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Proposal for a classification system supporting interdisciplinary model exchange between architecture and structural analysis

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Abstract

Interdisciplinary digital model exchange in the AEC industry is faced with numerous difficulties, involving both process and technology problems. The digital design tools aim to meet end user needs, support existing design and construction workflows, and bring innovations in the AEC industry.
However, there is a mismatch between the digital tools in the AEC industry and relevant standardisation due to: a) lack of standards for digital tools, and b) the standards developing slower than the digital technology; thus increasing differences between numerous exchange workflows and stepping away from a seamless exchange.

This paper presents a review and evaluation of existing classification systems through a comparative study of several BIM-based tools for architecture and structural analysis, as well as the standards related to the classification, thereby identifying the deficiencies for a seamless exchange. Based on the review and identified deficiencies, a proposal for a comprehensive classification system is created to support the interdisciplinary exchange. The proposal focuses on the interpretation processes that are an inevitable but neglected part of the data exchange process between architectural and structural analysis models. Singular interpretation processes, which are the key element for the development of classification are described.

The proposed classification system is implemented and tested in the central building data storage, where the data exchange towards structural analysis digital tools is performed. This newly developed classification system simplifies the mapping processes due to its domain specific character.

The presented research contributes to the bulk of knowledge on the classification systems with the measures to harmonise, simplify and prepare these for the users and workflows in the smart planning in AEC industry. The concepts analysed and described in this paper can be applied to other disciplines within the AEC and related industries, to create the classification systems which will bridge the gap between different models.

Keywords: Classification system, Standardisation, BIM, Data exchange, Structural analysis

1. Introduction

The digitisation of the AEC industry workflows has been a digital counterpart for the traditional planning approaches since the first CAD programs, supporting the established AEC processes, first with 2D drawings, and later with 3D models. The occurrence of the Building Information Modelling (BIM) knowledge domain affected processes of AEC workflows on different scales, but it did not shake the grounds of data exchange frameworks between architecture and structural analysis. Data exchange moved from physical, paper-based information transfer to digital information transfer, remaining sequential, requiring significant amounts of manual rework and allowing redundant and separate multiple models. BIM workflows promise seamless data exchange processes across all domains within AEC industry, but the solutions to the exchange problems have not yet been found. Only a limited number of domains or disciplines can be distinguished, even if their field of action is not understood in the same way worldwide. Different field of action makes it difficult to achieve a general standardisation of a domain and implies a certain amount of flexibility within the standards. Therefore, the international data exchange standards need to support varying exchange requirements, depending on the software tool, domain and national standards. Besides the varying exchange requirements, the software tools have similar model representations corresponding to the domain they support. The focus of this research is the exchange where data, created originally with architectural software tools, is imported to structural analysis tools.

The significance of harmonised classification systems to achieve better communication is recognized in many knowledge domains, including the AEC industry (Lou and Goulding, 2008). However, the heterogeneity of classification systems used in the digital tools is often not properly addressed by centralised data model standards (Lee and Jeong, 2012). The communication problems are regularly occurring during the data exchange processes in the design stage of a construction project. The aim of this paper is to propose a new classification system, based on the review of existing standards, a comparative study identifying the deficiencies in the state of the art classification systems and problems in the data exchange process. The research consists of three parts:

1. Part: comparative study
2. Part: classification proposal
3. Part: classification proposal testing

The main problem which we will address is the lack of support from the existing standards for the everyday model-based data exchange workflow. The comparative study will provide insights in the existing tools, and present the communication differences. Building element interpretations are regarded as intuitive processes and rarely raise issues in the planning stage if done manually. The AEC industry was unable to follow the exchange processes with standards, so the processes could be automated for the data exchange. The classification proposal that will be presented in this study, could offer a solution for various data exchange workflows, when fully developed. The classification proposal testing demonstrates the potential of the proposed system for interpretation automation.

This paper is structured as following: starting with the literature review in Chapter 2, the standards responsible for classification systems, followed by the national and international AEC classification systems, and the classification in the AEC software tools are presented. The Chapter 3 presents the comparative study. The classification proposal, resulting from the comparative study, is presented in Chapter 4. In Chapter 5 the classification proposal testing is presented, while the conclusion and discussion are in the final Chapter 6.

2. Literature Review: Classification standards and systems in the AEC industry and software tools

The most significant standards describing the approaches for classification systems and terminology are ISO 1087-1 (ISO, 2000a), ISO 860 (ISO, 2007b), ISO 704 (ISO, 2000b) and ISO 22274 (ISO, 2013). In this chapter, these standards will be reviewed, summarising the definitions and approaches which are part of each classification system. The above listed standards define objects, classes, concepts and classification and concept systems: Objects are "anything perceivable or conceivable" and "abstracted or conceptualized into concepts". Differences between the objects are addressed through properties which can be assigned to each object. Class is "a set of objects that share the same characteristics". Classification, is a "process of assigning objects to classes according to criteria", resulting with a classification system. Classification system is "a systematic collection of classes organized according to a known set of rules, and into which objects may be grouped". On the other side a concept system exists which interrelates with the classification system. Concept is a "unit of knowledge created by a unique combination of characteristics", and a characteristic is a "distinguishing feature". Feature is a "defined characteristic suitable for the description and differentiation of concepts in a concept system". Concept system is a "set of concepts structured according to the relations among them". "Concepts depict or correspond to a set of objects; are represented or expressed in language by designations or by definitions". Concept systems can be used as a basis for a classification system, or more of them. Concept system establishes the relations between the concepts in three different ways:

1. Hierarchical generic: the intention of the subordinate concept is included in the intention of the superordinate concept (the subordinate concept is a specific concept compared to the superordinate generic concept).
2. Hierarchical partitive: superordinate concept represents the whole and subordinate concept a part.
3. Associative: the non-hierarchical associative relations can be of various types, and are a "thematic connection by virtue of experience".

The base of each classification system is an appropriate concept system. Recommendations on how to use a concept system and build a classification system are given in ISO 22274 (ISO, 2013). A consistent terminology is a mandatory condition for achieving unambiguous communication. Users must be provided with definitions for the class in order to reduce ambiguities. A concept system reflects the knowledge about the concepts in a specific domain, and the relations between them. However, multiple classifications can be a product of a single concept system. ISO (2013) defines three types of classification systems: enumerative, faceted and combined. Enumerative system represents all the classes through the hierarchic system. The faceted system lists multiple classification of the object, where object can belong to any combination of classes from the facets (e.g. material and building element for a concrete wall). The standard suggests to use the combined system: enumerative system on higher and faceted on lower levels.

ISO 860 (ISO, 2007b) suggests that if there are multiple classification systems with non-minor differences, even if the concept systems are from the same subject field, they should not be harmonised. Architecture and structural analysis are domains with major conceptual model differences. The harmonisation of the terms present in architectural and structural analysis software is therefore considered unfeasible. Although both domains take part in the building design process, the two classification systems have different purpose.

Classification systems in the AEC industry are mainly created on the national levels. Some of them are Uniclass 2015 in United Kingdom, Omniclass, MasterFormat and Uniformat in the United States, CoClass in Sweden, CCS in Denmark, building 2000 in Finland, STABU LexiCon in Netherlands, NS 3451 in Norway (Dikbas and Ercoskun, 2006; Lou and Goulding, 2011). The significant attempts to classify building information in the so called DACH region: Germany, Austria and Switzerland can be found in the classification for costs in construction: DIN 276, ÖNORM 1801-1 or SIA 112 respectively. Common Procurement Vocabulary (CPV) developed by the European Union defines a classification system for all the matters regarding the public contracts. Two ISO standards are related to the classifications systems in the AEC industry, ISO 12006-2 (ISO, 2015) and ISO 12006-3 (ISO, 2007a). ISO 12006-2 recommends the classification systems, providing several classification tables regarding all stages in the construction project lifecycle with definitions. Classification systems like CCS and Uniclass 2015 are created based on this standard. ISO 12006-3 specifies the language-independent model defined with the EXPRESS data modelling language. The model identifies the way in which the objects, groups and relationships within them are created to represent the knowledge. STABU LexiCon and buildingSMART Data Dictionary (bSDD) are based on this standard.

Ekoholm and Häggström (2011) criticize the classification standard ISO 12006-2 for failing to uniform the existing national systems and not being suitable for specific disciplines in the construction sector, e.g. cost calculation using the Swedish and Danish systems. Further on, Kereshmeh and Eastman (2016) propose a way to compare different classification systems focusing on the classification systems from North America and United Kingdom. Ekholm (2005) describes the difference between the ISO 12006-2 and ISO 12006-3 classifications, and identifies some issues in the ISO 12006-3-based Industry Foundation Classes (IFC) building data model, like the definitions of building elements not being related to their spatial, functional or compositional view. The author also suggests several steps necessary for the harmonisation of the existing systems based on the two standards. The classification systems aim to encompass the whole AEC industry, eventually internationally harmonise the term codes, but still do not recognise the heterogeneity of the various domains. Classification systems are a prerequisite for organizing building product libraries so the building data models with varying purposes could be used for communication. The first critical step in creating a classification system is defining the purpose of classification (Ekholm, 1996; Ekholm and Haggstrom, 2011; Jorgensen, 2011; Kereshmeh and Eastman, 2016). The purpose of the classification defines various exchange requirements which need to be supported depending on the software tool and domain (Sibenik and Kovacic, 2018).

Most of the existing classification systems are not used in the international products of software industry for architectural design and structural analysis. Generally, terminology is not harmonised among the software tools supporting the AEC industry. Thereby, the reasons for low implementation levels can be classification systems being (ACCA software, 2018):

- Local - for their limited geographical and linguistic character
- Incomplete - for not encompassing all the relevant knowledge
- Technically behind - more advanced ways to classify information exist and can be supported with current technology.
- Specific - mainly created for cost calculation, differences in representations not addressed, interpretations would make data management more complicated in some cases.

This research addresses primarily the structural analysis tools, and the data originally created in the architectural software tools. The formerly described classification systems do not recognise the elements to be analysed in the structural analysis software tools (linear and planar elements). Classes like beam or column in structural software tools provide additional geometrical properties (beam: horizontal linear, column: vertical linear element), but might be referring to a single class (linear building element). This difference is recognised in the Industry Foundation Classes (IFC), which is a standard for building data model based on ISO 12006-3. The IFC standard conforms to the classification system buildingSMART Data Dictionary (bSDD), an international classification system which aims to encompass all relevant entities with their attributes. This is the most widely used standard for the data exchange. IFC recognises different representations of the same element, but the relation between the representations is not addressed.

In this part of the research the classification systems within AEC digital tools will be address. Software industry provides the AEC industry with the tools for architectural and structural design, analysis and optimization. BIM authoring tools support object-based modelling and different classification systems. The classification systems of the employed software do not conform to any of the previously mentioned national standards. End users are however required to deliver the information respecting the national standards, using the templates and defining the data exchange properties. This process might be complex and the software tools do not guarantee that the information will retain the definition after the data exchange. The process of information mapping during the exchange processes is left to the software developers.

BIM tools, as well as CAD tools, are object oriented. The objects represent the concepts of a specific domain. “Objects in the domain of interest are modelled as software objects with properties that represent domain object properties” (Ekholm, 2005). For the software industry, the property is known as an attribute. Using the classification, software developers are able to use the same code that can deal with multiple object properties, methods, relations, etc. The need to accommodate the classification systems in the AEC sector to the advances in software industry was recognized more than 20 years ago - to develop a classification system which will be used for both AEC and software industry. In the work of Ekholm (1996), the classification for product modelling needs to be classified within a series of different classification, where he refers to various project stages as purposes. Jorgensen (2011) emphasises the need to explore new opportunities in software industry that can be used in classification systems. Multiple misconceptions are described in current classification system, which need to be reconsidered since the software tools are increasing their stake in the construction projects and provide new possibilities.

The research dealing with the import of structural analysis models is most commonly performed with the IFC classification system. The models require significant amount of information interpretation (Sibenik, 2016; Ramaji and Memari, 2018; Deng and Chang, 2006) before the structural analysis tools can properly render them. Differences between the architectural and structural analysis models and the underlying classification systems are not clearly defined nor standardised. The relations between corresponding elements in two models are not described and the exchange process is not transparent. The differences between models are not part of the IFC standard. Lee and Jeong (2012) describe the necessities of interpretations between the AEC domains. They develop the filters which can facilitate the communication between the building models. The classification of knowledge is not in the focus of their work, however they recognise that the existing data-centric approach is not feasible and develop an ontology that can be used in multiple domains.

3. Comparative study

The comparative study analysing five software tools for: architectural design (Graphisoft, 2018), architectural and structural design (Allplan, 2018; Autodesk, 2018), and structural design and analysis (Dlubal Software, 2018; SCIA, 2018) was conducted within the presented research. Thereby, three common building elements present in almost every AEC project were identified: column, wall and slab. All the analysed software tools claim to be suitable for BIM workflows and are IFC certified. One of the characteristics of BIM models is that they consist of parametric 3D objects containing additional information, besides geometrical information. All of the examined tools are object oriented modelling, design and analysis tools. The software classification systems were analysed primarily through software tool interfaces, but also in regard to corresponding application programing interfaces (APIs) and the corresponding objects. Figure 1 presents the existing classification systems graphically based on the ISO standards. The relations between classes are hierarchical generic.

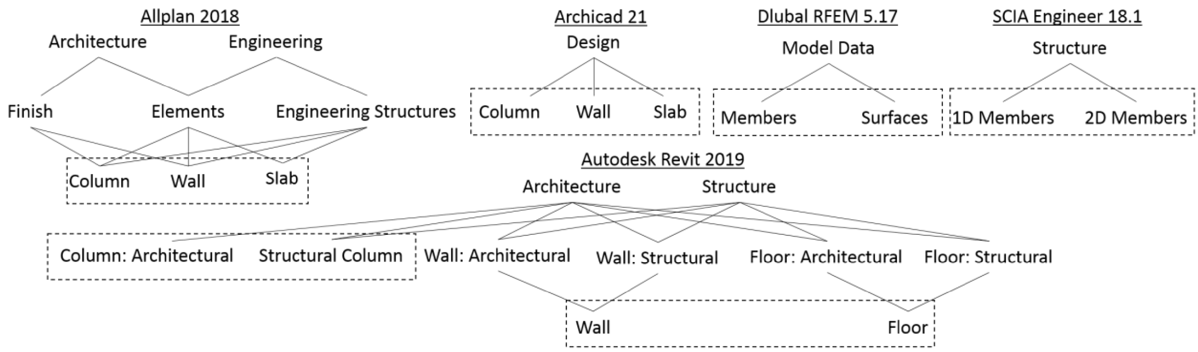

Figure 31 Different classification systems in software tools

The figure depicts the differences in software tool classification. Terms generally differ and the definitions describing the terms are missing, however they can be compared by analysing the existing object behaviour. Among the tools mainly used for architectural design (Archicad 21) and architectural and structural design (Allplan 2018 and Autodesk Revit 2019), the main difference are the possibilities to access the same class - except for the columns in Autodesk Revit which make two classes. The terms are similar in all three software tools, but the way they are structured differs. On the other hand, the structural design and analysis software solutions show similarities and the three elements are represented in only two classes. The reason for that is the reduced dimensionality of analytical models. In structural models columns are defined as linear elements, where the cross section is a non-geometrical information (not modelled), and walls and slabs are planar elements where thickness is a non-geometrical information. The column class suggests that a linear element is vertical, the wall class that the planar element is vertical and the slab class that a planar element is horizontal. These classes are not necessarily a part of the structural analysis software tools (e.g. RFEM Dlubal), and the class is not limited to the direction of the element, meaning they can be changed during the design and still remain in the same class (SCIA Engineer). Therefore, the classification as a column, wall or slab is considered irrelevant for a structural analysis models, and the main classification is on a higher level. IFC standard classification is the most widely accepted standard for the data exchange defining the object oriented building elements classification. IFC aims to encompass all the elements present in the AEC industry. The standard recognises the three building elements in an architectural as well as in the structural taxonomy. This results in five differing classes placed on the same level in the classification schema, as depicted in Figure 2.

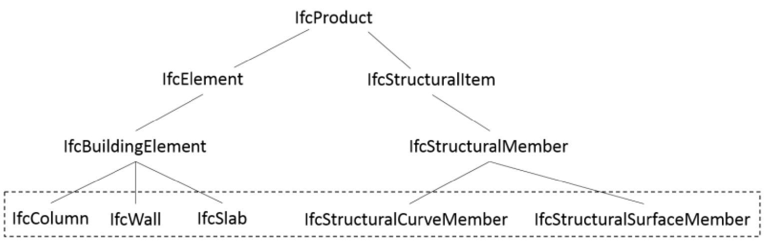

Figure 32 IFC classification system

The relations between the IfcElement and IfcStrucuralItem are not part of the standard. A preceding research showed that the interpretation standardisation is one of the core problems of the data exchange process (Sibenik and Kovacic, 2018). Based on the work of Ekholm (1996) it is necessary to disregard the properties that are not of interest and create a definite and exhaustive system. Definite means that an object may not belong to more than one class of the same rank, and exhaustive means that every object must be assigned to a class. It is impossible to disregard the properties for each discipline in a unique encompassing schema. The exchange standard also does not manage to be definite since the elements may occur in multiple classes simultaneously.

This comparative study does not include the properties, in order to reduce the complexity of analysis; each object contains additionally a number of properties, addressed in different ways in each software tool, requiring detailed analysis and harmonisation. The software tools deal with a single representation of elements, and mostly support domain specific concept systems behind it. The interfaces are not necessarily following the underlying classification system, and allow multiple terms and ways to access the same resulting class.

4. Classification Proposal

The comparative study shows that the relation between the architectural and structural elements requires more clarity. Still, the end users (structural engineers) are able to distinguish and interpret the architectural models without significant problems. We believe it is necessary to understand the concepts from both disciplines, and unite them in a single concept system. This approach opens the possibilities for the interpretation. The first recommendation from ISO (2015) for developing a classification system is defining the purpose. As already discussed, the harmonisation of classification systems for architecture and structural analysis domains is not a feasible solution. Thus, our recommendation is a development of **two classification systems** with architectural and structural purpose, based on a **unique concept system**. Starting with the comparative study and the standards responsible for the classification the following proposal of the classification system for these three building elements was developed (Figure 3):

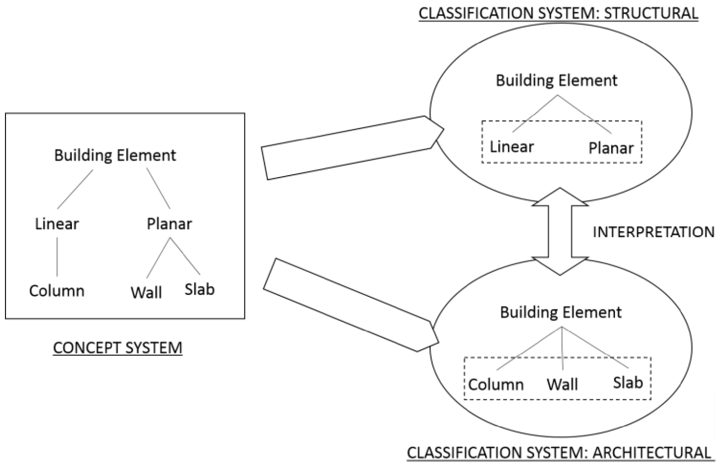

Figure 33 Proposal for domain specific classification systems based on the concept system

The approach involving multiple classification systems must retain the **interpretation rules** existing in the concept system. Without the interpretation rules, the systems lose their relations originating from the conceptual system and the data exchange between two classification systems becomes impossible. The proposal can be defined as "concept system = classification systems + interpretations".

Each concept is separated from the other concepts by its intension - the unique set of its characteristics. Each terminological entry should be composed of a statement explaining what the concept is (ISO, 2000b), but the software tools usually do not provide the end users with the clear definition. From the analysed classification systems, only IFC standard describes the terms textually. However, the definitions from IAI (buildingSMART, 2018) defining columns as "structural member of slender form, usually vertical", walls as "usually vertical, or nearly vertical, planar elements" and slabs as "the construction that normally encloses a space vertically" are too vague for the automatisation of the interpretation rules without introducing clearly defined tolerances. The AEC industry lacks definitions that would facilitate the automatization of the interpretation rules. This leads to overdifferencing of classes in software tools and excludes the possibility of an automated interpretation. Properties that determine the class create the definition of a class with a preferred textual definition. To facilitate the seamless data exchange, definitions of elements are required which will make automated interpretation possible. Therefore we decided to consider the elements strictly as horizontal or vertical. The elements are defined in order to allow for the automated interpretation:

Column
A linear vertical building element.
Wall
A vertical planar building element.
Slab
A horizontal planar building element.
Linear element
Building element where the largest dimension of a bounding box equals or is greater than 10 times next greatest dimension.
Planar element
Building element where the largest dimension of a bounding box is smaller than 10 times next greatest dimension.

The definitions are used as a proposal only and have not roots in any reviewed standards. They are used to describe a necessary amount of information which could clearly distinguish building elements and automate the processes between them. In this case, only the three building elements are considered. The differences are based on the element's geometrical information that can be automatically recognised. Proposed definitions serve for the classification proposal testing in the follow up, however, the comprehensive automation-suitable definitions need to be made with mutual consent in the industry and consider more building elements.

The interpretation of elements from the architectural to structural classification is straightforward, since the structural classes are superordinate concepts towards the architectural ones. In this case, columns are linear elements in the structural classification system, and the walls and slabs are planar. The interpretations in the reverse direction are more complex. The easiest way is to address the object by its ID if possible and update it, if it originates from the central database. If not, elements can be interpreted by analysing the geometry information. The linear elements contain the cross section information as a non-geometrical information, as planar do the thickness. In case of the three elements, it is possible to identify if the element is vertical or horizontal, if it is a horizontal planar element then it is a slab, if vertical it is a wall. The vertical linear element is column.

5. Classification proposal testing

The classification system described in the previous chapter was tested within the data exchange framework involving the central database with architectural information and structural design and analysis software tool (Dlubal Software, 2018). The building data information in the central database originates from the IFC 2x3-based file exported from Autodesk Revit 2019. The export was performed with the default setup for Coordination View 2.0. In order to make data model more accessible, the IFC file was converted to the Java Script Object Notation (JSON) format with a self-developed converter. The JSON-based central data is regarded as a starting point for the data exchange. The idea is to convert the central, architectural building data model to the structural building data model. All these steps are taking place before the communication with the importing software is initialized.

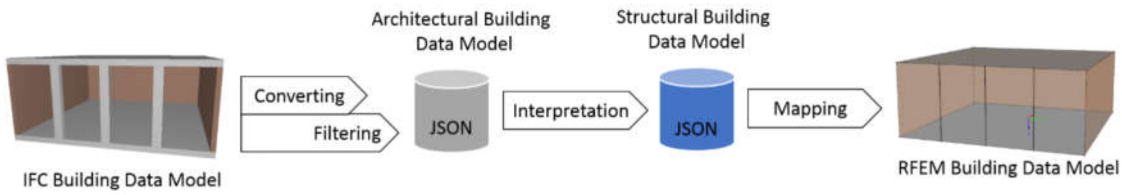

Figure 34 Classification proposal testing methodology with screenshots

The central architectural building data model uses the classification system described in the previous chapter, with the properties necessary for interpretation. The interpretations reduce the dimensionality of a physical architectural model to the analytical structural model, retaining the connections between the elements and transferring the geometrical to non-geometrical data on the central storage. In this way the structural building data model is created, based on its own classification system. The last step is the import to the structural analysis software tool. The actual import of data is taking place after the structural analysis building data model is created. The importing software tool is communicating only to the structural data model in the proof of concept. It is possible that the communication is achieved with multiple databases if it would make a viable option.

The developed testing framework shows that two different classification systems, architectural and structural, can significantly simplify the process of importing building data model to a structural analysis tool. The interpretation steps are taking place on the central data storage, based on the conceptual differences of different building models. If the structural design and analysis tool imports the data already classified with the structural classification system, the importing process is mainly reduced to mapping of information. In this way a great and expensive effort of defining and implementing interpretation rules from an architectural model to the structural model are relocated from an importing tool to a central storage. The importing tools gain a simplified data exchange procedure, and the origin of most of the data exchange problems in this particular exchange is bypassed. The lack of standards is identified as the main obstacle for this approach. New definitions for each element were created before the interpretation process could be developed. The implementation can only be possible with the clearly defined algorithms. This framework supports the creation of various classification systems which have been excluded in the standard digital exchange workflows, but remain necessary in heterogeneous AEC industry. The domain-based classification systems with interpretation rules are the missing links in the process of data exchange.

6. Conclusion

This research questions the data exchange framework used in the AEC industry. The first step when defining a new classification system is to define its purpose. The concepts present in architecture and structural analysis domains in AEC clearly require two classification systems. However, the classes within different systems must be interrelated with interpretation rules. The interpretation rules and inter-domain communications are a standardisation gap. The comparative study showed that software tools support domain specific concept systems, without mandatory interpretation standardisation. A proposed framework is based on a single concept system and two classification systems with mandatory interrelation standards. The proposal can be summarised as:

1. Single concept system
2. Multiple classification systems
3. Interpretation rules between the classification systems

The proposed framework allows significant simplification of the data import process by the structural analysis software tool since it is addressing a pre-processed architectural model with the reduced-dimension geometries, avoiding usually erroneous software tool-based interpretation process.

Multiple classification systems allow for the improvements in many aspects of the AEC industry by supporting domain specific knowledge, and the relations between them primarily in data exchange processes. The open exchange certification process which is currently not a relevant data exchange indicator for these domains could be improved if the classification would answer real domain-specific requirements (Sibenik, 2016). Open central storage facilitates the possibilities for greater community involvement, and increase the innovation potential related to information management in the AEC sector. BIM and seamless data exchange do not affect the sustainability directly. The seamless exchange aims to reduce errors and save time spent on redundant tasks during the planning process. The only way that sustainability can be indirectly affected is that the simulations related to sustainability would require less time and money, and therefore the building models could be earlier tested for their sustainability implications, which might, but does not necessarily, result with more sustainability awareness and building.

The research has several limitations: only three building elements were analysed; geometries and interpretations could become very complex depending on the original element; interpretations were examined only between architectural and structural models; and properties of elements were not included in the classification analysis. The research demonstrates the alternative approach to a data exchange framework and the results suggest that the complexity of information interpretation for each software tool should be avoided and moved to the central data management system. The framework implementation model is still not developed, which would be a challenge in not sufficiently regulated AEC industry. However, first the comprehensive concept system must be developed with clearly distinct building elements, followed by purpose oriented classification systems and the interrelating rules. The next step is the completion of the system for a proof of concept, involving more types of geometry and interpretation rules which need to take place in the central communication system. The classification systems and interpretation rules in a new framework need to be developed in a greater detail and expanded. The approach discussed in this paper has implementation potential in various AEC domains, especially the ones having varying concepts for same building elements (e.g. energy performance analysis, structural analysis), but even if only the filtering of the centrally available data model or models takes place (e.g. cost calculation, life cycle analysis).

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