Proposal for a discipline-specific open exchange framework

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Abstract –

Several data exchange standards support the open exchange of building data. Industry Foundation Classes (IFC) standard is the most widely implemented within software solutions and the most used in practice. This standard is developed by buildingSMART International and describes a schema defined with EXPRESS data modelling language also including the data validation rules.

Because of its richness and redundancy, inadequate support of specific disciplines, but also its variable application within software solutions, open data exchange has not achieved a satisfying level of reliability. To transfer building data, actors that exchange information turn to various alternative data exchange possibilities like other open exchange formats, software specific data exchange software solutions, and workarounds.

This paper aims at analysing the problem of data exchange among disciplines with varying exchange requirements. Depending on the discipline and its specific requirements, data exchange potentials with IFC differ largely. Overcoming the interoperability problems are often discipline-specific: providing new schemas, incorporating strict workflows (for native and receiving application), or using 2D drawing - based exchange, physically or digitally.

In this paper, two workflows that follow BIM modelling process are examined. The first step in both workflows is the creation of architectural BIM model. Consequently, two data transfers are considered: to structural analysis and to life cycle analysis (LCA) software tools. The actors' exchange requirements are identified, as well as their description through the data flow.

Thereby, the adequacy of a predefined set of exchange requirements in the construction industry is assessed. Results show that IFC schema, or any other schema defined in the same way, is not an optimal answer to the end user needs. An improved open exchange based framework is proposed with a data management concept that supports it. Finally, the implementation of the new concept aims to enhance the technological development of open standards and draw it towards the seamless exchange.

Keywords –

BIM; Data Exchange; Data Interpretation; Exchange Requirements; IFC schema; Structural Analysis; Life Cycle Analysis

1 Introduction

1.1 Current Modelling Framework

Construction industry practices differ worldwide. The role of an architect in Europe frequently overlaps or overtakes project manager roles, especially in small offices. An architect is the first actor in the planning process that defines geometrical and non-geometrical data of the object to be built. In BIM workflow, architect models a building using 3D objects representing the digital versions of building elements. These objects can be defined either within an architectural BIM modelling software or taken from the external sources. Besides that, architect produces drawings as planning documentation and provides other actors with the necessary information about building elements for further design, analysis, calculation, validation by authorities, etc.

Created geometric and non-geometric data is required by the other actors in the process, belonging to both design and non-design disciplines. The exchange processes in most cases are still performed using paper documents or 2D digital drawings. BIM workflow aims to change that. Open BIM initiative from software producers and buildingSMART [1] suggests the use of the same information by different disciplines. This workflow neglects the need for standardization of integrated model interpretation for different construction industry domains. However, exchange using the open exchange format is still the most promising way of exchanging information in the industry with numerous actors and disciplines involved, where each takes part in the planning process with their specific requirements.

1.2 IFC Open Exchange

Several standards define the open exchange. One of them is the IFC schema standard that specifies a building data model to be used for the data exchange. IFC schema describes the integrated building model representing some disciplines in the industry. The first actor providing data for an integrated model is most often an architect. Other actors who are part of the planning process use data that architects provide, and in the follow up enrich and change it. They contribute by introducing the new and modified information to the integrated model. Differences that exist in the disciplines are managed by different subschemas called Model View Definition (MVD). The latest version of IFC schema is IFC4. It includes two MVDs - Reference View and Design Transfer View. Software solution certification is only provided for Reference View. This MVD tends to provide the IFC building data model as a reference only [2]. It is not supposed to be used for further data editing. For Design Transfer View, that exists since July 2015 and should serve for further editing of the building model, the certification is still not launched. On the list of certified software solutions [3], there are currently no tools certified with IFC4 MVDs. Because of the inexistent formal practical implementation, a widely used IFC2x3 schema will be tested in this proposal. Software solutions that implement IFC 2x3 are officially certified only for MVD Coordination View version 2.0 (CV V2.0). CV V2.0 is used for three different disciplines: architecture, structural analysis, and building services. In this open exchange workflow, these three disciplines use the same subschema. However, implementation of MVD differs greatly between the software solutions. If open exchange workflow with IFC schema is used, all the involved construction industry disciplines must conform to the same schema and use specific parts of it with MVDs (Figure 1).

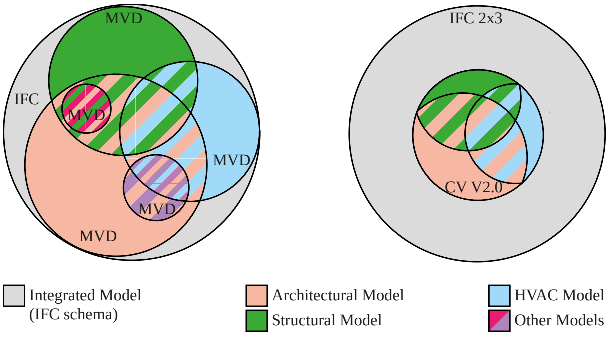

Figure 1 Concept of open data exchange with IFC schema and IFC2x3 with MVD CV V2.0

1.3 Asset Hierarchy

There is a strict asset hierarchy between geospatial industry, construction industry, and manufacturing industry. While the geospatial industry deals with the elements on the environmental scale and uses geographic information system (GIS) for its needs, manufacturing industry is on the product (or component) scale and uses product lifecycle management (PLM), construction industry deals with the products on the building scale [4]. There is an overlapping between the assets where GIS is interested in the data of a built facility as well as where the construction industry is interested in the components. Construction industry assets using BIM are represented through the IFC schema that defines the digital representation of building elements. However, the assets in the construction industry are getting evermore present within the other two industries. Architectural BIM software is mostly able to create product models as well (*.rvf files for Revit, *.gsm for Archicad or *.nmk for Allplan) and in that way, they are becoming part of the architectural model. Despite the fact that the product manufacturers are also interested in providing the digital content describing their product, its use within BIM workflow seems to be a gap in knowledge [5]. This field also lacks standards that relate it to open exchange. For instance, comparing to *.gsm and *.rvf files respectively, there are only 32% and 10% of digital objects provided in *.ifc format on one of the biggest online libraries for digital objects [6]. It is clear that product models are still generally exchanged with native software solution formats. These digital products are mainly developed to be used with software solutions in the construction industry. The new version of IFC5 [7] defines infrastructure elements which bring the schema closer to GIS. In other words, in the future, it will share more assets with geospatial industry. The schema provided by buildingSMART is in that way increasing its complexity and size, while the currently implemented MVD version is not sufficiently supported by software developers to achieve seamless exchange for most of the construction disciplines.

2 Background

2.1 STEP

Aspiration for standardisation of data for exchange purposes is present in all industries using digital models. STEP (Standard for the Exchange of Product Model Data) initially aimed to unify different national industry standards. It is widely implemented in the manufacturing industry, and it is the biggest standard of all ISO standards. It defines the way to exchange digital information about a product. Instead of defining an integrated model, its definition started by defining several part models called Application Protocols (APs) [8]. AP 225 called "Building elements using explicit shape representation" was a starting point for defining an IFC schema.

What construction industry lacks comparing to other industries is inter-firm adaptations. The construction industry represents loosely coupled system where every product is unique. For those reasons it is difficult, or maybe even inadequate to implement principles from other industries in the construction industry [9].

Actors involved in the planning process perform different actions that involve using different models of the same real-world product. Processes are complex and independent for each building in particular. Models of different domains differ from each other, where not only different data scope is used, but it also needs to be interpreted for a specific use (Figure 2).

If compared with the STEP standard, the whole range of disciplines that are used in the construction industry is reduced to a single Application Protocol that is later accepted as a starting point for the IFC standard. However, the construction industry with all its domains more resembles the STEP standard itself with multiple APs.

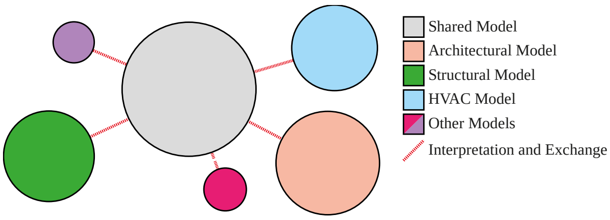

Figure 2 Concept of data exchange with domain specific models

2.2 Other work regarding structure

Two ISO standards are a base for the structure of building data model. Those are ISO 12006 "Building construction – an organization of information about construction works" Part 2 "Framework for classification" [10] and Part 3 "Framework for object-oriented information" [11]. IFC schema is based on 12006-3 addressing it as International Framework for Dictionaries (IFD). ISO 12006-2 is developed to standardise different national classification standards in construction and does not contain geometry information. Differences between IFC and 12006-2 are explained in [12]. IFC documentation does not state where the structure or model classes originate from.

Several works already described the necessity to expand the IFC schema to be able to support for instance structural analysis [13] or energy simulation [14]. buidlingSMART plans to involve several new disciplines in the future IFC editions [15]. The original plan is to create a steadily growing model that will eventually support all the involved disciplines. IFC2x3 covers eight domains including architecture and structural analysis. However, many problems are detected also in the domains supported by the schema [16]. A file-based data exchange is not a solution that has potential in the future [17]. Research by Lee et al. [18] states that schematic design is not enough for all the information needed for cost estimation. A necessity to bring the IFC schemas to an ontological level [19] describes transforming the IFC schema to ifcOWL, a terminology box definition using Web Ontology Language (OWL). For that reason, they propose to use semantic technology, where the IFC building data model is converted to RDF data.

The modularization of the ifcOWL ontology is suggested by Pauwels et al. [20] with the aim to use only the filtered model data. For that purpose, the particular modules need to be defined or the existing ones significantly redefined. Cost Estimation (CE) and Quantity Takeoff (QTO) framework by Aram et al. [21] suggests a knowledge-based system for using implicit besides explicit information in these two disciplines. Venugopal et al. [22] describe general schema structure reconsideration with MVD concepts to achieve a working modular exchange framework. The importing software needs to interpret the geometry and associate the meaning to the native objects for every discipline except simple geometry clash check. The mentioned research shows that the problems with the existing schema are detected in many disciplines. The focus is set on reaching the integrated model that will satisfy the requirements of more actors than the current open schema. On the other hand, the size of the current schema is also recognized as a problem, where data needs to be extracted, modularised and interpreted for specific applications.

3 Methodology

In this work, data transfers from architectural model to structural analysis and LCA using open exchange are reviewed. They both require specific geometric and non-geometric information about the building that is provided by the architect. Two workflows are depicted in Figure 3. The IFC data is considered for import into domain-specific software solutions. IFC2x3 with MVD CV V2.0 is used because of the lack of support for IFC4 in software tools, and because the certification of Design Transfer View MVD is still not taking place.

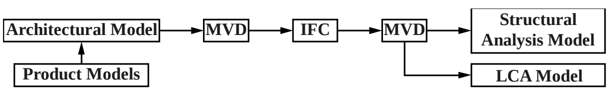

Figure 3 Two workflows considered in the study

Import exchange requirements are defined for each of the disciplines. These requirements are predefined with MVD concept list in the case of an open exchange. A simple case study model of door and wall is modelled in the architectural software [23]. Based on the previous research [16] [24], exports from the software solutions were generally using valid concepts of MVD, and therefore the exported model is considered valid.

Exchange requirements for two different imports that can be transferred from the native model to the exported model are identified and presented in Table 1. The structure of exchange requirements presented in the table is described from the end-user conception.

Table 1 Exchange requirements in the analysed case study model (SA = Structural Analysis)

Exchange Requirements			SA	LCA
wall	layer1	geometry	✓	✓
		material	✓	✓
		Load bearing	✓	×
	layer2	geometry	×	✓
		material	×	✓
		Load bearing	✓	×
door	handle		×	×
	panel	geometry	×	✓
		material	×	✓
	frame	geometry	×	✓
		material	×	✓
void		geometry	✓	×

The required data is allocated to the exported building data model and the structure of the export is analysed. Some special cases require additional information, but they are not considered in this work. The main aim is to describe various differences in exchange requirements, and how heterogeneity of disciplines and used software solutions require different ways of data exchange since it cannot be achieved with the current state of open exchange and MVD.

The presented case study questions if using an open exchange workflow with a predefined integrated schema answers the needs of actors in the construction industry. An open exchange framework allowing inclusion of more actors in the planning processes and bringing the digital building model closer to the real product is defined. With the results obtained from the case study and the related detected flaws, a new data managing structure is defined supporting the proposed framework.

4 Results

4.1 Geometrical Data

In this example (Figure 4) a wall consists of two layers, where one is load bearing. In IFC building data model it is represented as an entity IfcWallStandardCase. Its geometry definition is contained within the entity IfcProductDefinitionShape, where two different IfcShapeRepresentation entities are defined. First one is ‘Axis’ ‘Curve2D’ representation that is used for aligning material layer sets. Second is the ‘Body’ ‘Model’ representing the wall as a single homogeneous geometry, and not as a combination of two layers. Layer geometries are not specified separately. For structural analysis only the layer with load-bearing properties is relevant. That layer needs to be interpreted as a 2D element (with its axis and height). A common interpretation where a wall axis is placed in the central plane of the entire wall geometry creates an incorrect structural analysis element in this case.

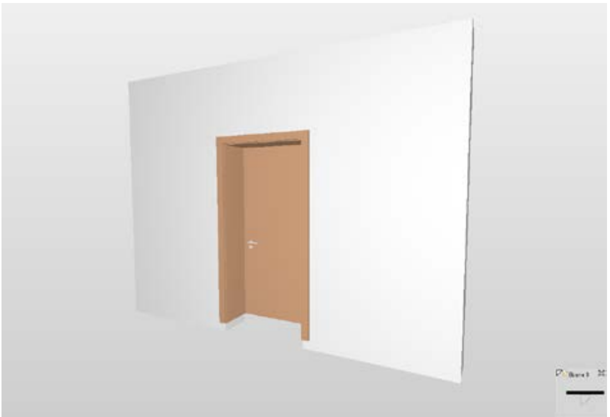

Figure 4 Screenshot from a viewer [25] of the

A door is represented by IfcDoor entity in IFC schema. There are two IfcShapeRepresentation that define its geometrical properties. This is ‘FootPrint’ ‘MappedRepresentation’ that defines an element representation in a 2D drawing, and ‘Body’ ‘MappedRepresentation’. Within the second one, geometry is represented using a boundary representation (‘Brep’) including all its parts. That means that a door handle, a door frame, and a door panel are creating a single geometry even though they are conceptually separate elements. For structural analysis the door does not represent an important element, only the void it creates in the wall. For LCA, a door panel and a door frame geometries are required. From these two geometries, the total width and height of the door information need to be extracted. In the IFC schema, the door total height and width are defined as attributes specific to the IfcDoor entity. In that way, it is easy to extract this information for LCA from individually defined attributes and not from its geometry, which makes redundant data.

The void is defined as IfcOpeningElement and its geometry is defined as ‘Body’ ‘SweptSolid’. It clearly specifies the cubic element that creates an opening in the wall.

Parameters that exist within the native model are generally lost during the mapping. This means that an ‘intelligent’ digital building model from the native software solution becomes a 'dumb' model [26]. For that reason, it is hard to interpret the future editing possibilities and constraints in the receiving applications. The details concerning the shape modelling aspects of the IFC models are not part of this work.

4.2 Non-geometrical Data

Non-geometrical data describing building element models, or attributes that represent them are mapped in three ways. They are declared as direct, inverse or derived attributes. In the study, all the analysed attributes are either direct or inverse ones. Direct attributes are attached to the model of interest, while the inverse ones are assigned through a relationship.

The structural analysis model requires the information about load-bearing properties for specific layers of the wall. The importing software tool only needs the load-bearing layers and to place the axis plane in the correct way. In the architectural software solution, the load-bearing properties of the layers are defined by an architect. In the IFC model, this is an inverse attribute defined through IfcRelDefinesByProperties. Property 'LoadBearing' is defined, but only for the wall as an entity, not for the specific layers within it. This property is not standardised and therefore not understandable by other software applications. Even if the load-bearing property can be successfully interpreted by an importing application, the specific layer cannot be extracted from the element. Another attribute necessary for proper interpretation is the information about the material. Materials are required by many disciplines and in this case both by LCA and structural analysis. For LCA materials of all layers are required. For structural analysis, it is necessary to import only the load bearing material information. Through IfcRelAssociateMaterial, IfcMaterialLayerSetUsage, and IfcMaterialLayerSet, materials are assigned to the wall. IfcMaterialLayer contains information about the layer thickness that could be used to extract information about the volume of a specific layer even if its geometry is not separately specified.

Data from the object IfcDoor is not required for structural analysis. For LCA calculation, it is necessary to have the total area of the door (including the frame) and materials of the door panel and the frame [27]. Materials are assigned with the relation IfcRel-AssociatesMaterial and IfcMaterialList to the door. There are three materials assigned to the whole element but without the details which specific parts of the geometry they describe. However, through IfcStyledItem, the geometry elements like the door panel, the handle, and the frame have different visual representation in IFC imports. These representations are defined using the inverse relations for geometry elements because objects like the door frame or the panel are not separately defined.

Most of the non-geometrical attributes are not standardised. In this case study, materials are mapped with the same names as in the native software solution. In the schema, there are some attempts to standardise attributes as IfcThermalTransmittanceMeasure, but that is not the case for any of the examined exchange requirements. In that way, the properties end up being machine unreadable and not relevant for future applications.

4.3 Data structure

The IFC schema structure, defined with the EXPRESS schema definition language, is rich and redundant. Attributes that can be optional or mandatory are inherited from the 'Supertype' of the entity or defined within it. In that way, entities are connected with the other types of entities. They can have simple or complex entities as attributes. That multiplies the possible definitions of the object. There are 812 optional and 625 mandatory attributes within IFC 2x3 schema. The mandatory attributes are often left as empty strings and not defined in the IFC building data model. Besides the hierarchically clear concepts, there are inverse relations that define inverse attributes. They act like containers of specific entities. This number of interrelated entities results with an extremely rich schema, which on the other side does not satisfy the needs of many actors involved in the industry. A simplified part of the case study model with the analysed exchange requirements is illustrated in Figure 5.

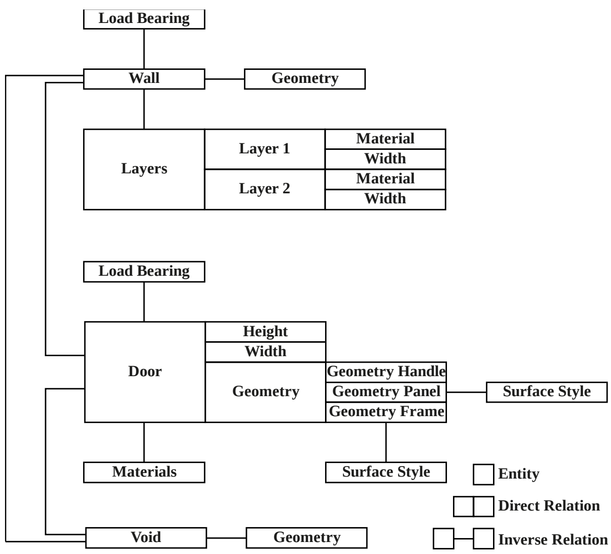

Figure 5 A simplified representation of the analysed case study building data model

A void element is connected to IfcWallStandardType with IfcRelVoidsElement which makes an opening in the wall and IfcRelFillsElement to IfcDoor that places the door in the opening element. The door and the wall are connected with IfcRelContainedInSpatialStructure to IfcBuildingStorey. For IfcDoor there are 7 different property sets connected with IfcRelDefinesByProperties, and 6 for IfcWall. Besides that, there are also IfcRelDefinesByType relations for defining IfcWallType and IfcDoorType for wall and door respectively. In total, for the door 45 IfcPropertySingleValue entities are defined, and for the wall 52, of which the majority is not standardised, machine-readable or required by the other software solutions.

5 Discussion

The intentions to use a single schema for a shared model in construction industry has not met user expectations yet. The history of IFC reaches back to 1994, but its main goal, achieving interoperability across the industry is still not achieved. In this paper, this schema is thoroughly analysed. The problems commonly occur due to three reasons: schema elements do not adequately represent the end user conceptions, some disciplines involved in the planning process and their requirements are not considered, and the schema implementation in software solutions is not trustworthy. To address these issues, a new concept for a schema is proposed followed by a framework that could result with an integrated building data schema definition.

A problem found in the case study is the lack of real-world object definitions that are required by the actors in the process. In the conducted analysis that problem is clearly presented with the door elements and wall layers. Upon the examined exchange requirements we propose a new structure from the end user perspective (Figure 6). The main property of the structure is to separate geometrical and non-geometrical data. Problems occurring within the geometry mapping are generally the problems of using different geometry kernels from the different software solution. The non-geometrical properties of objects belong rather to the standardisation category. Another advantage of this concept is that the end users can easily understand its structure. Thereby these two types of properties should be separated in the building data model (Figure 7).

The integrated data building model needs to support all the data exchanged in the planning process. The framework suggested in STEP standards, with different APs that would eventually form an integrated model, could deliver a functioning integrated schema. Due to numerous optional attributes that are left for users to define, the software solutions are already not able to follow with the support of the schema. Introducing new attributes and more possibilities to define the elements are not going to simplify its implementation and improve the interoperability without greater efforts by software developers. Mandatory attributes describing an entity are not necessarily a requirement for each discipline in practice. The planning processes differ between the countries and can be project-specific. Therefore the exact data exchange scenarios cannot always be predefined.

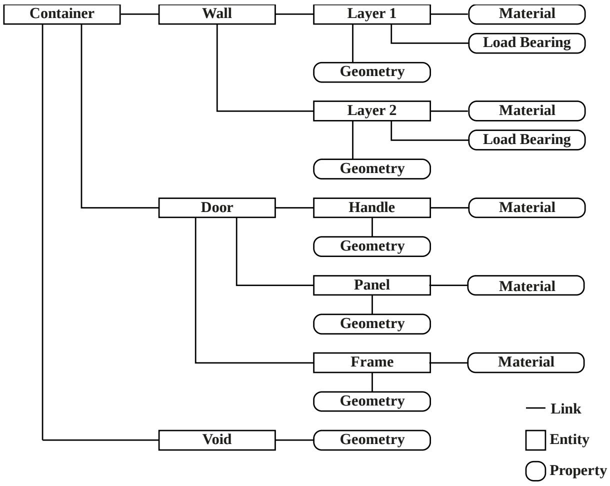

Figure 6 Schema proposal for easier implementation and validation

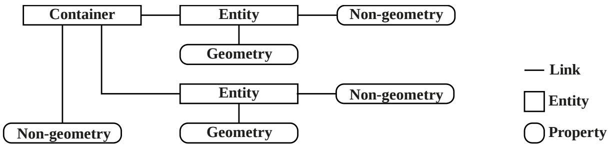

Figure 7 Basic part of the proposed structure

The attributes describing an object need to be defined as discipline-specific requirements, sometimes even software-specific requirements. Only after they are clearly stated, the schema definition can take place for the specific discipline. The limited integrated schema that cannot cover all the disciplines does not provide an answer. An integrated model can only exist with all the necessary requirements of every actor being supported. It can result from the coordinated unification of discipline-specific requirements across the industry. Following this concept, a base for an integrated schema would be a result of the specific disciplines' exchange requirements intersection. In this way, an extensive single schema is not avoided, but its definition is focused on the data exchange.

Implementation of the schema within software solutions, and especially software solution certification, is another obstacle for data exchange. This problem is extensively described in [24]. The idea of having different MVDs is still not implemented in practice since there is only one certified MVD used for data transfer between different disciplines (building service, structural planning, and architecture) that supports further planning tasks. Certification process of buildingSMART defines one concept list for import exchange requirements of all three disciplines. Software solutions certified without being able to support all the specified exchange requirements do not satisfy end-user expectations in practice. In order to achieve that, MVDs and the belonging concept lists need to reflect the discipline or software solution requirements.

When an integrated schema is defined as a product of discipline-specific schemas, a software solution does not need to support the integrated schema as a whole, or a single MVD, which is currently the case. Software solutions can in this way be tested for a specific purpose. Tools that are currently BIM capable would be BIM capable of a specific discipline, or more of them. It would be possible to measure which amount of relevant data a software solution is able to use based on the clearly defined end-user requirements. This concept can serve as a base for a metrics system for a discipline-specific certification process. The competitiveness of the software developers regarding the implementation of open exchange schema could improve the quality of its implementation. Defining a general metrics system and a certification that would provide end users with credible interoperability information can speed up a process of its implementation.

The analysis in this work is limited to three mentioned disciplines and a simple case study model. Analysis of a bigger example and its application in additional disciplines would surely address more issues regarding the schema. However, even this simple model demonstrates many problems that exist within an integrated schema currently used for open exchange. A more complex case study is avoided so the results could be presented as clearly as possible. Only one-way data exchange is considered.

The proposed structure concept is based on the end user conception of examined elements. The complete schema using the proposed structure would drastically increase in complexity, but comparing to the existing schema it would create a significant simplification of the integrated model. A software solution can only be certified for a domain specific or federative parts of an integrated schema, since there are no software solutions used for all the involved disciplines. The integrated model should support all actors involved in the process, without limitations and workarounds. Since there is a long way to achieve it, the focus can be set on the unification of federated models where the integrated model would be flexible enough and allow new concepts to become part of it. Its structure must, however, be clearly defined and validated. Another aspect of open exchange that needs to be standardised are interpretations for a specific domain and object properties. The uncertainties that occur during the mapping to the receiving application are one more thing that keeps the end users from using the schema. The same approach of filtering and interpretation must be applied in the other direction, federative or domain model to the integrated model. The future work regarding this topic is going to focus on the detailed structure development with a proof of concept to follow.

6 Conclusion

An integrated schema as a data managing concept in the construction industry was not able to provide satisfying results for many disciplines in the planning process. Processes like data filtering and interpretation are neglected in the general framework with the current IFC schema-based data exchange. Some disciplines can make use of the existing model only by filtering the information. However, the majority of actors involved find it easier not to use open exchange and to use other schemas, strict workflows that often include various workarounds and non-intuitive practices, and 2D drawing based exchange. Mapping processes are not standardised and clearly defined whereas many decisions are left to software producers. Viewers that are specifically made for the IFC schema are the most compliant with the integrated model. To solve the interoperability problems, schema has to cover the needs of all the software solutions involved in the exchange, and thereby consider all exchange requirements. Until then, all the disciplines that are not considered will turn to other options.

The required flexibility among the disciplines in the construction industry is not supported within the current open exchange schema. The taxonomy model defining exchange requirements could be a good start for the integrated schema. However, the schema that is limited does not satisfy the needs of the industry. The integrated schema must be complete and support all the product and project data from all the involved disciplines. For software solutions implementation, the focus needs to be set on filtering and interpretation processes. They need to support clearly defined subschemas similar to MVDs that are the answers for real end-user needs. Discipline-specific subschemas that represent exchange requirements are the key to achieving a working data exchange. The integrated schema unifying the discipline-specific requirements can offer answer to the interoperability problems in the construction industry.

References

[1] buildingSMART. *What is openBIM?*. [Video] On-line: https://www.buildingsmart.org/about/what-is-openbim/ifc-introduction/, Accessed: 15/01/2018.

[2] buildingSMART. On-line: http://www.

buildingsmart-tech.org/specifications/ifc-view-definition, Accessed: 15/01/2018.

[3] buildingSMART. On-line: https://www.buildingsmart.org/compliance/certified-software/, Accessed: 05/03/2018.

[4] Succar. B. *Asset Hierarchy*, 2011. [Image] On-line: http://www.bimframework.info/2014/10/asset-hierarchy.html, Accessed: 15/01/2018.

[5] Kin, M., Dawood, D. and Kassem, M. BIM for manufacturing: a case study demonstrating benefits and workflows and an approach for Enterprise Application Integration (EAI). In *Proceedings of 13th International Conference on Construction Applications of Virtual Reality*, Hong Kong, 2016.

[6] BIMobject. On-line: http://bimobject.com/de, Accessed: 19/12/2017.

[7] buildingSMART International. On-line: http://www.buildingsmart-tech.org/specifications/ifc-releases, Accessed: 15/01/2018.

[8] Eastman C. M. *Computer Environments Supporting Design and Construction*. CRC Press LLC, N.W. Corporate Blvd., Boca Raton, Florida, 1999.

[9] Dubois A. and Gadde L. E. The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management and Economics*, 20(7):621-631, 2010.

[10] ISO. *ISO 12006-2:2015: Building construction – Organization of information about construction works - Part 2: Framework for classification.* ISO, Geneva, Switzerland, 2015.

[11] ISO. *ISO 12006-3:2007: Building construction – Organization of information about construction works - Part 3: Framework for object-oriented Information.* ISO, Geneva, Switzerland, 2007.

[12] Ekholm A. ISO 12006-2 and IFC – prerequisites for coordination of standards for classification and interoperability. *The Journal of Information Technology in Construction (ITcon)*, volume 10, 2005.

[13] Weise M., Katranuschkov P., Liebich T. and Scherer R. Structural analysis extension of the IFC modelling framework. *The Journal of Information Technology in Construction (ITcon)*, volume 8, 2003.

[14] Cemesova A., Hopfe C.J., Mcleod R.S., PassivBIM: Enhancing interoperability between BIM and low energy design software, *Automation in Construction*, volume 57, pages 17-32, 2014.

[15] buildingSMART. On-line: http://www.buildingsmart-tech.org/future/old/ifc-future-extensions, Accessed 17.01.2018.

[16] Sibenik G. Building information modelling based interdisciplinary data exchange: a case study. In *Proceedings of 1st International UK BIM Academic Forum Conference*, pages 379-390, Glasgow, Scotland, 2016.

[17] Kiviniemi A., Fischer M. and Bazjanac V., Integration of Multiple Product Models: IFC Model Servers as a Potential Solution. In Proceedings of *W78 22nd Conference on Information Technology in Construction*, pages 37-41, Dresden, Germany, 2005.

[18] Lee S.K., Kim K.R. and Yu J.H., BIM and ontology-based approach for building cost estimation. *Automation in Construction*, volume 41, pages 96-105, 2014.

[19] Beetz J., Van Leeuwen J. and De Vries B. IfcOWL: A case of transforming EXPRESS schemas into ontologies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(1), pages 89-101, 2009.

[20] Pauwels P., Krijnen T., Terkaj W. and Beetz J. Enhancing the ifcOWL ontology with an alternative representation for geometric data. *Automation in Construction*, volume 80, pages 77-94, 2017.

[21] Aram S., Eastman C. and Sacks R. A Knowledge-Based Framework for Quantity Takeoff and Cost Estimation in the AEC Industry Using BIM. In *Proceedings of the 31st ISARC*, pages 434-442, Sydney, Australia, 2014.

[22] Venugopal M., Eastman C.M., Sacks R. and Teizer J. Semantics of model views for information exchanges using the industry foundation class schema. *Advanced Engineering Informatics*, volume 26, issue 2, pages 411-428, 2012.

[23] Autodesk Revit 2016. [Computer software]. Autodesk Inc., San Rafael, USA, 2015.

[24] Sibenik G. and Kovacic I. Current State of Data Exchange between Architectural and Structural Analysis Models - A Critical Review. In *LC3 2017: Volume I – Proceedings of the Joint Conference on Computing in Construction (JC3)*, pages 263-270, Heraklion, Greece, 2017.

[25] Solibri Model Viewer (Version 9.8.18). [Computer software]. Solibri, Inc., Helsinki, Finland, 2017.

[26] Pratt M. J. Geometric Modelling: Lessons Learned from the 'Step' Standard. In *Geometric Modelling. IFIP — The International Federation for Information Processing*, volume 75. Springer, Boston, MA, 2001.

[27] IBO – Österreichisches Institut für Bauen und Ökologie GmbH. *OI3-Indikator. Leitfaden zur Berechnung von Ökokennzahlen für Gebäude*, version 3.1. IBO – Österreichisches Institut für Bauen und Ökologie GmbH, Alserbachstr. 5/8, 1090 Vienna, Austria, 2016.