BIM model.

For the proposed use of a main BIM model, file interoperability is necessary. To achieve interoperability, Industry Foundation Classes (IFC) (BuildingSMART 2016) is used to create file exchanges that are read by different programs. IFC currently supports conversion of geometry and corresponding material information. Additionally, IfcOpenShell (IfcOpenShell 2018) houses IFC's data schema which is manipulated to increase the amount of conversions that can be taken place. IfcOpenShell is used as the basis for IFCs file conversion.

This paper presents 1) background information on BIM, IFC, and a similar study, 2) three case studies that illustrates the current practices of exchanging digital information, 3) the proposed automated exchange of digital information by integrating Revit (Autodesk 2019) and Mastodon (Idaho National Laboratory 2019) (an open source data framework created by Idaho National Lab (INL) that is a modeling and simulation tool used for risk assessment and non-linear soil structure analysis) and 4) potential solutions for future studies.

BACKGROUND

Building Information Modeling (BIM) is one or more virtual models of a building that accommodates information on the building and models the lifecycle of a building while providing larger capabilities in design and construction rather than that of 2D modeling or 3D geometric rendering. BIM is emerging in the construction industry due to its capabilities and enhanced visualization of 3D models. Traditionally, the delivery process in the AEC industry (architecture, engineering and construction) has been communicated using 2D drawings. Errors in these drawings have led to unanticipated costs, delays, and in consequence, lawsuits (Sacks et al. 2018). BIM decreases these errors by increasing visualization and communication between parties. In addition, analyses are usually done last, and can lead to compromises to the original design. Commonly during construction, changes are made in the design due to unknown errors, unanticipated conditions and other omissions or confusions of the documents (Sacks et al. 2018). Figure 1 (a) shows the current process of design and analysis. The communication between parties is not always sufficient when a change is made, and due to the lack of a consistent design or analysis tool, the need for changes can cause errors, time hindrances and cost increases.

To increase the interoperability between tools, IFC (industry foundation classes) was designed to conduct file exchanges. IFC is a data schema that is able to convert geometries and corresponding material properties between file formats to be incorporated or used in BIM models. The Industry Foundation Classes (IFC) is a schema developed to define a set of data representations of building information for exchange between AEC software (Sacks et al. 2018). IFC is relatively new to the industry, and has recently updated its code to account for more building information and bug fixes. IFC2x3 is used as an exported data file format in most software, but the more recent version (IFC 4), includes better data transfer, more instances and objects within the data schema (BuildingSMART 2016). However, adoption of IFC 4 by all programs has yet to be expedited by all software developers. With the incorporation of BIM and IFC, a proposed solution to the lack of communication in infrastructure is shown in Figure 1 (b) which uses a BIM model as the main basis for design so that changes can be made and converted into a format that the BIM model can read. Changes can then be communicated indirectly this way, decreasing confusion and error and maximizing efficiency.

Steps toward the BIM solution has already been taken and is discussed in further detail in "Computationally Efficient Simulation in Urban Mechanized Tunneling based on multilevel BIM models" (Nini 2019). Nini (2019) discusses a potential solution to finite element analysis (FEM) of tunnel design. They found that BIM use in coordination with FEM of tunnel design was best achieved through parallelization techniques and the use of a multi-level detail approach through metamodels. To analyze tunnel systems through FEM and using metamodels, they used open source frameworks like SATBIM and Kratos in their methodology (Nini 2019). Similarly, the proposed idea is to use IFC to create file formats that analysis software can read (i.e., FEM). IFC currently does not have the capabilities to transfer data to FEM software. Concern of large file size is taken into consideration, in which the idea of level-of-detail analyzation techniques are considered

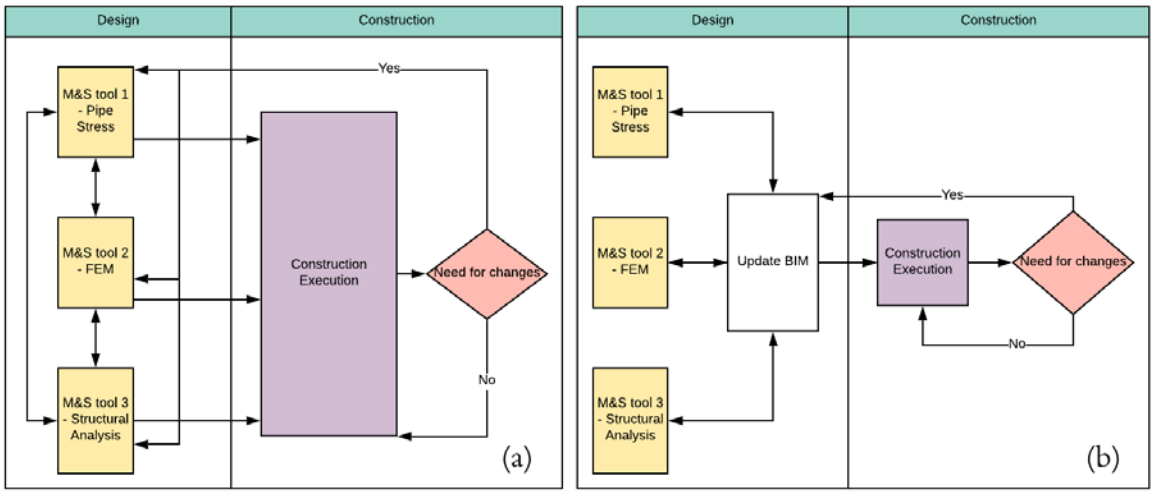

Figure 1: a) Exchange of digital models in the current use of design tools and (b) – potential use of BIM as a data hub to improve communication and maintain versions.

BUILDING INFORMATION EXCHANGE USING CURRENT METHODS

The case studies below show the use of IFC files with three software Abaqus (Dassault Systemes 2019), SAP2000 (Computers & Structures Inc 2019) and Revit(Autodesk 2019). A simple structure is modeled using Revit for the case studies (see Figure 2). The case studies will show the transformation of geometry and information between file formats.

Case 1: SAP 2000 and Revit

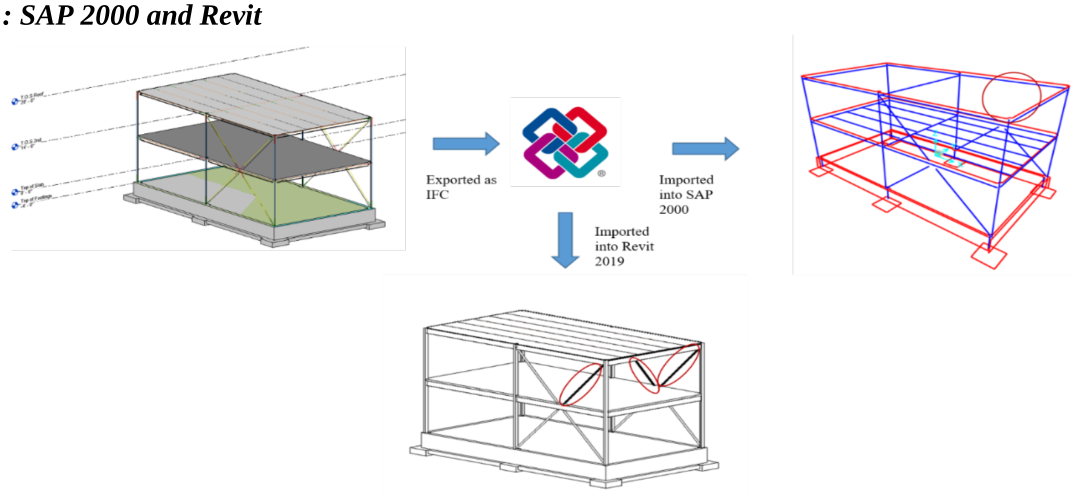

Figure 2: Revit exporting as IFC file and represented geometry

Information can be exported from Revit into SAP 2000 through the IFC2x3 data schema. Although IFC4 is the most recent update given by IFC, it is not yet compatible with all models. Therefore, in this example, the IFC2x3 coordination view was used, as it had the least amount of inconsistencies and errors. In this conversion, not all information is transferred. Once the file is transferred, in order to proceed with analysis, an establishment of connection types (i.e. pin, roller, fixed) are required in the SAP 2000 model. The establishment of loads is also required. In this transfer, however, not all of the steel structural members are converted. For example, some of the bracing is not included. The subsequent log file shows some of the HSS steel columns as having trouble importing due to issues with the instances *IfcArbitraryProfileDefWithVoids* and *IfcSweptSolid*. The joists included in the original Revit file were also not imported due to issues with the *IfcSweptSolid* instance. However, IFC does convert the footings and foundation information. Figure 2 shows this transfer. In the SAP 2000 model, the blue represents the structural steel members, and the red represents the concrete members.

Along with missing information in the SAP 2000 file, the IFC file was imported back into Revit to display missing pieces. Similar to the SAP 2000 file, the joists in the Revit model did not contain information within them. The same occurred with a few of the HSS braces. However, unlike the SAP model, the geometry of these supports remained intact. In addition, the use of a grid and elevation were not able to transfer in the data exchange. Within the both models, the circled areas indicate missing geometry and/or information.

Case 2: Revit to Abaqus

In order to best convert information from Revit to Abaqus, it is vital to export information from Revit into a file format that Abaqus can read. Currently, Abaqus reads the following file formats:

Table 1: Abaqus Import Files

Import Type	Importing Parts	Importing Models	Importing Sketches	Importing Assemblies
Files Supported	ACIS SAT	Abaqus/CAE Database	ACIS SAT	Assembly Neutral
	IGES	Abaqus input file	IGES	CATIA V4
	VDA	Nastran input file	STEP	Parasolid
	ProE/NX Elysium Neutral	Ansys input file	AutoCAD DXF	ProE/NX Elysium Neutral
	CATIA V4			
	CATIA V5			
	Parasolid			
	STEP			
	Output database			
	Substructure			

Since Revit does not have all file formats that can be exported directly into Abaqus, another model is needed. In this example, SAP 2000 was used. Revit was exported as an IFC file into SAP 2000. The SAP 2000 model was then exported as both an IGES file, and an SAT file. These were imported as parts into Abaqus to make analysis achievable. An IGES file is similar to IFC in that it has been used as a graphics exchange for CAD software(IGES 2008). This file is often seen to be used with FEM. The conversion of IFC to IGES could open more possibilities in interoperability amongst different disciplines. The import of the IGES file (Figure 3) neglected the majority of the geometry, and therefore could not accurately be analyzed. Similarly, the import of the SAT files could not be analyzed. Each contained limited geometry and were difficult to manipulate.

Summary of software conversion

The tables below show what is currently converted through an IFC file. Instructions are included to show how the software can be manipulated to include more data.

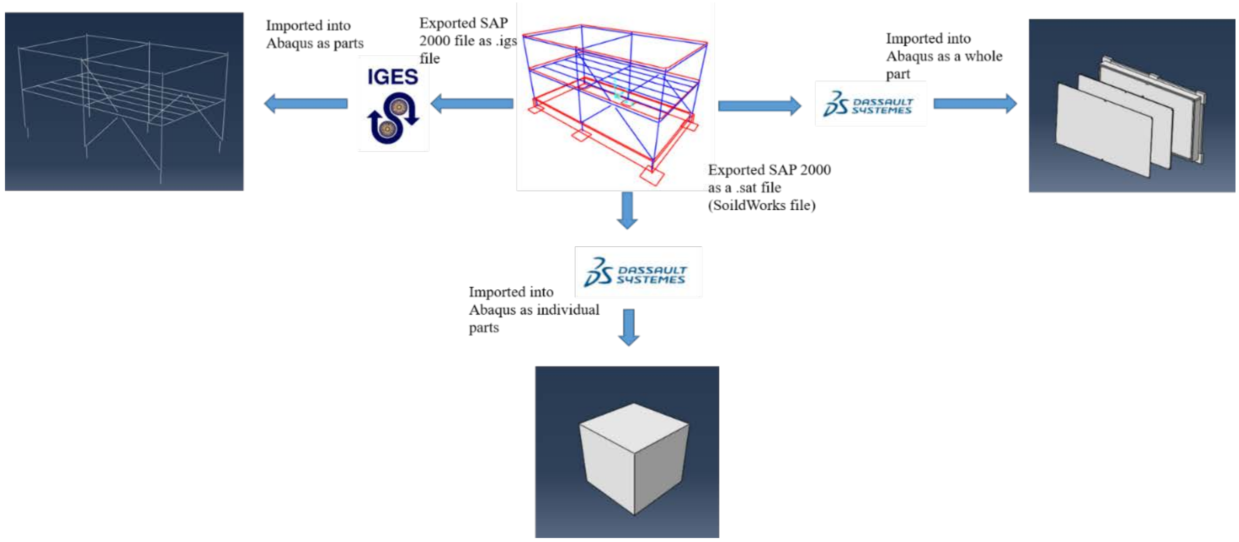

Figure 3: Geometry tranformation from SAP 2000 to IGES and ACIS SAT into Abaqus

Table 2: IFC Conversion

IFC Conversion: SAP 2000	
Converted	• Basic geometry for analysis from steel beams, columns, and footings, foundation wall, slabs some steel bracing • Section property information for standard beams • Material information is loaded into materials
Instruction	• Boundary conditions and loading conditions need to be reestablished for each element (the import from a 3D Revit model to a mesh model establishes gaps that once withheld boundary condition information) • A check needs to be made in regards to the different materials (make sure they are applied appropriately • Re-establishing connections (fixing the gaps created from convergence) • Simplify model for analysis (i.e., remove footings and replace with fixed boundary conditions)
IFC Conversion: Abaqus	
Converted	• Basic geometry lines for steel beams, steel bracing and columns • 3D geometry (based on the input file)
Instruction	• Because Abaqus cannot directly take in IFC files, it uses geometry specific files (such as IGES and SAT). Because of this, when importing, a lot of information is lost. It is suggested that the parts imported in Abaqus be used as a baseline for recreating the structure or certain parts of the structure (and therefore assigning materials, etc.) for analyzing parts of the system.
IFC Conversion: Revit	
Converted	• Basic geometry (3D) • Information regarding standard steel structures • Grid lines and spacing

Instruction	• Re-establishing information for steel that was lost (i.e. for this example, bracing with HSS columns and K3 joists) • A review of elevations and floor plans (make sure everything is appearing properly – the conversion may have caused changes in the interface). To do this it may be helpful to reestablish grid lines while in the 3D view. For the best way to do this please see Autodesk's instructions listed in text box "A" • The analytical model may not show everything and therefore needs to be updated. This can be done with recreating a new analytical model. This can also be done in step 1 of Autodesk's instructions by assigning Revit categories to IFC classes and types (such as IFC Column to Column for Revit)

As can be seen from the conversion process, IFC mainly converts geometry and corresponding architectures. However, IFC cannot yet analyze or convert finite element structures and analysis. Also, while IFC does include information on connections, it does not convert these connections to boundary conditions, which would be useful in a SAP 2000 model. Just as well, not all information is included on "non-standard" beams, columns, etc. Therefore, this information would need manual input.

Although IFC currently converts between a finite number of tools, the capabilities of the conversion of IFC can be expanded to other tools within the design and analysis process. Table 3 shows what IFC is able and unable to convert among the current set of tools (i.e. WaveFront OBJ, Collada, STEP, IGES, XML, and SVG). This table shows general types of tools to show the capabilities of IFC. The cells left blank indicate that the offered component of IFC would not apply to that tool. BIM models can be built within IFC and these components are shared in Table 3 as well.

Table 3: IFC Capabilities for Different Tools

IFC Capabilities Expanded to Different types of Tools				
			Hazard and Soil Analysis for Earthquake Design	
	Frame Analysis	FEM	Structural Model	Soil Model
Geometries (3D, 2D) (Tessellated, curved, meshed, swept-solid, Brep) - Spatial awareness of geometries and their corresponding hierarchies - Material properties of geometries - Displays voids Displays architectural elements (i.e. door, window,)	✓	✓	✓	✓
Assignment of tasks for execution of construction				
Monitor of behavior of flow elements				✓
Survey points				✓
Material profile sets (to standard beams, columns, and other longitudinal elements)	✓	✓	✓	✓
Thermal boundaries	✓	✓		✓
Support reactions	✓		✓	✓
Texture				

Structural Analysis: • Point, curve and surface connections and supports • Specifications of loading including point, curve, surface loads, temperature loads, assignment to load groups, load cases and load combinations, • Type of loads and corresponding safety factors (i.e. wind, dead, live, rain, etc.)			✓	✓
Definition of eccentricity	✓		✓	
Footing and Pile type information			✓	✓
Analysis of segments, fittings and connections that constitute duct and piping distribution systems, equipment (HVAC), terminal and flow control devices			✗	
Dynamic analysis	✗			
Finite element topology		✗		
Detailed results in finite element meshes as well as stresses and strains in structural elements		✗		
Description of prestressed loads	✗			✗
Boundary conditions (i.e. fixed, roller, pin, etc.)	✗	✗		
public utility water and waste services			✗	✗
industrial and institutional specialty equipment such as that for power production	✗			
provisions dealing with hazardous materials			✗	

As can be seen in Table 3, IFC has a large impact on the transfer of geometry and their corresponding information sets. IFC can convert mesh models as well as transfer material information. IFC cannot, however, execute finite element analysis.

IFC in Comparison to Other Exchanges

There are other data exchanges, plugins, addins, etc., within data exchange for specific programs (i.e., csixRevit, a plug-in for Revit and SAP 2000) that can provide similar results. However, IFC has the potential to convert between multiple programs and uses an open source data exchange to do so. For example, Figure 4 shows the data exchange of SAP 2000 and Revit using the conversion of a .dxf (AutoCAD file).

As shown in Figure 4, a SAP file was imported from the dxf file, however, only the beams could be imported. There were less converted objects in this file, which increases the need for manual input for analysis to be conducted.

FILE CONVERSION USING IFCOPENSHELL

IfcOpenShell is an open source software library that allows the information exchange of geometry between IFC files and WaveFront OBJ, Collada, STEP, IGES, XML, and SVG files. When using IfcOpenShell, conversion is done through the Terminal commands (IfcOpenShell 2018).

Figure 4: Revit exported as AutoCAD file and imported into SAP2000

IFC OpenShell Case Study 1

IfcOpenShell, as an open source software library, allows for analysis and manipulation of source code. In this case study, the use of Mastodon and IfcOpenShell was analyzed to perform a conversion on a simple geometry. A structural wall from a Revit model was converted. The goal of this conversion was to convert just the geometry. Using a standard input format (.i file) from Mastodon for a mesh model (Figure 5), IfcOpenShell was manipulated to convert the Revit file into an input file. The model was first converted from Revit as an IFC file. Using IfcOpenShell, the code for the conversion of WaveFront OBJ was analyzed. WaveFront geometries are created in a way that specifies vertices in an *x*, *y*, and *z* format (i.e. *v (x, y, z)* where *v* is vertex), with the origin set at the centroid of the object. Using this information, we used similar code to analyze a wall, looking for the maximum *x*, *y*, and *z* coordinates to fit the file format of the input file. Our results are shown in Figure 6 using the graphical user interfaces (GUI) Peacock from the MOOSE framework (Idaho National Laboratory 2019) (a framework that contains the Mastodon tool).

IfcOpenShell Case Study 2

Currently, Idaho National Laboratory uses Mastodon as a method of analysis for nonlinear SSI (soil structure interaction), risk assessment, and quality assurance (Idaho National Laboratory 2019). It can import many files, one of which being of the exodus format. Exodus is a finite element data model used to store and retrieve data for analysis. The file type is a "random access, machine independent, binary file" (Sandia National Laboratory 2019). Since Mastodon can read exodus files, a file conversion from a WaveFront object file to an exodus file was used for this case study. The WaveFront object file was used as a starting file format due to its simplicity and conversion located within IfcOpenShell.

```
[Mesh]
  type = GeneratedMesh # Can generate simple lines, rectangles and rectangular prisms
  dim = 3 # Dimension of the mesh
  nx = 1 # Number of elements in the x direction
  ny = 1 # Number of elements in the y direction
  nz = 1 # Number of elements in the z direction
  xmin = 0.0
  xmax = 1
  ymin = 0.0
  ymax = 1
  zmin = 0.0
  zmax = 1
[]
```

Figure 5: Mesh input (.i file) from Mastodon

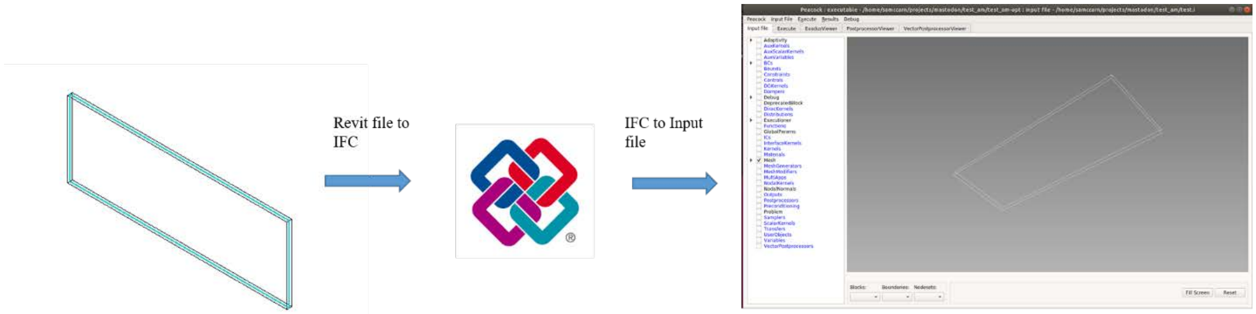

Figure 6: Revit file to input (.i file) via IFC

To convert a WaveFront file to an exodus file, the interface Exomerge (Kostka 2013) was used to manipulate and create the exodus file. The coordinates and faces given in the WaveFront file are converted into nodal coordinates and elements of the exodus file, respectively. The element blocks are then created as triangles from the elements created, and the exodus file is completed. The Exomerge file is then added into IfcOpenShell as a dependency to convert an IFC file into an exodus file, and adopting IFC's source code of conversion for the WaveFront file, the IFC file is converted directly into an exodus file. The result is shown in Figure 7 a and b. There are some limitations with analysis of the model, as the FE model will not be accurate due to the size of the mesh and the type of element (for example, shear locking). To increase the accuracy of the analysis of the mesh, it is suggested that certain parts of the structure (i.e., beams, columns, etc.) be analyzed separately as indicated by the user. This will allow for finer mesh model, shorter run times, more accurate analysis, and corresponding properties to be allocated.

To test the capabilities of this conversion, more complicated geometries (Figure 8a) were converted with this tool. The conversion took a longer amount of time (approximately 15 minutes versus 10 seconds), but the geometry conversion worked satisfactorily. However, the geometry the exodus file was too large for the graphical user interface (GUI) of Mastodon, so the GUI in VisIt was used (VisIt is an open source animation and analysis tool) (VisIt 2019).

CONCLUSION

Conversion of file formats can increase the efficiency and effectiveness in design and construction. The current methods of conversion are time consuming and can produce inaccurate results. This paper analyzes these issues and proposes solutions along with limitations in the conversion process.

Potential Problems and Their Solutions

As previously discussed, current file conversion between M&S and BIM contains information loss and may requires the need for manual input. This paper discussed one particular solution to overcome the lack of

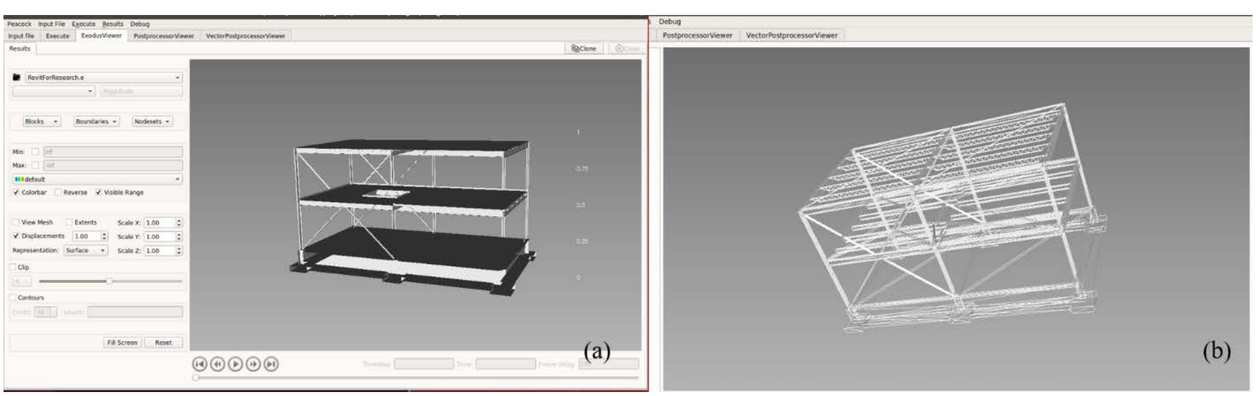

Figure 7: (a) Revit file converted to Exodus file (b) Revit file converted to Input file

data exchange between BIM and M&S tools by using a data schema to export geometries. However, other approaches can be made:

1. **Manual Input:** The user can manually convert from one software to another by mapping what is converted and what is not converted. In the case of a conversion from Revit to Abaqus, though direct conversion is not possible, one can re-model the part that needs to be analyzed. However, this is a time consuming process and can lead to human errors of mismatched geometry and connections.

2. **Use of a known API or SDK for specific software:** Some software have application program interfaces (APIs) or software development kits (SDKs) that can be used to store and export additional building information. For example, SAP2000 has an API made by CSI products(Computers & Structures INC 2018) to convert Revit files into SAP2000 files. This approach is similar to IFC in that it converts the geometries. Similarly, AutoCAD products typically have API's between their products. However, like the CSI product, many API's and SDK's require financial cost. Also, there are not API's for all sources of conversion. Although many of them convert most information, some will require manual input such as loads, boundary conditions, etc.

3. **Conversion using IFC (or an alike open source data schema):** The last option is manipulating and adding code to a data schema such as IFC. Parsing IFC and writing in a file format that M&S tools can read is needed. As discussed through the case studies in this paper, IfcOpenShell can serve as a baseline code. IfcOpenShell currently does not convert information for finite element models. Although IFC is able to convert geometries, it does not, however convert all geometries, and it does not currently guarantee conversion of analysis information, such as loads and boundary conditions. A set of guidelines should be created to guide users to additional information that needs to be manually inputted after conversion.

Although data exchange is achievable, with each case, manual input will be still be required. However, manual input alone is less efficient and a short-term solution. Approaches 2 and 3 present long-term solutions. Approach 3 is the authors' ongoing research that has the potential of being more efficient for the conversion process.

Impact

The objective of this research is to create a basis of conversion (i.e., IfcOpenShell) to share information between software. It will increase the efficiency of the design and construction phases through better communication in using one BIM tool for the final project outcome. By having a conversion tool for different parts of analyses, it can encourage better visualization, leading to less inconsistencies and confusion and, therefore, less revisions and rework in the future. For example, piping design can cause frustration for designers and builders alike in reading 2D plans of pipe designs that have a small boundary spaces. The use of converting such piping done through a piping analysis software into a 3D BIM tool can decrease confusion and increase visualization of potential errors and design flaws. Although better conversion process would be beneficial in the building industry, there will still be the need of manual input. However, the goal is to increase the efficiency in order to reduce errors and decrease cost and time overflows for a construction project.

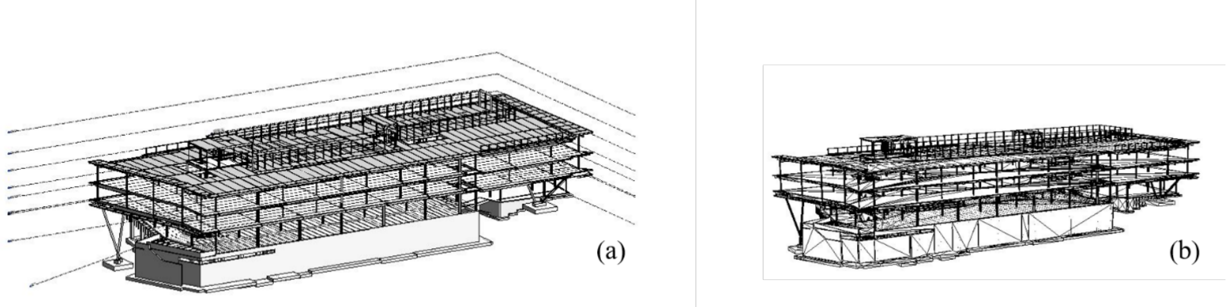

Figure 8: (a) NCSU Oval Revit Structure (b) NCSU Oval Exodus File

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