Jabin J., Dimyadi J. and Amor R. (2020). " Classifying IFC entities by their relative importance for accurate interoperability measurement" In: *Proc. 37th CIB W78 Information Technology for Construction Conference* (CIB W78), São Paulo, Brazil, pp. 85-97. DOI: http://dx.doi.org/10.46421/2706-6568.37.2020.paper007

CLASSIFYING IFC ENTITIES BY THEIR RELATIVE IMPORTANCE FOR ACCURATE INTEROPERABILITY MEASUREMENT

Joseph Jabin[1], Johannes Dimyadi[2] and Robert Amor[3]

Abstract: The IFC data model has several hundred entities and thousands of attributes, relationships, quantity and property sets that can represent various aspects of a construction project. A one-to-one mapping between a BIM software tool's native data format and the IFC data exchange standard is not possible. This complexity makes it difficult for the translator modules in a BIM software tool to accurately map the IFC elements, causing interoperability problems while exchanging BIM data using IFC. Also, there are mistakes made by the software developers in implementing the mapping to and from IFC data exchange standard, which adds to the issue. A proposed approach to tackle the interoperability problem is to adopt a 'divide and conquer' method by classifying IFC entities as per their relative importance for a discipline and to rectify the interoperability issues of the most important entities first. This paper proposes a framework to classify the IFC entities as per their relative importance with respect to various disciplines and introduce an index called `RI` (Relative Importance). This paper also suggests the application of the proposed framework in the interoperability measurement (conformance testing) implementation for BIM software tools, and in presenting the results of conformance tests.

Keywords: BIM, Relative importance, Interoperability measurement, Framework, IFC classification.

1 INTRODUCTION

There are numerous Building Information Modelling (BIM) software tools currently available. Data exchange between those BIM software tools is crucial for collaboration between various disciplines in Architectural, Engineering, Construction, and Facility Management (AEC-FM) industries. Industry Foundation Classes (IFC) were introduced for this purpose and have become the de-facto standard for data exchange between various BIM software tools (Lai and Deng, 2018). The IFC data model has several hundred entities and thousands of attributes, relationships, quantity and property sets that can represent various aspects of a construction project. Data accuracy during a data exchange is of the utmost importance when commercial projects rely on IFC as a mechanism to reliably exchange their BIM models between various BIM software tools (Amor, Jiang, and Chen, 2007). However, the translation modules of BIM software tools do not always accurately map the elements of a BIM model onto the IFC data structure during data exchange. In general, this is because a complete mapping is not possible, but

[1] Ph. D Student, University of Auckland, Auckland, New Zealand, jkan585@aucklanduni.ac.nz
[2] CEO, Compliance Audit Systems Limited, Auckland, New Zealand, jdimyadi@complianceauditsystems.com
[3] Professor, University of Auckland, Auckland, New Zealand, trebor@cs.auckland.ac.nz

also due to mistakes made in implementing the mapping to and from IFC data exchange standard. There is a significantly large number of possible mappings between various entities and their attributes that makes it extremely hard to completely address the interoperability problem.

This research adopts a 'divide and conquer' problem solving approach to tackle the interoperability problem by classifying IFC entities according to their importance to a particular discipline and to identify the interoperability problems associated with entities in the higher level of importance first. The 'more important IFC entities' in this context are those that can have a more significant negative impact on the project if there were any unintended alteration during data exchange. The insight for this type of classification was gained from software testing principles where modules to be tested are classified based on their impact on the safety and reliability of the final software system.

This paper proposes a novel framework to classify IFC entities along with their attributes and property sets based on their importance to a particular discipline. Classifying the IFC entities and properties is a complex process that requires significant effort, and it will take a long time to classify the majority of the elements because the importance of an IFC entity changes with different disciplines and processes. The framework incorporates methods to overcome the complexities described above by introducing a relative importance index to quantify the relative importance of IFC elements. This paper also suggests two areas of application for the proposed framework: in the interoperability measurement (conformance testing) implementation for BIM software tools; and in presenting the results of conformance tests.

2 BACKGROUND

Building Information Modelling (BIM) is a multi-faceted technology and process that enables the sharing of the physical and functional representation of a built environment throughout its life cycle. The objects of BIM processes are building models or BIM models (Sacks, Eastman, Lee, and Teicholz, 2018). There are numerous software tools currently available to create and manipulate these BIM models. A construction project needs a multitude of these BIM software tools to assist the execution of the project and will need BIM models to be exchanged between these software tools (Lipman, 2006). Interoperability between BIM software tools is a crucial requirement for AEC-FM industries to enhance their efficiency and to support new business processes (Amor, 2008). Data can be exchanged directly between these BIM tools by implementing one set of translators between each pair of software tools to map the native representation of the BIM model of one software tool to the native representation of the other. Developing and maintaining numerous sets of translators for direct data exchange between various software tools is extremely inefficient (Laakso and Kiviniemi, 2012). Hence, the preferred method of exchanging data between BIM software tools is to have a data exchange standard so that each software tool only needs to implement one translator specifically for that standard.

The Industry Foundation Classes (IFC) is one of the data exchange standards that was introduced to achieve interoperability in AEC-FM industries. IFC was developed and is maintained and controlled by an industry consortium known as buildingSMART (formerly IAI). The AEC-FM industries in many countries and the majority of the BIM software tool vendors have adopted IFC as their preferred data exchange standard, and strong government-level policies and mandates are in place in many countries to ensure the adoption of this standard (Amor et al., 2007). The first version of IFC (IFC1.0) was released in 1997, and it has been developed and updated periodically. The initial versions only supported basic architectural elements such as wall, floors, doors, windows, beams, and columns (Lipman, 2006). Further versions enhanced its capability to represent building components, fixtures, and equipment in various disciplines such as HVAC, Plumbing, Electrical, Mechanical, as well as Facilities management. The current candidate standard IFC4.2 has included entities to represent bridges (buildingSMART, 2019d). The increase in the capability of the IFC schema to represent more building elements and processes resulted in a significant increase in the number of the entities, attributes, property sets, and relations in the IFC schema (Amor, 2015). The current official release of IFC version has 801 entities, 413 property sets, 93 Quantity sets, and 1694 Individual properties (buildingSMART, 2019c).

The evolution of IFC into an increasingly complex schema has negatively impacted the ability of the BIM tool's translator systems to correctly handle IFC data, which is a crucial aspect of the maturity of the BIM marketplace and the confidence of the industry to work with IFC data models (Amor et al., 2007; Amor, 2015). Exchanging data between BIM software tools and the IFC data model is a highly complex process as the translators cannot have a one-to-one mapping between the software tool's native data format and the IFC schema; and also in many cases, there can be multiple possible mappings for the same elements between native and IFC schemas (Lai and Deng, 2018). Hence, it is challenging for software vendors to develop and maintain translators that can accurately handle the IFC data. Many studies since the mid-2000s have pointed out translation errors that have caused data loss and misinterpretation of intent (Amor and Ma, 2006; Lai and Deng, 2018).

The interoperability issues caused by the inaccurate translation by BIM tools have created a psychological barrier for the wholehearted adoption of BIM by the industry (Solihin, Eastman, and Lee, 2015). Hence, it is critical that the translation process be improved to gain the confidence of the AEC-FM industries. However, the software industry is well aware that it is impossible to create error-free software (Amor, 2015). It is also challenging to correct all the errors, because the removal of a fault in a software product may affect the existence, number, location and nature of other faults in that software (Mili and Tchier, 2015, p. 287). Also, the fact that translators of the various design tools are constantly changing (Amor et al., 2007), and the increase in the number of IFC elements with each version updates adds to the complexity of the situation (Amor, 2015). buildingSMART is aware of this issue and has introduced methods to reduce the scope of information exchanges and to make IFC data exchanges manageable (Laakso and Kiviniemi, 2011). The Model View Definition (MVD) mechanism was introduced to reduce the complexity of the IFC schema in applications by focusing only on a subset required by a specific discipline (e.g., structural analysis) or for a specific application (e.g., project and design coordination). Thus, MVD can be viewed as a type of 'divide and conquer' solution to improving interoperability. However, current approved MVD are practically still too complex to handle as a single unit for the purposes of troubleshooting translation errors in BIM software tools.

Insights to improve the accuracy of the IFC translators can be gained from the software testing discipline. Software testing suggests that not all errors carry the same stakes even for the same stakeholders, let alone for different stakeholders (Mili and Tchier, 2015, p. 300). Since different errors in software impact each stakeholder differently, the software testing discipline advises the software testers to target the high impact errors before correcting lower impact errors in software (Mili and Tchier, 2015, p. 288). Similarly, in BIM, "not all errors are equal in terms of their impact downstream to the receiving application within the exchange workflow" (Solihin et al., 2015). For example, during an IFC data exchange, a missing or altered structural element of a building such as a load-bearing beam will have a higher impact on the integrity and stability of the building than a missing or altered non-load-bearing beam for a stakeholder in the structural engineering discipline. However, any alteration during data exchange for the same non-load-bearing beam may have a higher impact on the execution cost (but less on safety aspects) for a non-structural stakeholder. Likewise, a missing piece of furniture in the data exchange may only have a negligible impact to the interior designer, and no impact at all to the other stakeholders. Thus, each IFC element has different levels of importance relative to the discipline they are associated with, in terms of the impact caused by an alteration of data during an IFC data exchange. Therefore, as suggested by the software testing discipline, the translation error of an IFC element that has higher importance for a particular discipline should be targeted before correcting translation errors of IFC elements with lesser relative importance. Currently, the only mechanism to group IFC elements as a subset of the IFC schema is an MVD. However, elements in an MVD do not vary in their level of importance, and there are no methods available to further segregate IFC elements as per their relative importance to each other. Hence, this research introduces a 'Relative Importance' framework to classify IFC elements as per their relative importance to each other with respect to their perceived impact on different disciplines.

3 THE RELATIVE IMPORTANCE (`RI`) FRAMEWORK

A relative importance (`RI`) framework is proposed to overcome the complexities described in the previous section and to help improve the accuracy of the translators in BIM software tools. Different parts of a system have different degrees of importance as per each component's significance or criticality in the system, and the difference in importance needs to be recognised by giving a weightage to each component (Pridmore and Rumens, 1989). Hence, this framework introduces an index called 'Relative Importance' (`RI`) to give due weighting to IFC elements to recognise the difference in the importance of each IFC component in the whole building system.

This index can be used for enhancing the interoperability measurement process in a conformance test. Interoperability measurement is the process of measuring the correctness of data exchange given a set of criteria. To accurately measure the correctness of the data exchange during a conformance test, the measurement process is to be conducted as per the principles established by measurement theories (Fenton and Pfleeger, 1997; Tal, 2017). Measuring interoperability between a BIM software tool and IFC data exchange standard as per measurement theory has three main steps (Fenton and Pfleeger, 1997; Jabin, Dimyadi, and Amor, 2019; Tal, 2017), (1) quantify how accurately the translator systems in the BIM software tool maps its native representation to the IFC data exchange standard. The outcome of this process is known as 'quantified indications' (Tal, 2017). (2) Convert quantified indications into a measurement outcome using a 'measurement model'. A measurement model is used to abstract away the complexities of the quantified indications (Fenton and Pfleeger, 1997) and present the outcome in a manner understandable by the end-user. (3) Represent the measure derived using the measurement model on a particular scale which is known as the 'measurement outcome' (Jabin et al., 2019; Tal, 2017). Since the relative importance index needs to be used in all of the measurement processes, the notation for the index is designed in two different ways to differentiate where the indexes are being used. The relative importance index used to represent the values in calculation steps (first and second steps of the measurement process) shall be represented using the notation 'ri'; and the measurement outcome represented on a particular scale (third step of the measurement) which has abstracted away all the complications and calculations of the measurement process shall be represented using the notation 'RI'.

As mentioned in the previous section, the relative importance of the same IFC element changes with each discipline from which the elements are viewed from. Therefore, the values of RI or ri are always dependent on the perspective of the discipline it is viewed from. Hence, the respective discipline needs to be represented along with the notation. Thus, RI and ri notations shall be written as RI_d and ri_d where the subscript 'd' is a placeholder to denote the name of the discipline for which the relative importance of IFC elements are derived from. For example, if the relative importance values are derived from the perspective of Structural engineering discipline, it will be denoted as $RI_{Structural}$ or $ri_{Structural}$. The next section explains how the RI_d and ri_d indexes can be used to enhance the interoperability measurement process.

4 IMPLEMENTATION OF THE RI FRAMEWORK

The first step to improve data exchange accuracy is to quantify errors in the translator. This is effectively measuring the interoperability between a BIM software tool and the IFC data exchange standard. Specific conformance tests designed to measure the interoperability for a particular data exchange standard are conducted by various researchers and organisations. Conformance testing is conducted by one of the following three methods: 1) checking for accurate translation of a test model exported from the native file format to an IFC file by a BIM software tool, or 2) checking the accuracy of translation of a test model imported into the native file format from an IFC file by a BIM software tool, or 3) importing an IFC file into the native file format of a BIM software tool and immediately exporting it back to IFC file format (round-trip) and comparing the original against the re-exported IFC file for changes. (Lipman, Palmer, and Palacios, 2010). The primary output of these tests will be a list of quantified indications which denotes the correctly and incorrectly translated IFC elements (the first step of measurement). These results are intended for the end-users to be aware of the translator issues, and more importantly, intended for the software developers to correct the errors found during the translation.

The official conformance test to certify BIM software tools on their capability for correct data exchange with the IFC data exchange format is conducted by buildingSMART (buildingSMART, 2019b). The test results are published online as a list of conforming and non-conforming IFC elements (or concepts as they are called in the report). Also, buildingSMART awards a certificate to the vendor of the compliant software, and the vendor can display a certified logo on their software products to indicate to customers that the software is conforming to the IFC data exchange standard (buildingSMART, 2019a). Eventhough a certified logo and certificate conveys the impression that certified BIM software tools can accurately exchange data with the IFC data exchange standard, numerous researchers have conducted independent conformance tests and discovered critical errors in the translation systems of many BIM software tools certified by buildingSMART (Amor and Dimyadi, 2010; Jeong, Eastman, Sacks, and Kaner, 2009; Kiviniemi, 2008; Lai and Deng, 2018; Lipman et al., 2010; Ma, Ha, Chung, and Amor, 2006). It is to be noted that the conformance test report that buildingSMART publishes does show that some of the IFC elements are not supported, or is only partially supported (or restricted as called in the report) by the BIM software tools being tested and certified. It means that the certified BIM software tool will cause some interopreablity issues when data is exchanged using the unsupported IFC elements. However, this infomation that the certified software tool was certified with some unsupported IFC elements is not explicitily conveyed in the certification logo or marketing materials provided by the vendors. Therefore, the end-users are not able to correctly interpret the conformance test results making them unable to accurately assess the data exchange accuracy of the BIM tools they use.

Hence, it is crucial that a conformance test output should be able to explicitly convey the data exchange accuracy and data exchange limitations of the certified BIM software tool. The RI_d framework can be used to augment the conformance test reports to make it more meaningful for the end-users and software developers. The next section demonstrates an example approach to how the RI_d framework can enhance the meaning of the interoperability measurement outcome. It also describes how the result of a conformance test could be displayed in a meaningful manner, along with the current certification logo (issued by buildingSMART).

4.1 RI_d framework to enhance the meaning of interoperability measurement outcome

The first step to implement the RI_d framework is to classify the IFC elements along with their attributes and property sets as per their relative importance by assigning ri_d values for each of them. Since the RI_d framework is being introduced to manage the complexities of the IFC data model, it is preferred to follow a minimalistic approach for the concepts involved within the framework. Therefore, the granularity for the RI_d framework for differentiating the relative importance levels of IFC elements is kept to just three levels; which are ‘Low’, ‘Med’, and ‘High’, which can be equated numerically as 1, 2, and 3 respectively. The assigned ri_d values will be influencing calculations done for the interoperability measurement and will determine how the conformance test results are shown to the end-users. Also, these values serve as an indicator for the software developers to help them understand the importance of IFC elements from the perspective of various disciplines.

The importance level of each IFC element and its attributes should be assigned by an expert in each discipline based on their acceptable tolerance for any inaccuracy during data exchange with IFC. When an IFC element is directly related to a discipline and needs to be exchanged precisely, the element is considered as high importance for that discipline and would be assigned a ri_d value of 3 (high importance). Directly related elements are those elements which are directly used by the discipline. For example, elements such as pipes, pipe joints, etc. are directly related to plumbing discipline, and load-bearing beams, columns, walls, slabs, etc. are directly related to structural discipline. Also, there will be many elements that are indirectly related and important to a specific discipline. These indirectly related elements would be assigned a ri_d value of 2. For example, the plumbing contractor needs the structural layout data of load-bearing beams to locate the position where structural penetrations could be made to allow the pipes to pass through the beams. These positions on a load-bearing beam are designed in such a way that the structural penetrations do not cut the reinforcement bars inside them. If there are any unintended alterations during data exchange to the marked positions, the plumbing contractor might make the penetration in the wrong position on the beam and may cut the reinforcement bars inside it, causing damage to the beam. Thus, the accuracy of structural data is also important to the plumbing discipline, though not as important as the data of the elements directly related to the discipline. Hence, a ri_d value of 2 (medium importance) is assigned to structural elements when viewed from the perspective of the plumbing discipline. All other elements that are not related to the plumbing discipline would be assigned a ri_d value of 1 (low importance). The assignment of ri_d values will be a one-time process for each version of a schema (e.g., IFC 4.1) for each discipline. The ri_d values decided by experts should be assigned at the IFC schema level, and preferably verified and maintained by the organisation that manages the IFC standard.

Table 1 shows a sample assignment of the ri_d values for three IFC elements (E1, E2, and E3) along with their attributes. In a real implementation, 'E1.PropertySet1.property = xxx' listed in column 1 could be substituted with a real IFC property set and its value, e.g., 'IfcBeam.Pset_BeamCommon.LoadBearing = True'. The assignment of ri_d value for this element value combination will be based on the importance of a loadbearing beam from the perspective of various disciplines.

Table 1. An example allocation of ri_d values by disciplines.

IFC Elements	$ri_{Structural}$	$ri_{Interior}$	$ri_{Plumbing}$
E1.PropertySet1.property = xxx	3	1	1
E1.PropertySet2. property = xxx	1	3	1
E2. PropertySet1.property = xxx	2	2	1
E2. PropertySet2.property = xxx	3	1	2
E2. PropertySet3.property = xxx	1	2	1
E2.QuantitySet1.Quantity = xxx	1	2	3
E3.QuantitySet1.Quantity = xxx	1	2	3

For example, any data associated with a load-bearing beam is of high importance to the structural discipline, and therefore should be translated exactly as it is. Hence, a ri_d value of '3' would be assigned for the element 'IfcBeam.Pset_BeamCommon.LoadBearing = True' and the assignment will be listed under '$ri_{Structural}$'. Therefore, in Table 1, when ri_d value of '3' is assigned for 'E1.PropertySet1.property = xxx' (Row 1) under $ri_{Structural}$, it implies that all IFC elements with that particular property and value occurring in an IFC file will be considered high importance for stakeholders in the Structural discipline. Hence, following the previous example, all the IfcBeam elements with the property LoadBearing=true will be considered as high importance for the Structural discipline. Similarly, if the accuracy of an element is not of concern for a particular discipline, then it can be assigned a ri_d value of 1. For example, a load-bearing beam is not a concern for an interior works contractor; hence $ri_{Interior}$ shall be assigned a value of '1', and all other elements shall be assigned ri_d values using the same principle.

The next step in the implementation of the RI_d framework is to map the results of an interoperability measurement test conducted between a BIM software tool and IFC data exchange standard to the ri_d values. Since this paper focuses on the theoretical implementation of the RI_d framework, a comprehensive interoperability test has not yet been conducted; instead, sample test data was chosen taking insights from literature on actual interoperability measurements (Amor et al., 2007; Jeong et al., 2009; Lai and Deng, 2018; Ma et al., 2006). A common method adopted by researchers to represent the interoperability measurement output is to list out the number of correctly or incorrectly (or both) translated elements. All the tests in these research projects were done using one of the three conformance testing methods described in section 4. Table 2 lists out an exemplar outcome of an interoperability measurement test conducted using a round-trip test for demonstrating a sample implementation of the $\mathtt{RI}_\mathtt{d}$ framework. The first column of the table lists three types of IFC entities (E1, E2, and E3) along with their attributes and values that were present in the test models used for the round-trip test. The second column lists the number of total elements (N) tested of the corresponding element and attribute value in column 1 (e.g., the total number of IfcBeams with property Beam.Loadbearing=true), and the third column lists the total number of correctly translated elements (n) out of (N).

Table 2. Exemplar outcome of a round-trip test.

IFC Elements	Total No. of elements tested N	No. of correctly translated elements n
E1.PropertySet1.property = xxx	1500	1450
E1.PropertySet2. property = xxx	225	200
E2. PropertySet1.property = xxx	5000	4250
E2. PropertySet2.property = xxx	500	499
E2. PropertySet3.property = xxx	3250	3200
E2.QuantitySet1.Quantity = xxx	75	60
E3.QuantitySet1.Quantity = xxx	125	100

To determine the $\mathtt{ri}_\mathtt{d}$ value of the elements listed in Table 2, a row by row calculation is performed against the corresponding $\mathtt{ri}_\mathtt{d}$ values listed in Table 1. Table 3 shows the mapped $\mathtt{ri}_\mathtt{d}$ values for the Structural discipline. Also, the sum of the total number of elements which has been assigned the same $\mathtt{ri}_\mathtt{d}$ value is calculated from the table (ΣN and Σn). The same process is applied to all the disciplines for which a measurement outcome is needed.

Table 3. Calculations for $\mathtt{ri}_\mathtt{d}$ values for the Structural discipline.

IFC Elements	$\mathtt{ri}_{\mathtt{Structural}}$	N	n	ΣN	Σn
E1.PropertySet1.property = xxx	3	1500	1450	2000	1949
E2. PropertySet2.property = xxx		500	499		
E2. PropertySet1.property = xxx	2	5000	4250	5000	4250
E1.PropertySet2. property = xxx	1	225	200	3657	3560
E2. PropertySet3.property = xxx		3250	3200		
E2.QuantitySet1.Quantity = xxx		75	60		
E3.QuantitySet1.Quantity = xxx		125	100		

Once calculated, the values (quantified indications) in Table 3 are converted into a measurement outcome ($\mathtt{RI}_{\mathtt{Structural}}$). Our measurement outcome has two parts, an 'Overall Score', and an 'Individual Score'. The Overall Score is the percentage of the total number of correctly translated IFC elements weighted by the corresponding ri_d values. Since the overall score is weighted by the ri_d value, an inaccurate translation of a more important IFC element (with ri_d value of 3) will reduce the overall score more, compared to that in a lesser important IFC element (with ri_d value of 2 or 1). The Individual Score is the percentage of the total number of correctly translated IFC element under each ri_d value. These scores are calculated using the measurement model represented by equations (1) and (2). The equations are used to calculate the scores for each discipline separately.

$$Overall\ Score\ (RI_d) = \left[\frac{\sum_{i=1}^{ri=3}\left(\frac{\Sigma n}{\Sigma N} \times ri_d\right)}{\Sigma ri_d}\right] \times 100 \qquad (1)$$

$$Individual\ Score = \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 \qquad (2)$$

Where:

ΣN is the sum of the total number of IFC elements tested during the conformance test, grouped by the type of IFC element and the assigned ri_d value.

Σn is the sum of the total number of IFC elements correctly translated during the conformance test, grouped by the type of IFC element and the assigned ri_d value.

ri_d is the relative importance value assigned to corresponding IFC elements.

The measurement outcome calculated using the measurement model will be displayed in the format shown in Figure 1. The top-right cell denotes the discipline for which the measurement outcome is calculated. The left column shows the Overall Score. The values below High, Med, and Low, show the Individual Scores under the corresponding importance level. These individual scores represent the 'interoperability level' which conveys to end-users the percentage of accurately translated IFC elements under each importance level during the conformance test. The proposed format abstracts away all the complications of the interoperability measurement process and represents the results in a simple manner that could be easily understood by the end-users. The format is designed in a manner that could be displayed along with the IFC certification logo so that end-users can clearly understand the current interoperability level and the limitations of the accuracy of translation of the BIM software tool that was tested for conformance. This format could be used as a standard method to represent the outcome of any interoperability measurement tests that generate measurement results in the manner shown in Table 2; thus enabling the end-users to compare the interoperability level of one BIM software tool to another, even though the interoperability measurement could be conducted by different bodies.

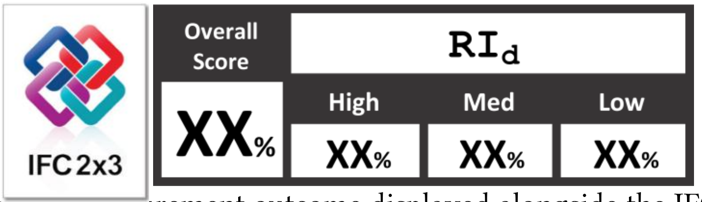

Figure 1: Proposed measurement outcome displayed alongside the IFC logo

For clarity on how the measurement model converts the quantified indications into measurement outcome, the steps required for the calculation is demonstrated for $\mathtt{RI}_{\mathtt{Structural}}$ (data referenced from Table 3).

Individual Score for $\mathtt{RI}_{\mathtt{Structural}}$ for $\mathtt{ri}_{\mathtt{d}}$ value '3'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{1949}{2000}\right] \times 100 = 97.45\%$$

Individual Score for $\mathtt{RI}_{\mathtt{Structural}}$ for $\mathtt{ri}_{\mathtt{d}}$ value '2'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{4250}{5000}\right] \times 100 = 85\%$$

Individual Score for $\mathtt{RI}_{\mathtt{Structural}}$ for $\mathtt{ri}_{\mathtt{d}}$ value '1'

$$= \left[\frac{\Sigma n}{\Sigma N}\right] \times 100 = \left[\frac{3560}{3657}\right] \times 100 = 97.34\%$$

Overall Score for $\mathtt{RI}_{\mathtt{Structural}}$ $= \left[\frac{\sum_{i=1}^{ri=3}\left(\frac{\Sigma n}{\Sigma N} \times ri_d\right)}{\Sigma ri_d}\right] \times 100$

$$= \left[\frac{\left(\frac{1949}{2000} \times 3\right) + \left(\frac{4250}{5000} \times 2\right) + \left(\frac{3560}{3657} \times 1\right)}{(3+2+1)}\right] \times 100 = 93.28\%$$

The result of the calculation could be displayed as shown in Figure 2

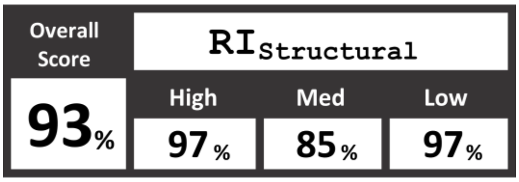

Figure 2: $\mathtt{RI}_{\mathtt{d}}$ for the Structural discipline

Using the same principle, $\mathtt{RI}_{\mathtt{Interior}}$, and $\mathtt{RI}_{\mathtt{Plumbing}}$ are calculated and shown in Figure 3 and Figure 4, respectively.

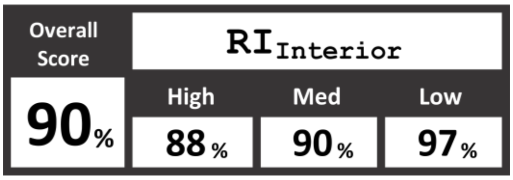

Figure 3: RI_d for the Interior discipline

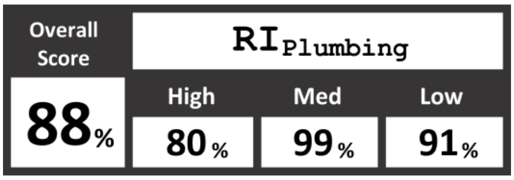

Figure 4: RI_d for the Plumbing discipline

Even though the outcome of the round-trip tests (Table 2) used for calculating the RI_d was the same, the measurement outcome clearly shows that there are noticeable differences in the interoperability levels for each discipline. The end-users from each discipline now can understand what the results mean from their perspective, for the data exchanges done using the BIM software tool that was tested. The measurement outcome can be interpreted as follows: the BIM software tool that was tested is better suited for data exchange in the Structural discipline because 97% of the most important IFC elements needed for the Structural discipline were translated accurately. The support of the BIM software tool is not as strong for the Plumbing discipline. Even though the medium and low importance IFC elements in plumbing discipline show high accuracy, the high importance IFC elements related to plumbing discipline are only 80% and may show inaccuracies while doing a data exchange. Hence, with this measurement outcome, the stakeholders in these disciplines can take an informed decision whether to go ahead or not with the current data exchange or wait till the vendors to update the translator modules of the BIM software tool or look for another tool.

As for software developers, they could refer to the ri_d result data in Table 3 and could make a priority list of IFC elements that are of high importance, and can focus on correcting the errors associated with those elements first. They could rerun the conformance test to check whether the percentage accuracy has increased after a bug fix, if the value is not increasing, it may indicate that the latest bug fix might have introduced other errors with other IFC elements. Thus, the proposed format can provide clear insights for software developers on which errors are to be corrected first and what effect those corrections cause to the system as a whole.

5 Conclusion

Using a mechanism to segregate IFC elements according to their relative importance with respect to various disciplines enables new dimensions in handling the complexities of the IFC data model for interoperability measurement. The proposed RI_d framework demonstrates the possibility of viewing IFC elements from the perspective of the end-user in various disciplines to allow them to focus only on what is relevant to them. It also enables the representation of conformance test results in a segregated manner relevant to each discipline. The standardised format to represent the measurement outcome enables one-to-one comparison of the interoperability levels of different BIM software tools on a standard scale. It can also serve as a gauge for the software developers to analyse the progress of their efforts to rectify the translator errors. Also, a standardised measurement outcome will enable the customers and the vendors know how accurate their software tools are as compared to other competing software tools. This could be a self-motivation or a 'forced' motivation for vendors to improve the accuracy of their translators.

This paper serves as a starting point of the research on the subject of the relative importance of IFC elements, and reports on the basic functionalities of a mechanism for segregating IFC elements as per their relative importance for various disciplines. A limitation of this work is that the sample implementation of the RI_d framework has only demonstrated the theoretical implementation and does not assign ri_d values to real IFC entities. Further research is being conducted by the authors to develop an improved conformance test methodology which incorporates the RI_d framework.

6 REFERENCES

Amor, R. (2008). *A better BIM: ideas from other industries.* Proceedings of 25th CIB W78 Conference on "Improving the management of construction projects through IT adoption", July 15-17, Santiago, Chile

Amor, R. (2015). *Analysis of the Evolving IFC Schema.* Proceedings of 32nd CIB W78 Conference on Applications of IT in the Architecture, Engineering and Construction Industry, October 27-29 Eindhoven, The Netherlands, 39-48

Amor, R., and Dimyadi, J. (2010). *An Open Repository of IFC Data Models and Analyses to Support Interoperability Deployment.* Proceedings of 27th CIB W78 Conference on "Applications of IT in the AEC Industry", November 16-19, Cairo, Egypt, 16-18

Amor, R., Jiang, Y., and Chen, X. (2007). *BIM in 2007–are we there yet.* In Proceedings of 24th CIB W78 Conference on "Bringing ITC Knowledge to Work", June 27-29, Maribor, Slovenia

Amor, R., and Ma, H. (2006). *Preservation of meaning in mapped IFCs.* In Proceedings of the 6th European Conference on Product and Process Modelling (ECPPM 2006), 233-236

buildingSMART. (2019a). Certified Software. Retrieved April 7, 2019, from https://www.buildingsmart.org/compliance/certified-software/

buildingSMART. (2019b). IFC Certification 3.0 Specification. Retrieved September 5, 2019, from https://www.b-cert.org/Documentation/d45350f2-f2ec-407e-b178-08d49c378a68

buildingSMART. (2019c). Industry Foundation Classes Version 4.1.0.0. Retrieved December 18, 2019, from https://standards.buildingsmart.org/IFC/RELEASE/IFC4_1/FINAL/HTML/

buildingSMART. (2019d). Industry Foundation Classes, Version 4.2 bSI Draft Standard, IFC Bridge proposed extension. Retrieved December 18, 2019, from https://standards.buildingsmart.org/IFC/DEV/IFC4_2/FINAL/HTML/

Fenton, N., and Pfleeger, S. (1997). *Software Metrics: A Rigorous Practical Approach* (2nd ed.). Boston, MA: PWS Publishing Company.

Jabin, J., Dimyadi, J., and Amor, R. (2019). *From a Meagre 'Testing for Interoperability' to the 'Measurement of Interoperability' in BIM.* In Proceedings of the 36th CIB W78 Conference "ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO)", September 18-20, Newcastle, UK, 1-10, 306-316

Jeong, Y. S., Eastman, C. M., Sacks, R., and Kaner, I. (2009). Benchmark tests for BIM data exchanges of precast concrete. *Automation in Construction, 18*(4), 469-484. doi:10.1016/j.autcon.2008.11.001

Kiviniemi, A. (2008). *IFC Certification process and data exchange problems.* Proceedings of the 7th European Conference on Product and Process Modelling (ECPPM 2008), Sophia antipolis, France, 517-522

Laakso, M., and Kiviniemi, A. (2011). *A Review of Ifc Standardization – Interoperability Through Complementary Development Approaches.* Proceedings of 28th CIB W78 Conference "Information Technology for Construction, October 25-28, Sophia Antipolis, France, 26-28 October

Laakso, M., and Kiviniemi, A. (2012). The IFC standard : A review of History , development , and standardization, Information Technology. *Journal of Information Technology in Construction, 17*, 135-161.

Lai, H., and Deng, X. (2018). Interoperability analysis of IFC-based data exchange between heterogeneous BIM software. *Journal of Civil Engineering and Management, 24*(7), 537-555. doi:10.3846/jcem.2018.6132

Lipman, R., Palmer, M., and Palacios, S. (2010). Assessment of conformance and interoperability testing methods used for construction industry product models. *Automation in Construction, 20*, 418-428.

Lipman, R. (2006). *Mapping Between the CIMsteel Integration Standards (CIS/2) and Industry Foundation Classes (IFC) Product Model for Structural Steel.* Proceedings of Conference on Computing in Civil and Building Engineering, Montreal, Canada, 14-16 June, 3087-3096

Ma, H., Ha, K. M. E., Chung, C. K. J., and Amor, R. (2006). *Testing semantic interoperability.* In Proceedings of Joint International Conference on Computing and Decision Making in Civil and Building Engineering (JICCDMCBE), Montreal, Canada, 1216-1225

Mili, A., and Tchier, F. (2015). *Software Testing : Concepts and Operations*. Hoboken, NJ, USA: John Wiley and Sons.

Pridmore, J., and Rumens, D. (1989). *Interoperability-how do we know when we have achieved it? (Military systems).* Proceedings of Third International Conference on Command, Control, Communications and Management Information Systems, Bournemouth, UK, 2-4 May, 192-205

Sacks, R., Eastman, C., Lee, G., and Teicholz, P. (2018). *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers* (Third ed.). Hoboken, NJ: John Wiley and Sons.

Solihin, W., Eastman, C., and Lee, Y.-c. (2015). Toward robust and quantifiable automated IFC quality validation. *Advanced Engineering Informatics, 29*, 739-756. doi:10.1016/j.aei.2015.07.006

Tal, E. (2017). A Model-Based Epistemology of Measurement. In *Reasoning in Measurement* (pp. 233-251). New York, NY: Routledge.