A theoretical holistic decision-making framework supporting collaborative design based on common data analysis (CDA) method

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Abstract

The enormous expansion of information, which is assembled from various design tools, has caused challenges in data exchange and compelled companies to find various solutions to improve collaboration. Data exchange within Building Information Modelling (BIM) context has been mainly focused on individual disciplines. Even though several attempts have been made to develop data exchange requirements for BIM models, there is still a lack of homogeneity since no method for classifying and sharing those requirements is clearly outlined. A clearly defined "single truth of information" is still not acknowledged yet. Software tools require unambiguous clarity of the semantics, which can help various stakeholders to proceed with their design tasks. However, there is still a lack of multi-dimensional knowledgebase for holistic decision-making within a BIM workflow. Therefore, this paper presents a common data analysis (CDA) referencing various concepts such as the standardised Information Delivery Manual (IDM) method, model view definition (MVD) and the concept of semantic intersection to conclude "single truth of information" and "partial truth of information" data sets that form the basis for a theoretical holistic decision-making framework to support collaborative design. The information defined in this research was validated based on existing resources and literature. Following the concluded data sets, a model can be transformed automatically at the minimum commonality level, creating a starting point for other professions. Following the analysis, a theoretical holistic decision-making framework was proposed. The innovation of the proposed framework lies in providing a holistic decision-making system that combines both data extraction using the concluded data sets and semantic web technology to eliminate inefficiencies in data sharing and improve the decision-making process in the early design stage by providing the stakeholders with rational solutions with less effort and time. This paper provides the essential requirement for a holistic decision framework from a data processing perspective.

keywords: Building information modelling (BIM); Industry Foundation Classes (IFC); data exchange; semantic subset; semantic intersection; single truth of information; partial truth of information; Model view definition (MVD)

1. Introduction

The architecture, engineering, and construction (AEC) industry are changing its traditional business methods, with information now being exchanged digitally rather than in paper form. However, moving forward with this digitalisation within the AEC industry requires companies to adopt new techniques to help to improve their way of working to collaborate more effectively. BIM has been utilised to provide better collaboration and integration in a project [1,2]. It is described as "a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility" [3]. Consequently, the BIM model at one end needs to be transferred to a model that can be understood by other design and analysis tools at the other end

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[4] and also need to be supported by a holistic decision-making system to produce an ideal design collectively. However, interoperability, which is described as the ability to exchange data seamlessly across various disciplines and stakeholders [5], has been acknowledged as an important issue in BIM due to heterogeneous tools [6,7].

Manso, Wachowicz and Bernabé [8] defined the level of interoperability as a "set of criteria and associated processes for assessing information system capabilities and implementation in the context of the degree of interoperability required". Paviot et al.[9] mentioned three levels of interoperability that need to be considered to realise the full potential of interoperability. First, technical level, which is associated with communication protocols that involve providing communication between systems. Secondly, the semantic level focuses on having a shared, common vocabulary exchanged among the parties involved in a project. Finally, the organisational level focuses on procedures and guidelines for accessing and using data in an organisation. It is seen that enhancing interoperability in an organisation is not only concentrated on developing tools but also solving issues related to business processes and functional organisation. On a similar topic, Steel, Drogemuller and Toth [10] classify interoperability into four levels: The first level is limited to provide a successful file exchange among tools, while the second level goes further by focusing on parsing the exchanged file correctly. The third level concentrates on the visualisation aspects of the exchanged model among different tools. The fourth level is the most critical level, where models need to be semantically rich. It requires understanding the intention behind the exchanged model to avoid any data loss [10].

The information delivery process plays a significant part in enhancing collaboration by identifying what and when information needs to be exchanged and who is responsible for that information [11]. Lee [12] stated that "Information generally flows from the more informed to the less informed" [12], bearing in mind it can flow in the opposite direction in certain situations. However, the data exchange process faces several concerns that restrict its progress, mainly related to data mapping, which requires an informed understanding of various disciplines and domains. UK BIM Alliance [13], which was founded to provide a guideline on how to run BIM Level 2 and the digital transformation of the UK industry, stated that the power of BIM is not focused only on the geometrical information but also on the non-geometrical information, which plays a significant part in the delivery of a project. This information includes the entire project lifecycle starting from conceptual design and covering all other stages [13]. However, there is still a lack of multi-dimensional knowledgebase for holistic decision-making within a BIM workflow that considers the non-geometrical information.

Lee [12] mentioned four main issues behind data exchange: (1) Incomplete coverage of a data model, (2) issues raised with using translators due to the lack of guidelines while developing these tools, (3) system errors due to the use of various vendors tools inside the same organisation, (4) Software domain complications since the used tools were developed for a specific domain and lack of knowledge about other domains. Hence, the stream of information is not all the time unidirectional [12]. There are three types of data exchange [14,15]: First, exchange using the same authoring tools. Secondly, exchange through an application programming interface (API) and thirdly, exchange using a common data schema such as industry foundation classes (IFC), which is a rich BIM schema for data exchange, and it is known as the industry standard for interoperability [16]. Since IFC schema covers various domains, it is not convenient to implement the entire schema in software vendors. Consequently, a concept such as Model View Definition (MVD), which is described as a subset of the IFC schema to specify the requirements of the exchange data to serve a specific domain [17], has been used as a solution to enhance data exchange. However, Lee [18] stated that MVD is a document rather than a subset that describes how the IFC model specification is applied to data exchange between different application types. Moreover, Lai and Deng [19] stated that although many pieces of research have been presented in the area of data exchange and MVDs, several issues still exist within these topics since data exchange within the BIM context has been mainly focused on individual disciplines. The data exchange requirements that were defined using the above concepts were developed independently [20] and require end-users to have prior knowledge about other domains. Furthermore, IFC was not designed to deduce new information from a BIM model. Consequently, using technologies such as the semantic web, which can represent complex domain knowledge, can help support BIM models with a holistic decision-making system that further enhances interoperability.

Cheung et al. [21] indicated that “In computer applications, it is rather common for users to employ one tool to deal with a type of task and another tool for a different type of task even though the two tools may have overlapping functions to handle both tasks”. Hence, many BIM models are created in a given project by various stakeholders to achieve different objectives. Each of these models represents an individual part of the entire building, and it is called a domain-specific partial model [22]. Despite the different use of these sub-models, they share some commonalities that are not exclusive to a specific domain. The more commonalities exist within two systems, the less data loss will exist between the two systems [23]. However, a clearly defined “single truth of information” is still not acknowledged due to the lack of a robust standard for defining building semantics and requirements for data exchange [20]. To define a “single truth of information” shared throughout the building lifecycle, which allows models to be transformed automatically at minimum commonality level, the connections between different models need to be distinguished. Therefore, this research presents a CDA referencing various concepts such as the IDM method, which is described as “documentation which captures the business process and gives detailed specifications of the information that a user fulfilling a particular role would need to provide at a particular point within a project” [24], MVD and the concept of semantic intersection adopted from Lee [12]. This CDA will form the foundation for developing a theoretical holistic decision-making framework that can help to produce an ideal design collectively.

This paper is structured as follows: Following the Introduction in **Section 1**, the Background, which reflects the research that was accomplished using IFC schema to improve data exchange and collaboration in the AEC industry, is given in **Section 2**. This literature is by no means an exhaustive review. However, it indicates the many developments taking place in this area and their limitations. The methodology is given in **Section 3**. In **Section 4**, the requirements collected from models and literature are discussed. **Section 5** discusses the similarities and differences between several MVDs, followed by a discussion in **Section 6** and the proposed framework in **Section 7**. Finally, the conclusion is given in **Section 8**.

2. Background

The work that has been accomplished to deliver a high level of BIM data exchange in the AEC industry can be classified into two groups: (1) Defining and standardising information delivery (2) Developing tools and platforms to back up the delivery of data across various stakeholders.

2.1. Defining and standardising information delivery

To solve the concerns within the IFC schema, BuildingSMART proposed the IDM and the MVD concepts [25], **Fig. 1**. They have been utilised to define and standardise information delivery. IDM composes of a project map (PM), exchange requirements (ERs), and functional parts (FPs) [26]. For instance, the PM helps define the overall and detailed workflow of tasks in a given discipline or among more than one. In this map, what information need to be created and exchanged can be defined. In contrast, the FP can help link this information to a schema by matching it to the correct entity in that schema to support software solutions, which form the initial steps that can help develop what is called MVD. However, the flexible nature of IFC schema is giving room to map the same information in different ways [5], which depends mainly on the developers, especially that there is no clear, logical connection between the units of information in the exchange requirements of an IDM and those of MVDs [20]. Furthermore, the number of MVDs is expanding since the construction industry is more eager to utilise BIM, where the information will be exchanged digitally rather than in document form. However, Lai, Zhou and Deng [27] indicated that the current Industry is still a shortage of MVDs to deliver structural design data to the collaborative design stage. The development process of an IDM-MVD is complicated and time-consuming [5], which is causing several challenges [26] that constrain their embracement [14]. For instance, due to the continuous rise in the number of ERs and FPs as the development process reach completion, it becomes hard for the developers to re-use or track these ERs and FPs [26], which lead to the duplication of time and effort spent on finding those ERs again by tracking them down or recreating new ones. Moreover, Gui et al. [28] stated that MVD is designed for one-time data delivery and its valuable for the developers, but it is challenging to be understood by non-experts and end-users. Producing an MVD entails knowledge from the developers regarding the intricate structure of the IFC schema that can be hard to understand by non-experts [29]. Hence, defining a “single truth of information” shared throughout the building lifecycle can help reduce duplication of developing efforts and inconsistency.

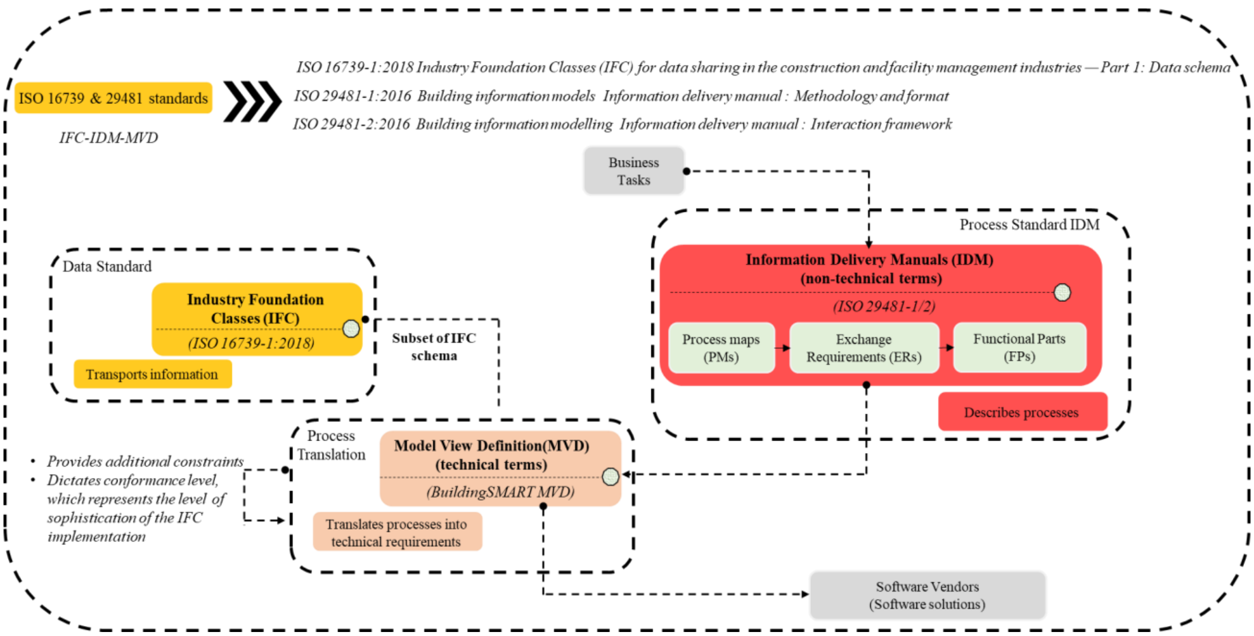

Fig. 1: The relationship between IFC, IDM and MVD concepts

2.2. Developing tools and platforms for data exchange

Several research articles have focused on emerging tools and platforms. Bearing in mind that the first group (Section 2.1) can play a significant part in the development process of these tools by providing them with clearly defined input data. Deng and Chang [30] developed a method to create a structural model from an architectural model based on the IFC schema. They pointed out that the differences in model representation and input format are the main reasons behind the lack of integration between design disciplines [30]; thus, adopting a common format by software developers can be an excellent solution for interoperability issues. On a similar subject, Qin, Deng and Liu [31] used IFC and extensible mark-up language (XML) technology, which is used to store and maintain data in a text file format, to build a framework to manage the information between architectural and structural disciplines. XML technology has an excellent structure to store and maintain information. They identify that the lack of a unified data exchange method limits the data exchange among diverse disciplines and results in integration issues [31]. They stated that the process of automating the data exchange between IFC models comprises of two aspects: the IFC parser, which is utilised to read the IFC physical file, and the IFC model schema that is used to create the equivalent objects defined in the IFC file in a machine comprehensible format.

Chen et al. [32] formed an IFC-based data web server for collaborative design between the architectural and structural domains. They stated that to augment the building design process, the IFC demands to be reinforced by additional tools or platforms. Moreover, a tool was developed by Liu, Li and Zhang [33] to improve the data transfer from IFC-format architectural model to the PKPM structural analysis tool, which is one of the leading structure design software tools in China [33]. [33] were able to enhance the collaboration between the architectural and structural domains. However, the tool was a one-way conversion tool and did not reflect the information exchange of loads and support conditions. Furthermore, Wang, Yang and Zhang [34] developed an IFC-based software tool for structural model conversion, which helped extract the required information by the structural domain to form the required structural model.

Hu et al. [35] proposed a unified data model approach and developed a web-based platform based on IFC and several algorithms to solve interoperability issues between architectural, structural and structural analysis models. They stated that there is a lack of techniques based on utilising a common data model, where all the data is standardised, which can play a substantial part in providing an improved data exchange. On a similar focus, Ramaji and Memari [14,36][36] developed an approach to transform the architectural model into a structural analytical model using the architectural coordination view as a starting point for this conversion. According to Ramaji and Memari [36], information exchange can be divided into direct data exchange, which does not require semantic modifications, and interpreted data exchange that requires semantic enhancement.

There have been few studies that explore providing information to other downstream processes, and the focus of these researches was on the extraction of partial models from the IFC model. Won et al. [29] proposed an algorithm to extract a partial model from an IFC-based model without using the data structure in the IFC schema, where they used a pre-specified set of building elements (IDM) as an input. They mentioned that an extraction algorithm is semantically successful if it can preserve the same semantic relationships before extraction without any data loss. Furthermore, Zhang et al. [37] used web ontology language (OWL) to develop an algorithm to extract a partial BIM model. They mentioned that processing the IFC file against the IFC ontology is the most crucial step in the developed algorithm. On a similar topic, Nepal et al. [38] used ontology-based feature modelling to extract construction-specific data from a BIM model.

Gui et al. [28] developed a method to extract domain-specific information to remove unrelated IFC information. MVD was used to provide the algorithm with the required data. They stated that although several collaboration platforms have been developed with a central BIM database, the model becomes hard to manage as the model size increases and results in inefficiency in data sharing. Moreover, Lai, Zhou and Deng [27] developed an algorithm to transfer structural design data for collaborative design, where they also proposed an ER Matrix based on XML. It is seen that although authors mentioned the applicability of such methods for other domains, most of the researches emphasis on architectural and structural models, which supports the statement made by Lai and Deng [19].

Furthermore, BIM realisation can be achieved either by a single data model or a series of closely linked federated models [39]. However, Preidel et al. (2018) indicated that direct utilisation of a single shared model is not recommended since it results in a complicated large model that can be hard to handle. On a similar subject, a collaboration between project stakeholders can be categorised into two main components: file-based collaboration or model-based collaboration. The file-based exchange of BIM information caused several construction industry issues, such as data transfer inefficiency, lack of interoperability, and data inconsistency [40]. Whereas Munkley, Kassem and Dawood (2014) indicated that using BIM servers and cloud computing are the main approaches utilised to facilitate model-based collaboration.

Several developments related to BIM servers have been developed to enhance collaboration in the AEC industry. Beach et al. (2018) indicated that these servers could be classified into two groups. First, centralised data repositories include Graphisoft BIM Server, Graphisoft BIM Cloud, Autodesk BIM 360, BIM 360 Glue, Forge, Onuma system, and 3DRepo. Secondly, distributed data repositories (decentralised), where data is stored across multiple servers, such as Autodesk Revit server and Bentley ProjectWise. Although certain developed tools such as Autodesk Revit Server and Graphisoft BIM Server deliver numerous essential features to enhance collaboration, they were developed initially to work with tools produced by vendor-specific such as Autodesk and Graphisoft [11]. Hence, they cannot work efficiently with tools from other vendors. Besides, they do not offer functionality for acquiring non-building related information [40]. Das, Cheng and Kumar (2015) stated that BIM files generated using a vendor-specific tool could only be divided into sub models if an organisation developed an API. Consequently, open BIM efforts such as IFC has been introduced to overcome such challenges, given that some of the mentioned tools implemented IFC in their tools. However, in most of them, IFC was not the essence of the tool. Moreover, other platforms also showed advantages, such as the BIM server, an open-source web-based platform. However, Das, Cheng and Kumar (2015) mentioned that this platform does not facilitate dynamic splitting and merging of BIM models.

Following the literature analysis conducted in this paper, several issues have been identified and require further considerations: First, the data exchange faces issues related to data mapping, which requires an informed understanding of various disciplines and domains, especially that IFC schema is giving room to map the same information in different ways. Hence, a clearly defined "single truth of information" is required. Secondly, most investigations have been concentrating on individual areas such as the architectural design and the structural analysis domains, and the majority of the proposed tools were computer-based. The data shared between the architectural design and the structural analysis domains are the most critical in a project [31]. However, to have a high-performance building within the budget of a project requires the engagement of multi-disciplines such as cost analysis, energy performance and others. Consequently, in order to get a comprehensive understanding of how different models can work together and what information is shared among them, a CDA was designed that focuses not only on the architectural and structural models but also goes further to cover the information required for cost estimation. Thirdly, IFC was not designed to deduce new information from a BIM model. There is still a lack of multi-dimensional knowledgebase for holistic decision-making within a BIM workflow that considers the non-geometrical information. Most of the researches were mainly focused on data exchange without providing a holistic decision-making system. Consequently, using technologies such as the semantic web can help support BIM models with a holistic decision-making system that can further enhance interoperability.

3. Methodology

In this section, the overall research methodology through this research will be described. The methodology consists of problem examination, requirement definition and discussion.

3.1. Problem examination

The problem and challenges were reviewed in the introduction and background section, which informed that the AEC industry still lacks guidelines and methods that show what information is necessary for a specific task [26] and what are the common information shared among different design models. Therefore, a better understanding of how different models can work together by identifying a "single truth of information" that can be shared among different domains and throughout the lifecycle could be valuable to deliver the foundation for a holistic decision-making system from a data processing perspective. However, a clearly defined "single truth of information" is still not acknowledged. Moreover, IFC was not designed to deduce new information from a BIM model. Consequently, using technologies such as the semantic web can help support BIM models with a holistic decision-making system that considers various perspectives to produce a joint decision.

3.2. Requirement definition

A CDA was designed to understand for each profession what sort of data is required and what information needs to be exchanged to define a "single truth of information" and "partial truth of information" data sets. This CDA will form the foundation for a theoretical holistic decision-making framework. The research data were collected in two stages, **Fig. 2**, as follows:

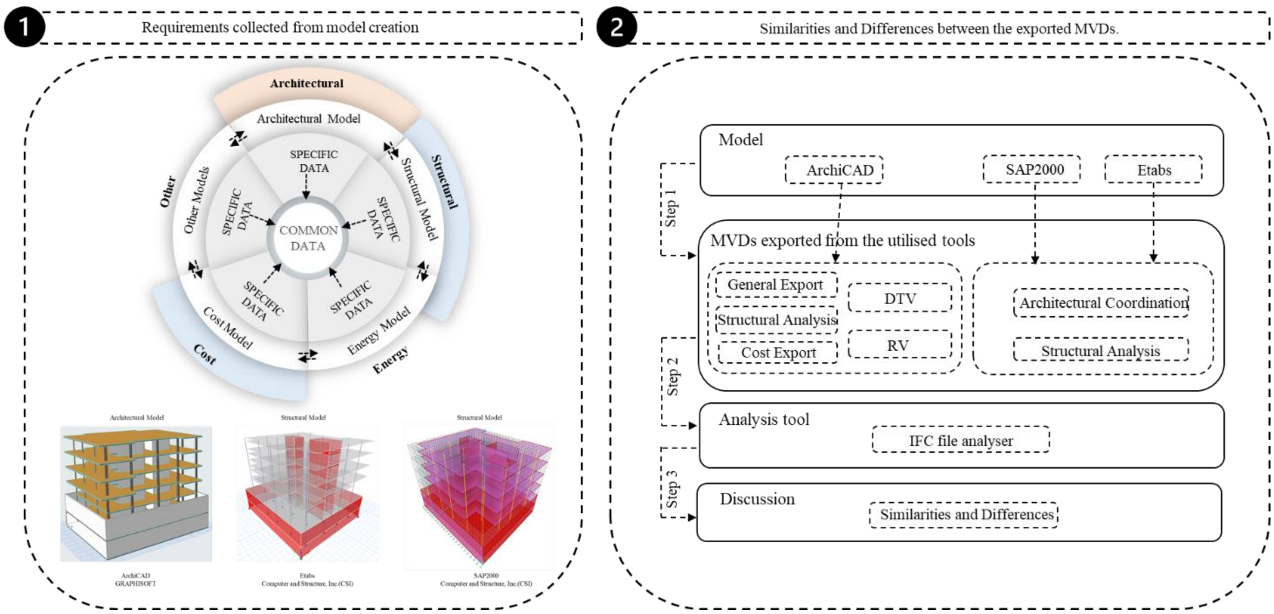

Fig. 2: Common data analysis (CDA)

(1) Requirements collected from models. The IDM-MVD method provides the essential structure for information delivery and exchange requirement. Hence, to analyse the information required, the IDM concept was considered in this investigation, and an overall process map reproduced from RIBA was produced to provide the flow and sequence of tasks (**Section 4**). Moreover, three BIM models were chosen and investigated in this study based on experts' Points of View to understand what sort of information is required when these models were created and what information is required for exchanging by different end-users. The architectural model is considered the source model, whereas the structural and cost models represent the delivered models to the end-users. To support the findings of this step, previous work in this area was used to validate and approve those results.

(2) Similarities and Differences between the exported MVDs. Several MVDs have been officially released, such as IFC2x3 Coordination View 2.0 (CV), IFC2x3 Structural Analysis View (SA), IFC4 ADD2 Design Transfer View (DTV 1.1) and IFC4 ADD2 Reference View (RV). These MVDs are generated independently and not interconnected. Consequently, by using the models created in step one, several MVDs were exported using the functionalities embedded within the selected software tools. Each of the exported IFC files was imported into IFC File Analyser for analysis, which is a tool developed by the National Institute of Standards and Technology (NIST) to generate spreadsheet files from an IFC file [42], to understand the IFC schema structure by identifying what IFC entities, relations and properties are used in the exported MVDs. Hence, this step can support in defining "single truth of information". This step will be further discussed later in this article (**Section 5**).

3.3. Discussion

Lee [12] defined semantic intersection as “a set of information items in different data sets that are functionally dependent”. This definition also aligns with the concept of “dependency modelling”, which states that to advance to the next design stage, one model will mainly rely on data shared with another model or several models since these models are interconnected and share some commonalities. Therefore, to better understand how different models can work together, the authors adopted Lee [12] approach (**Section 6**). The findings from the above two stages and the discussion in this paper form the foundation for developing and implementing a holistic decision making framework (**Section 7**), which intends to eliminate inefficiencies in data sharing and improve the decision making process.

4. Requirements collected from models

In the design stage, the exchange of information can significantly affect the decision-making process, which can affect the downstream stages. The design stage necessitates specific inputs to create the required outputs. Architectural design and structural design are extensive and intricate processes. Changes at these two design stages are more common and have a higher overall impact on design than those at the downstream stages. A structural design process consists of several stages, starting with the conceptualisation moving to the modelling and analysis, then followed by designing, detailing, drafting and cost estimation [43], **Fig. 3**. The conceptual stage involves the development of the primary structural model, such as selecting the structural system, building elements, material, and the location of the building elements. The information needed at this stage is mainly based on the information stated by architecture. Once the basic structural model is created, the structural engineer enriches the model with more specific information to create a structural analysis model. The architect and the engineers start to perform numerous analyses. For instance, they study the structural behaviour of the proposed system or conduct energy analysis of the building. At this stage, geometric data is not enough since more information is required to evaluate the model, such as loads, load combinations, materials, boundary conditions, etc. After the structural analysis model passes all the checks, it is time to design, detail and draft all the elements included in the project and ensure they meet the design code specifications. However, this stage is influenced by the engineer’s personal experience.

Not forget to mention cost estimation, which plays an essential role in the decision-making process. It can help in creating the first glance on bills of quantities and bills of materials. Having an initial cost of the project earlier can help select various design alternatives, give stakeholders the chance to modify the structure, and spinoff the project towards its goals, which can help control the project’s budget and save money during the construction stage. However, the cost estimation process is not done only at the start of the project; instead, it needs to be updated and modified as the project moves further from one stage to another, **Fig. 3**. Choi, Kim, and Kim [44] categorised the cost estimation for each stage as conceptual estimation in the planning phase, schematic estimation in the schematic design phase, and detailed estimation in the design development phase.

Moreover, Xu, Liu and Tang [45] classified the data required for cost estimation into five components: product data, cost item data, quantity data, resource data, and price data. Consequently, fully automating the cost estimation process is difficult because of the dynamic resources needed and human intervention [45]. On a similar topic, [46,47] divided a building cost estimate process into three main steps: Firstly, classifying a building into its functional elements such as footings, columns, beams, walls, slabs, and other elements. Secondly, measuring the total quantity of each functional element. Finally, calculate the total cost by multiplying the total quantity of each functional element with the unit cost of each functional element [47].

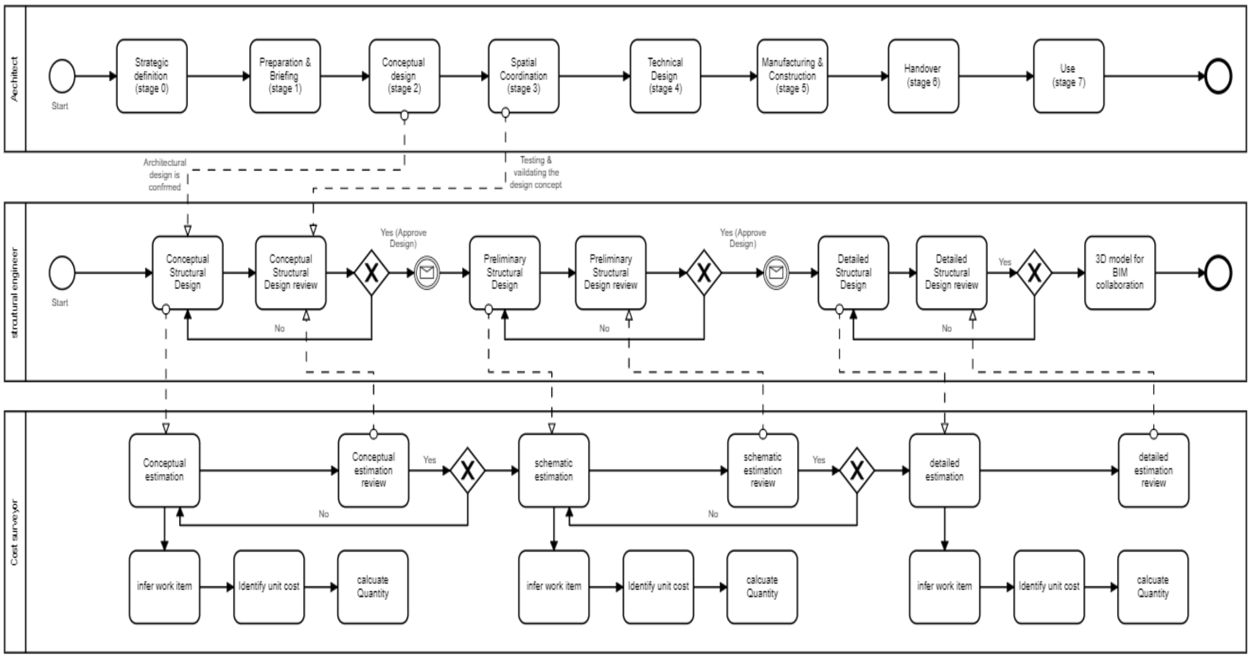

Fig. 3: Overall process map reproduced from RIBA

Despite these models having different roles, all those models have related tasks and require data to be exchanged seamlessly across them. Therefore, as Steel, Drogemuller and Toth [10] stated, models need to be exchangeably interoperable on a semantic level to move further with BIM developments. Several software tools are available in the AEC industry, which provides users with many features and functionality. However, not all these tools support IFC file export functionality yet. Based on the BuildingSMART software implementation database [48] and due to their popularity, the following software tools were selected for this study: ArchiCAD (version 21) to represent the architectural model, SAP2000 (version 21.1.0) and Etabs (version 18.0.2) to represent the structural model. These software tools are developed by Graphisoft and Computers & Structures, Inc, respectively. However, this paper is focused on the data requirements and not on the abilities of these software tools, knowing that each software is standalone software that is created to perform a sophisticated analysis.

In order to identify the required data, certain questions need to be answered. For instance, is the data required by the structural model, the architectural model or common among them? The same questions apply to any model that is used in other disciplines. Three models were created based on the selected software tools, as shown in **Fig. 4**. The selection of two structural software tools instead of one was to investigate not only the unified information between architectural and structural models but also between the structural software tools themselves. The models created are consist of the most common elements and related attributes in building construction, such as slab, column, and wall. Moreover, the structural models created using SAP2000 and Etabs consisted of a multi-story concrete building with uniformly distributed live and dead loads. Note that the ends of columns connected to the ground are assigned as fixed support. The data collected from all three models are shown in **Table 1** and **Table 2**. Furthermore, to support the findings in this section, previous work in this area was used to justify and endorse those results.

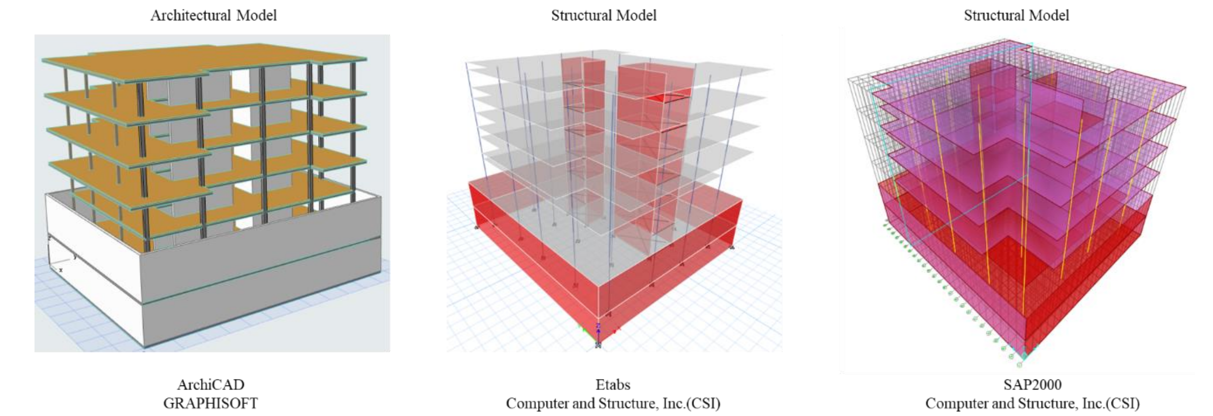

Fig. 4: Models created based on the selected software tools

Table. 1
Data required by ArchiCAD

Project details	Unit system		Measuring unit type (SI/ Metric)
	Project & engineering description		ID Contact info Description
Building Structure	Grid spacing		No of grid lines (x direction, y direction) Spacing of Grid (x direction, y direction)
	Simple story data		No of stories Typical story height Bottom story height
Visualising (Geometry)	Drawing functions		To represent members and surfaces
Column	Geometry & Positioning	Structure	Structure Type (circular, complex profile) Dimensions (width and depth) Building material (concrete/steel) Complexity (Vertical or slanted)
		Top and home story	Top offset to top linked story Bottom offset to home story Assigning to column layer
Wall	Geometry & Positioning	Structure	Structure Type (composite or complex profile) Building material (concrete/Steel)
		Geometry method	Straight /Trapezoid/ Polygonal
		Wall complexity	Straight / Slanted/ Double
		Top and home story	Top offset to top linked story Bottom offset to home story Assigning to Wall layer
		Reference line	Outside face / Inside face/ Centre
Slab	Geometry & Positioning		Building material (concrete/steel) Edge angle
	Reference plan location		Top / Bottom Slab thickness Assigning to Floor layer

Table. 2
Data required by SAP2000 and Etabs

Data	Sub-data	Attribute

Project details	Unit system				Measuring unit type (SI/ Metric)
	Project & engineering description				ID Contact information Description
Building Structure	Grid spacing				No of grid lines (x direction, y direction) Spacing of Grid (x direction, y direction)
	simple story data				No of stories Typical story height Bottom story height
Visualising (Geometry)	Drawing functions				To represent members (linear element) & surfaces (planar element)
Material	Defining properties	Material properties	General data		Material Name Material Type Directional symmetry type
			Material Weight and Mass		Weight/ unit volume Mass / unit volume
			Mechanical property data		Modulus of elasticity Compressive strength Poisson's ratio Coefficient of thermal expansion Shear modulus Yield Stress Tensile Strength
		Section properties	Frame section (linear element)	General data Shape Section dimensions	Property name material Section shape Depth & Width or Diameter
			Slab section (planar element)	General data	Property name Slab material Modelling type (Shell element/Membrane element/Plate element)
				Property data	Type of slab (Shell element/Membrane element/Plate element) Thickness of slab
			Wall section (planar element)	General data	Property name Slab material Modelling type(shell/membrane/plate)
				Property data:	Thickness of wall
Load data	Load patterns	Self-weight			Type Self-weight multiplier
		SIDL (superimposed dead load)			Type Self-weight multiplier
		LL (live load)			Type Self-weight multiplier
	Load assignment	Joint load			The load can be of type point
		Frame load			The load can be of type linear

	Shell load	The load can be of type planar (uniform load, area load)
	Load direction	Direction (Gravity or Local)
Load conditions	General data	Load combination name Combination type
	Define combinations of load cases	Load name Scale factor
Boundary conditions	Restraints	Restraints in global directions (rigid/ pin /roller)
	Springs	-
	Diaphragm	Joint Shell (rigid diaphragm)
Other data	Meshing Shell (Wall mesh/ Floor mesh)	To divide the floor into small areas

The architectural model provides the first wave of data required by the structural model that primarily includes geometrical and material information [49]. Although a structural model requires various information such as structural elements, mechanical connectivity, support conditions, mechanical properties and loadings, an architectural model can only provide structural elements, materials, and connectivity data while the other information needs to be added manually [32]. Hence, the structure model requires information that the architect might not define since it is out of the architectural design scope. Several researchers pointed out the data needed and the differences between architectural and structural design. An architect is more concerned with the spatial arrangement of building elements such as shape, layout, the location of the geometry, member section profiles and material data, while a structural engineer focuses on the mechanical properties of elements, building behaviour and stability [31,33,35,50,51]. Furthermore, Wang, Yang and Zhang [34] mentioned that although the same element might be represented in both the architectural and structural models, the detailed data of that element can be different. This difference is due to the unique use of that element in specific domain disciplines. The results identified in this section validate the previous statements since ArchiCAD is an architectural software tool built according to the architectural perspective to do a specific task.

On a similar topic, Wan, Chen and Tiong [52] evaluated the IFC2X2 schema for the structural analysis field by looking into the information required by SAP2000's structural analysis software. They stated that the data needed by SAP2000 was geometry data, section data, material data, load data, and load combinations. A structural model can be represented as a simplified analysis model, which provides uncomplicated information [49]. Whereas a sophisticated analysis model, which is based on a finite element model (FEM), is used for complex analysis [49]. Moreover, to have a perfect structural model, it is necessary to consider the way two elements are connected. For instance, a structural element in a structural model is represented as a linear element or a planar element and that two elements are connected through the centroid [32]; otherwise, it will result in instability. Whereas in the architectural model, the section is represented as a 3D shaped section, and two elements can be connected face to face, edge to edge or centre to the centre since that will not affect the design. The finite element mesh (FEM) plays a vital role in the structural analysis model accuracy [31,53]. For instance, meshing is based on dividing an element into small elements. The smaller the element size is, the more accurate results can be generated. However, this can increase the time of analysis. Exchanging mesh data is a difficult task and hard to preserve. Therefore, each structural analysis tool is designed to perform such advanced analysis, and hence this part will not be covered in this article. The research above supports the results in **Tables 1** and **2**, where data is more fixated on geometry and material in the architectural model. Whereas data related to mechanical properties (unit weight, Modulus of elasticity, Compressive strength, shear modulus), boundary conditions (fixed, pinned, and roller supports), meshes, loads (Self-weight, live load, superimposed dead load), and load combination can be categorised as specific data essential for the structural domain.

Furthermore, Yaman and Taş [47] pointed out the information required in the cost estimation area. For instance, they stated that project details, including Project number, address, description, and project owners' details, are required in addition to building structure information such as site, building, building storeys, and spaces. Not forgetting to mention the total gross construction area of the project, the quantity of the Building Elements, Building Element Types, product cost information, bearing in mind that the measurement units used in a project are important since it has relation to the unit price information selected by the stakeholders. However, despite that dataset for cost estimates are produced from the architectural model, the architectural model could provide only a few data such as space, element area, floor height, building parameter and gross area [54].

5. Similarities and differences between the exported MVDs

There are three types of data exchange: Firstly, exchange using the same authoring tools. Secondly, exchange through an application programming interface (API) and thirdly, exchange using a common data schema [14,15]. Each of these workflows is briefly discussed in this section. The first type assisted in overcoming interoperability issues. However, the solutions that were provided are only for vendors' applications that belong to the same companies, for instance, Autodesk software tools packages. Such a type of data exchange could limit data exchange if stakeholders opt to use tools from different vendors. The second type is achieved by developing an API. For instance, CSIRevit was developed to link Revit to CSI tools such as ETABS, SAP2000, and SAFE to enhance collaboration between architectural designers and structural engineers [15]. This type of development might require access to the internal structure of software tools and excellent computing skills from the developers. The third type, which is the focus of this article, uses a unified file format such as IFC. Lai and Deng [19] stated that using IFC as data exchange is viable since it can reduce the number of solutions developed. However, they pointed out that it still facing some problems.

5.1. Comparison using IFC file analyser

According to the BuildingSMART database [55], several MVDs have been officially released. The MVDs that are discussed in this section are IFC2x3 Coordination View 2.0 (CV), IFC2x3 Structural Analysis View (SA), IFC4 Design Transfer View (DTV), IFC4 Reference View (RV), in addition to some other exported MVDs from ArchiCAD such as General Export, structural analysis, and CostX Export. Based on the models that were created previously, IFC files representing those MVDs were exported, **Fig. 2**. The first Five are exported from the ArchiCAD and were named as follows: "General Export", "Structural Analysis"," DTV",' RV' and "CostX Export" bearing in mind that ArchiCAD software tool allows the export of several custom IFC files for different design tasks and end-users. However, these functionalities are specific to this tool. "Architecture Coordination View" (CV) and "Structural Analysis View" (SA) were exported from SAP2000 and Etabs. The exported MVDs were imported into the IFC File analyser to identify IFC entities, relations, and properties in the exported Models, **Table 3**

Table. 3
Similarities and differences between some of the existing MVDs using IFC file analyser

Data classification	Entities	ArchiCAD					Etabs & SAP2000	
		General Export	Structural analysis	CostX	DTV	RV	CV	SA
Building element & type	IfcColumn	√	√	√	√	√	√	-
	IfcColumnType	√	√	√	√	√	-	-
	IfcSlab	√	√	√	√	√	√	-

		IfcSlabType	√	√	√	√	√	-	-
		IfcWall	√	√	√	√	√	√	-
		IfcWallType	√	√	√	√	√	-	-
		IfcStructuralCurveMember	-	-	-	-	-	-	√
		IfcStructuralSurfaceMember	-	-	-	-	-	-	√
		IfcBuilding	√	√	√	√	√	√	√
		IfcBuildingStorey	√	√	√	√	√	√	√
		IfcOwnerHistory	√	√	√	√	√	√	√
		IfcProject	√	√	√	√	√	√	√
Project details & Spatial structure		IfcSite	√	√	√	√	√	√	√
		IfcActorRole	-	-	-	-	-	√	√
		IfcUnitAssignment	√	√	√	√	√	√	√
		IfcSIUnit	√	√	√	√	√	√	√
		IfcRelAggregates	√	√	√	√	√	√	√
		IfcRelContainedInSpatialStructure	√	√	√	√	√	√	√
		IfcRelDefinesByProperties	√	√	√	√	√	-	-
		IfcRelDefinesByType	√	√	√	√	√	-	-
Property Sets		IfcPropertySet	√	√	√	√	√	-	-
		IfcPropertySingleValue	√	√	√	√	√	√	√
		IfcMaterialProperties	-	-	-	√	√	√	√
		IfcElementQuantity	-	-	√	-	-	-	-
		IfcQuantityArea	-	-	√	-	-	-	-
Quantities		IfcQuantityCount	-	-	√	-	-	-	-
		IfcQuantityLength	-	-	√	-	-	-	-
		IfcQuantityVolume	-	-	√	-	-	-	-
		IfcMaterial	√	√	√	√	√	√	√
		IfcRelAssociatesMaterial	√	√	√	√	√	√	√
		IfcMaterialLayerSet	√	√	-	√	-	√	-
		IfcMaterialProfileSet	-	-	-	-	-	√	√
		IfcMaterialDefinitionRepresentation	√	√	√	√	√	-	-
		IfcStyledRepresentation	√	√	√	√	√	-	-
Material		IfcStyledItem	√	√	√	√	√	-	-
		IfcColourRgb	√	√	√	√	√	-	-
		IfcSurfaceStyle	√	√	√	√	√	-	-
		IfcMaterialList	-	-	√	-	√	-	-
		IfcMaterialLayer	√	√	-	√	-	√	-
		IfcMaterialLayerSetUsage	√	√	-	√	-	√	-
		IfcMaterialProfile	-	-	-	-	-	√	√
		IfcMaterialProfileSetUsage	-	-	-	-	-	√	√
		IfcArbitraryClosedProfileDef	√	√	-	√	-	√	-
		IfcExtrudedAreaSolid	√	√	-	√	-	√	-
	Extrusion	IfcRectangleProfileDef	√	√	-	√	-	√	√
		IfcCircleProfileDef	√	√	-	√	-	√	√
		IfcAxis2Placement3D	√	√	√	√	√	√	√
Geometric Representation s		IfcDirection	√	√	√	√	√	√	√
		IfcCartesianPoint	√	√	√			√	√
		IfcFacetedBrep	-	-	√	-	-	-	-
		IfcFaceOuterBound	-	-	√	-	-	-	-
	B -Rep	IfcFaceBound	-	-	√	-	-	-	√
		IfcFace	-	-	√	-	-	-	-
		IfcClosedShell	-	-	√	-	-	-	-
		IfcPolyLoop	-	-	√	-	-	-	-

	IfcProductDefinitionShape	√	√	√	√	√	√	√
	IfcShapeRepresentation	√	√	√	√	√	√	-
	IfcLocalPlacement	√	√	√	√	√	√	√
	IfcGeometricRepresentationContext	√	√	√	√	√	√	√
	IfcRelConnectsPathElements	√	√	√			-	-
	IfcStructuralAnalysisModel	-	-	-	-	-	-	√
	IfcRelAssignsToGroup	-	-	-	-	-	-	√
	IfcRelConnectsStructuralActivity	-	-	-	-	-	-	√
	IfcStructuralPlanarAction	-	-	-	-	-	-	√
	IfcBoundaryNodeCondition	-	-	-	-	-	-	√
	IfcRelConnectsStructuralMember	-	-	-	-	-	-	√
Structural Information	IfcStructuralPointConnection	-	-	-	-	-	-	√
	IfcStructuralLoadPlanarForce	-	-	-	-	-	-	√
	IfcStructuralLoadCase	-	-	-	-	-	-	√
	IfcStructuralLoadGroup	-	-	-	-	-	-	√
	IfcRelAssignsToGroupByFactor	-	-	-			-	√
	IfcRelServicesBuildings	-	-	-	-	-	-	√
	IfcTopologyRepresentation	-	-	-			-	√

Architectural coordination view (CV) is comprehensively utilised in most BIM software tools [35] and defines the elements of a building as volumetric objects [14]. However, although only a few entities can be imported using this View since not all data are valid to ETABS and SAP2000 tools [56], the Coordination View could be utilised to create a basic structural model [14,36]. On the other hand, the structural analysis view (SA), which defines a building in terms of nodes, elements, and loads [56], is used to transfer the structural analysis model to other structural analysis tools [35]. However, it is not supported by many software tools [56], and it only covers the data required by the structural domain (design and analysis) [35]. It can exchange data related to boundary conditions, loads, load combinations, connections, and other structural data, **Table 3**. Furthermore, based on the IFC4 schema, BuildingSMART developed Design Transfer View (DTV) and IFC4 Reference View (RV). The Design transfer view was developed to share parametric elements for further editing and coordination. Whereas, Reference view, which is a subset of the Design transfer view [14], is used to share geometry representation for model referencing and clash detection, knowing that the model can be imported as a read-only model. Geometrical data can be necessary for coordination and clash detections. However, the analysis models necessitate additional information to establish a full model; therefore, this MVD will not provide a complete analysis model. Ramaji and Memari [14] considered that the design transfer view could be assumed to replace the coordination view.

Furthermore, “CostX Export” is used for cost estimation purposes. Sherif, Jinkook and Chuck [54] stated that “ although more cost estimating applications are moving toward IFC compatibility, IFC does not solely cover all components required to generate an estimate, as estimating requires not only quantity take off data, but other types of associated databases. These carry labour, material and equipment unit costs, location parameters, market conditions, and other factors that require continuous adjustment and updating”. However, Jadid and Idrees [57] stated that using the IFC schema in the cost estimating process can provide the stakeholder with product data that form a necessary aspect to calculate the cost of a project. Further details about the insides of those MVDs are as follows:

- **Building element & type**. Object type was shown in all the exported files from the ArchiCAD, while that was not the case with the IFC files exported from Etabs and SAP2000. The building members were represented as IfcColumn, IfcSlab and IfcWall in all MVDs except for the structural analysis view exported from Etabs and SAP2000. The building members were represented as IfcStructuralCurveMember for linear elements such as Column and IfcStructuralSurfaceMember for surface elements such as Wall and Slab, **Fig. 5**. For cases where the IFC does not provide a particular modelling construct, the language contains a mechanism for modelling IfcProxy Elements [10].

However, this was not shown in any model. It is more likely to happen when an MVD is imported into another software and re-exported again, which might be because some entities cannot be recognised by the receiving tool. Hence the tool will convert them to the IfcBuildingElementProxy entity.

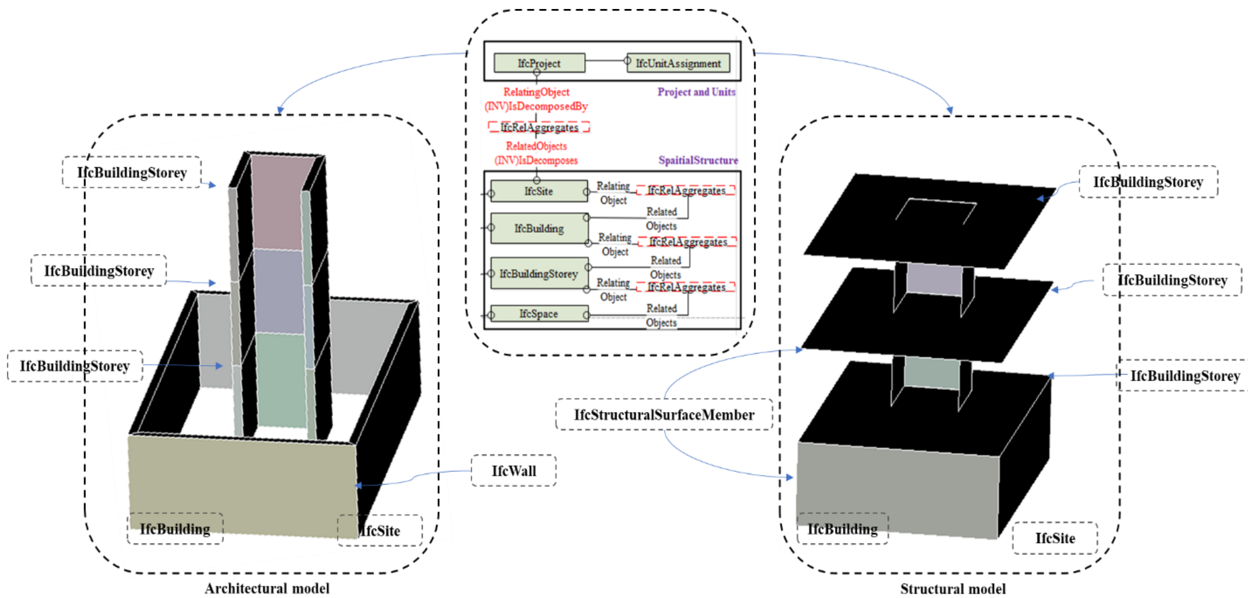

Fig. 5: Architectural model versus Structural model in IFC format

- **Project details and Spatial structure** The IfcProject entity is used to contain project data and the units used in the project, which is represented by IfcUnitAssignment that specifies a set of units [58]. Data related to project ownership is represented in the IFC schema by the IfcOwnerHistory entity and obtained through the IfcProject entity [58]. IfcActorRole, which assigns a role that an actor performs in a project [58], was only used in the exported files from Etabs and SAP2000. Furthermore, the spatial structure is used to deliver the project structure to form a building. Entities contained by the spatial structure are IfcSite, IfcBuilding, IfcBuildingStorey and IfcSpace [58]. These entities are included under the IfcSpatialStructureElement relation entity in the IFC schema [58]. The IfcRelAggregates relation entity, **Figure 5**, a special type of IfcRelDecomposes, shows the relation among IfcProject, IfcSite, IfcBuilding, IfcBuildingStorey and IfcSpace [58]. Furthermore, the IfcRelContainedInSpatialStructure relation relates elements to spatial structure [58]. For instance, it is used to relate IfcElement, such as IfcColumn, to IfcBuildingStorey. It was noticed that all these entities were shown in all the exported MVDs.
- **Properties.** IfcPropertySet is used to hold properties within a property tree (BuildingSMART website). Building elements are linked to their properties following two paths: direct link using IfcRelDefinesByProperties and indirect link using IfcRelDefinesByType [58,59]. These two entities are relation entities that relate an element to a property set (IfcPropertySet) and elements to an element type (IfcTypeObject) that has a property set (IfcPropertySet) [58], respectively. For instance, by using the IfcRelDefinesByProperties relationship entity, the IfcWall entity can be related to an instance of IfcPropertySet. Whereas IfcRelDefinesByType allows for the assignment of one type of information, for instance, (IfcWallType) to a single or many elements (IfcWall) [58]. It was shown that these relation entities were not shown in the file exported from Etabs and SAP2000. Instead, IfcPropertySingleValue, a sub-entity of IfcPropertySet, defines a property object with a single numeric or descriptive value (BuildingSMART website) exported directly. Furthermore, IfcMaterialProperties is used to assigns a set of material properties to associated material definitions.

- **Quantities**. IfcElementQuantity defines a "set of derived measures of an element's physical property" [58]. To relate this entity to the elements, IfcRelDefinesByProperties is used. IfcElementQuantity is used to obtain properties such as length (IfcQuantityLength), area (IfcQuantityArea), volume (IfcQuantityVolume), and others. Since these properties are related to cost estimation, they were only shown in the CostX export.
- **Material.** IfcMaterial is the basic entity for material designation and definition [58]. Similar to IfcRelDefinesByType relation entity, IfcRelAssociatesMaterial relation is used to relate an instance of IfcMaterial to an element or element type [58]. A single material can be assigned directly or represented by other set entities such as IfcMaterialLayerSet, IfcMaterialProfileSet [58]. IfcMaterialLayerSet was shown in General Export, Structural Analysis, and DTV exported from the ArchiCAD and in CV exported from Etabs and SAP2000. Whereas IfcMaterialProfileSet was only shown in the files exported from Etabs and SAP2000. IfcMaterialDefinitionRepresentation is used to provide presentation information associated with IfcMaterial [58]. It can apply different presentation styles for different representation contexts. However, this entity was not shown in the files exported from Etabs and SAP2000. Material colour is specified in IfcStyledItem. Nevertheless, this entity and its related entities were not shown in the Etabs and SAP2000. In contrast, they were shown in all other models. Furthermore, the IfcMaterialList, which is a list of the different materials that are used in an element [58], was shown only in CostX and RV.
- **Geometric Representations.** The variety of geometric representations of structural elements in different tools might be a reason behind data exchange issues [28], and it can be more related to the software internal mapping schema. The IFC entities used for the geometry representation are of three types: Extrusion (Swept Solid) [32], Boundary representation (B-rep) [32], which is widely used in computer graphics [35], and Constructive solid geometry (CSG). The IfcExtrudedAreaSolid entity inherits entities such as Swept Area (IfcArbitraryClosedProfileDef, IfcRectangleProfileDef, IfcCircleProfileDef), position (IfcAxis2Placement3D), Extruded Direction (IfcDirection) and Depth (IfcPositiveLengthMeasure). Extrusion type was used in all exported files except CostX, RV and SA. However, in the SA, IfcRectangleProfileDef and IfcCircleProfileDef were shown. These two entities are a subtype of IfcProfileDef, which is used to define section profile. Instead of IfcExtrudedAreaSolid entity, IfcFacetedBrep with IfcClosedShell and IfcFace entities were used in the cost model. The IfcFacetedBrep is used to represent planar surfaces only. Boundary representation is used in clash detection and volume calculation cases, which justify using this type in the cost MVD. It is also shown that extrusion type is used in Coordination View. Furthermore, an Element has two geometric representation attributes. Object placement is denoted by IfcObjectPlacement, and object representation is denoted by IfcProductRepresenation [32]. The Position and dimensions of an element are determined with the IfcObjectPlacement, which is provided for an object with a shape representation (IfcProductDefinitionShape) [32]. A subtype entity inherits all the attributes from its supertype. For instance, IfcProductDefinitionShape is a subtype of IfcProductRepresenation. Hence, all the Information in IfcProductRepresenation will be assigned to IfcProductDefinitionShape automatically. Furthermore, the object placement can have different types, such as an absolute, relative, or constrained.
- **Structural Information.** IfcStructuralAnalysisModel is used to assemble all information needed to represent a structural analysis model [58]. Thus, it was shown only in the SA MVD exported from the structural analysis software and was not shown in the Structural analysis MVD exported from ArchiCAD. It comprises a structural element, structural connection, structural activities, and others. The relationship entity IfcRelAssignsToGroup is used to relate the structural analysis model to the structural member's entity (IfcStructuralMember). IfcStructuralMember is a supertype entity for IfcStructuralCurveMember (Linear elements) and IfcStructuralSurfaceMember (planar elements) [34]. The structural information comprises structural loads, boundary conditions, load cases (IfcStructuralLoadCase) and load combinations (IfcStructuralLoadGroup). For instance, the load is represented by an "IfcStructuralLoadPlanarForce" entity as part of an "IfcStructuralPlanarAction" instance. IfcStructuralPlanarAction entity is used to represent the load, and

IfcRelConnectsStructuralActivity relationship entity is used to relate structural elements such as IfcStructuralSurfaceMember to an activity [34]. Structural connection is represented by IfcStructuralConnection, divided into a point (IfcStructuralPointConnection), line and face connections[34]. The restraints of joints or release of frame elements are obtained from IfcBoundaryNodeCondition. As shown in **Table 3**, these entities are used only in the SA view exported from the Etabs and Sap2000. Whereas the structural analysis view exported from ArchiCAD did not show these entities. Hence these data are specific data required in the structural domain and can be only provided by structural analysis tools. In summary, information associated with structural behaviour of elements, connectivity, boundary conditions, mechanical properties of the material, and others is not included in the coordination view, DTV, and RV. These MVDs can only deliver the physical part of a model.

5.2. Comparison based on similarity rate between MVDs

In this section, the similarity rate equation below, adopted from Lee et al. [60], was utilised to compare the exported MVDs to see how much information is maintained and shared between them. According to Lee *et al.* [60], the similarity rate from File A to File B is defined as "the number of matching instances in File A divided by the total number of instances in File A". For instance, the number of matching entities in "General Export" MVD and DTV is divided by the total number of entities in the "General Export" MVD. The comparison in this section is an extension of **Section 5.1**. Hence, only the main entities shown in **Table 3** are used to calculate the similarity ratio.

$$Similarity\ rate\ (\%) = \frac{\text{Number of matching instances in File A}}{\text{Total number of instances in File A}} \times 100\%$$

In **Table 4,** one to one comparison, only two cases had a similarity rate of 100 per cent, which was recorded between "General Export" MVD and "Structural Analysis" MVD. However, those two MVDs are used for different purposes but belong to the same vendor. On the other hand, the "SA Etabs & SAP2000" has an almost 50% similarity rate compared to the "General Export" MVD, the "structural analysis" MVD, the "CostX ArchiCAD" MVD and the "DTV ArchiCAD" MVD except for the similarity rate from "SA Etabs & SAP2000" to "CV Etabs & SAP2000" was more than 60%. Moreover, if we compare the "General Export" to the "CV Etabs & SAP2000", the similarity rate between them is high, but not 100 per cent, which in essence need to be 100 per cent matching since they are representing the same MVD that is used for the same purpose. Furthermore, "RV ArchiCAD" has shown high similarity rate (above 90%) to several MVDs such as "General Export" (94.12 %)," DTV ArchiCAD" (97.1 %),"Structural Analysis" (94 %), and "CostX ArchiCAD" (97 %). However, this was not the same results recorded with other MVDs such as "SA Etabs & SAP2000" (52.94%) and "CV Etabs & SAP2000" (64.7%).

On the other hand, one to many comparisons was made by comparing one MVDs among the other selected MVDs to give an overall evaluation, **Figure 6**. The MVDs with the highest similarity rate to other MVDs were "RV ArchiCAD" (58.82%) and "CV Etabs & SAP2000" (58.82%), followed by "DTV ArchiCAD" with a percentage of 50%. The above result supports the statement made by Ramaji and Memari [14], where the RV can be a subset of the DTV and other MVDs. Hence, the similarity rate of "RV ArchiCAD" to "DTV ArchiCAD" was high. Furthermore, "CV Etabs & SAP2000" also showed a high similarity rate. Although the implementation of the "CV Etabs & SAP2000" is specific for Etabs and SAP2000", it showed a high similarity rate similar to "RV ArchiCAD". This result shows that there is still a lack of homogeneity when creating those MVD since they are not clearly outlined. Although different MVDs are generated for different tools, they all build in a similar way, which state that various MVDs share some commonalities that are not exclusive to specific MVDs. Moreover, some of these MVDs are built and restricted to a specific domain, which justifies why in some cases, such as the case of “CostX ArchiCAD” to “SA Etabs & SAP2000”, showed the lowest percentage (41.3%).

Table. 4
One to one comparison based on similarity rate equation

	General Export ArchiCAD	Structural Analysis ArchiCAD	CostX ArchiCAD	DTV ArchiCAD	RV ArchiCAD	CV Etabs & SAP2000	SA Etabs & SAP2000
General Export ArchiCAD	-	100	73.91	97.5	94.12	88.23	48.78
Structural. Analysis ArchiCAD	100	-	74	97.5	94	82.92	48.78
CostX ArchiCAD	82.93	83	-	80	97	61.76	46.34
DTV ArchiCAD	95.12	95.12	69.56	-	97.1	82.35	48.8
RV ArchiCAD	78	78	71.73	82.5	-	64.7	43.9
CV Etabs & SAP2000	73.17	70.73	45.65	70	64.7	-	60.97
SA Etabs & SAP2000	48.78	48.78	41.3	50	52.94	73.5	-

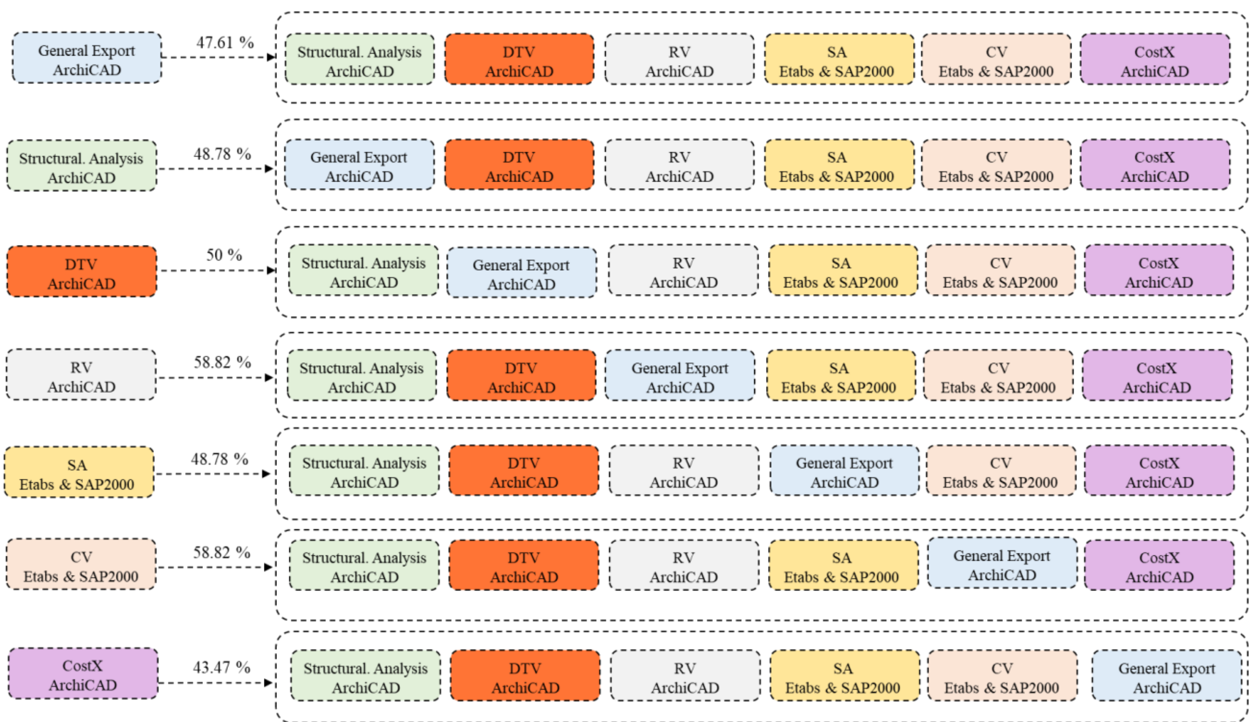

Figure 6: One to many comparisons based on similarity rate equation

6. Discussion

In this paper, the example considered to elaborate on the intersections between data sets was based on the data collected in stage 1 (Section 4), the exported MVDs in stage 2 (Section 5) and the concepts adopted from Lee [12]. The architectural model is considered as the source model, whereas the structural and cost models represent the models delivered to the end-users.

- **One to One data exchange.** This type of data sharing represents the commonality shared between two models, associated with two distinct disciplines, and it is denoted by **CsharedDS $_{1-1}$** (commonly shared data set), **Fig. 7**.

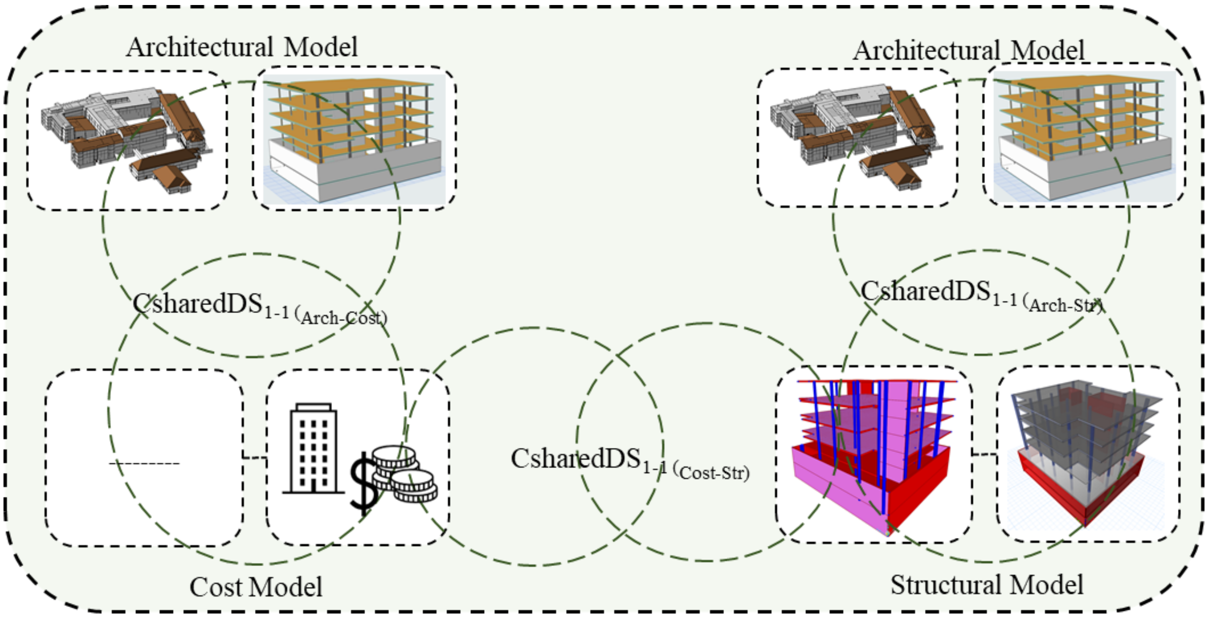

Fig. 7: One to one data exchange between two different disciplines

Architectural data set (ADS) = { project details, unit system, building, building storey, building site, building space, connectivity data, building elements, building element types, geometry data, member section profiles, material data, layout}

Structural data set (SDS) = {project details, unit system, building, building storey, building site, building space, structural elements, Structural Element types mechanical connectivity/ boundary conditions (fixed, pinned, and roller supports), loads (Self-weight, live load, superimposed dead load), load combination, meshes, mechanical properties (unit weight, Modulus of elasticity, Compressive strength, shear modulus), Section properties, layout }

Cost data set (CDS) = {project details, unit system, building, building storey, building site, building space, gross area, element area, building elements, building element types, geometry data, product cost information, the quantity of the building elements}

Regular intersection (∩) was defined as a " set of information items in different data sets that share the same item" [12]. Taking the **CsharedDS $_{1-1}$** between the models selected in this article as an example, some of the data shared among those disciplines can be represented as follows:

CsharedDS $_{1-1}$ $_{(Arch-Str)}$ = ADS ∩ SDS = { project details, Unit system, Building, building storey, Site, space, structural elements, geometry data }

CsharedDS $_{1-1}$ $_{(Arch-Cost)}$ = ADS ∩ CDS = { project details, unit system, building, building storey, Site, space, building elements, geometry data }

$$\textbf{CsharedDS}_{\textbf{1-1}\ (\text{Str-Cost})} = \text{SDS} \cap \text{CDS} = \{\ \text{Project details, Unit system, Building, building storey, Site, space, structural elements, geometry data}\ \}$$

The same information can be represented in the IFC format as follows:

ADS ∩ SDS = { IfcProject, IfcUnitAssignment, IfcBuilding, IfcBuildingStorey, IfcSite, IfcSpace}

ADS ∩ CDS = { IfcProject, IfcUnitAssignment, IfcBuilding, IfcBuildingStorey, IfcSite, IfcSpace}

SDS ∩ CDS = { IfcProject, IfcUnitAssignment, IfcBuilding, IfcBuildingStorey, IfcSite, IfcSpace}

As Lee [12] mentioned, “two different systems do not always use the same terms to mean the same thing or have the same internal data structure.” [12]. Therefore, if two information items have two different definitions but are used for the same intention, they are also exchangeable, and this is called semantic intersection ∩* or exchangeable synonym data. For instance, taking the connectivity data as an example, connectivity is represented as “connectivity data” in the architectural data set whereas, “mechanical connectivity” represents connectivity in a structural data set. This semantic intersection can be represented as :

ASD ∩* SDS = { <connectivity data : mechanical connectivity> }

However, there is always a set of information that cannot be exchanged, which can be direction sensitive or not defined since it is out of the sender design scope. In the case of cost estimation, for instance, the gross area is important. Hence, this information can be obtained by calculating the appropriate area from the available dimensions for the appropriate section. However, it can be challenging to reverse this process. Hence, it is a one-way data exchange. Such data exchange is called “the driving and driven entities” [12].

Moreover, in some cases, some entities can hold the same definitions or names. However, these entities are not used for the same purpose. Consequently, they cannot be exchanged and need to be excluded. Furthermore, building elements are required by all three data sets. However, to be more accurate, building elements can be divided into structural and non-structural elements. The structural elements are the load-bearing elements required for structural design, whereas the structural and non-structural elements need to be considered in a cost model to calculate the total cost of each item and the entire project. Hence the structural elements required by the structural model is a subset of the building elements sent by the architectural model.

- **Many to many data exchanges.** This data set consists of a common data set shared within three or more disciplines, denoted by $\textbf{CsharedDS}_{\text{Many- Many}}$. For instance, the architectural model will be linked to the structural and cost estimation models (**Fig. 8**).

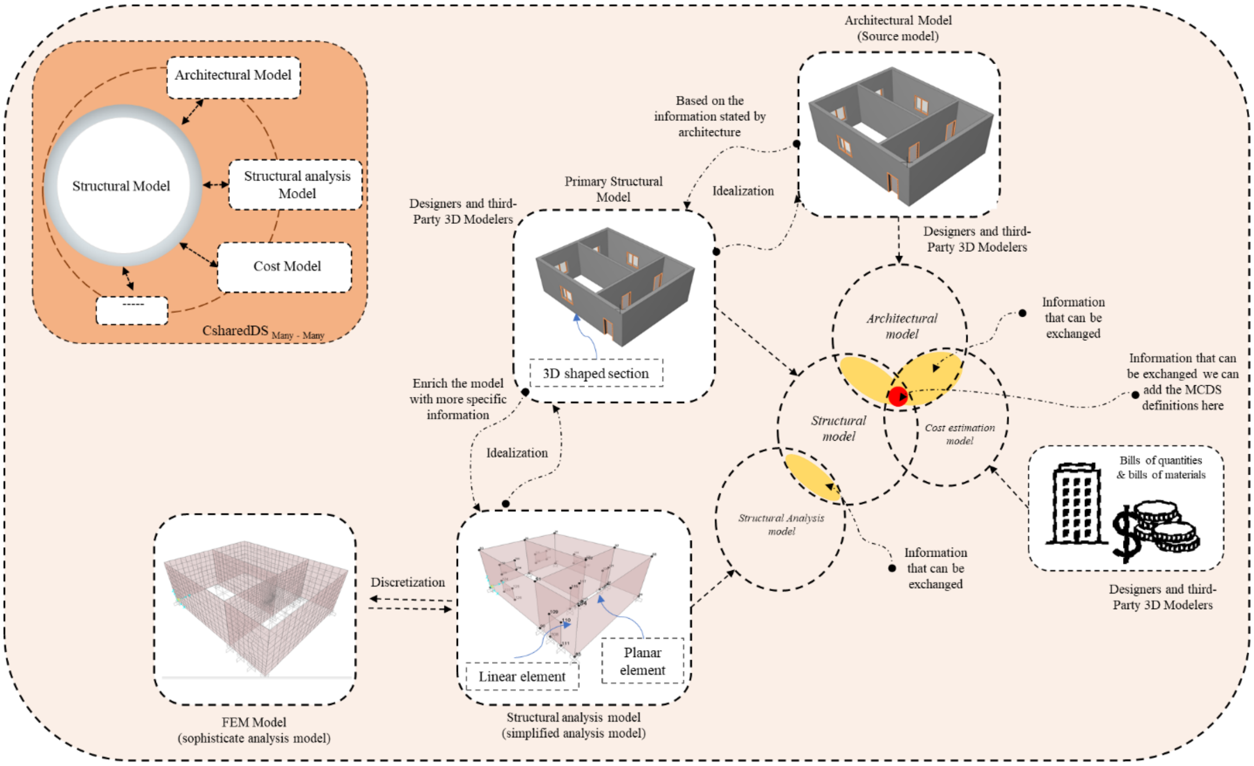

Fig. 8: Correlation between architectural, structural, and cost models

Some of the data shared among those disciplines can be represented as follows:

CsharedDS $_{\text{Many- Many (Arch-Str-Cost)}}$ = ASD ⋂* SDS⋂* CDS = { project details, Unit system, building, building storey, Site, space, geometry data }

This data set comprises the minimum common data set (MCDS), or what is called "single truth of the information", **Fig. 9**. This data set will be shared throughout the entire building lifecycle, where models can be transformed automatically at the minimum commonality level. However, some of the information can be domain-specific. Therefore, on top of this MCDS, there will be several common specific data sets (CSDS) or what is represented as "partial truth of information", which represent the common specific data for a specific domain. For instance, taking the structural domain as an example, this data set represents the common data shared among all structural software tools (**Fig. 9**). Lee [18] defined it as the smallest nonempty complete subset of a schema that corresponds to a given concept. However, in some cases, some tools will require more specific data, which is limited to precise tools. An example for such data can be represented as shown below and is donated by "¬" symbol, which means this information will be presented in the structural data set, but will not be included in the architectural data set or cost data set:

¬ ADS = { Loads , Load combination, Boundary conditions }

¬ CDS = { Loads , Load combination, Boundary conditions }

An example of this data set representation in IFC format is as follows:

¬ Architectural data set = { IfcStructuralLoadPlanarForce , IfcStructuralLoadGroup, IfcBoundaryNodeCondition }

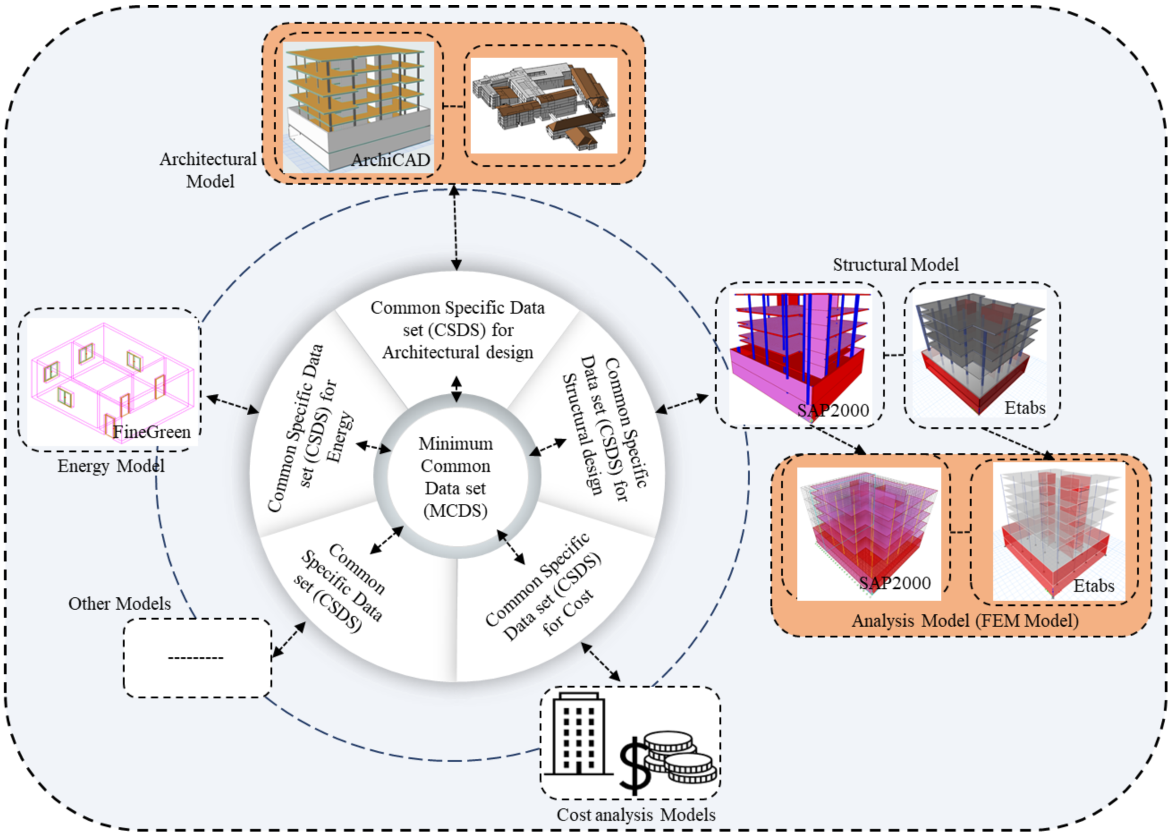

Fig. 9: Many to many data exchange

7. A theoretical holistic decision-making framework from a data processing perspective

Many BIM models are created in a given project by various stakeholders. Each of these models represents an individual subset of the entire building, and it is called a domain-specific partial model [22]. Despite the different use of these sub-models, they share some commonalities that are not exclusive to a specific domain. However, although several attempts have been made to develop data exchange requirements for BIM models, there is still a lack of homogeneity since no method for classifying and sharing those requirements are clearly outlined [61]. A clearly defined "single truth of information" is still not acknowledged yet. Moreover, the decision-making process plays a significant role in project development. The design stage requires decisions concerning conceptualisation, modelling, analysis, designing, detailing and cost estimation. These decisions are made to help designers and stakeholders develop an ideal design with less effort and time, especially since some decisions rely mainly on other disciplines. However, the lack of knowledge from stakeholders about other domains can slow down the decision-making process. Different professions need to come together to come up with comprehensive decision making. While significant steps have been made focusing on developing a mathematical model, a complicated mathematical equation produced by putting several factors together to describe holistic decision making, there is still a significant gap when looking at leveraging several models to work together holistically through automatic application model transformation and supported by data exchanging knowledgebase.

Therefore, based on the analysis and discussion in this paper, a theoretical holistic decision-making framework is proposed, which intends to eliminate inefficiencies in data sharing by using a MCDS approach supplemented by other data sets and supported by an automated holistic knowledgebase system using semantic web, **Fig. 10**.

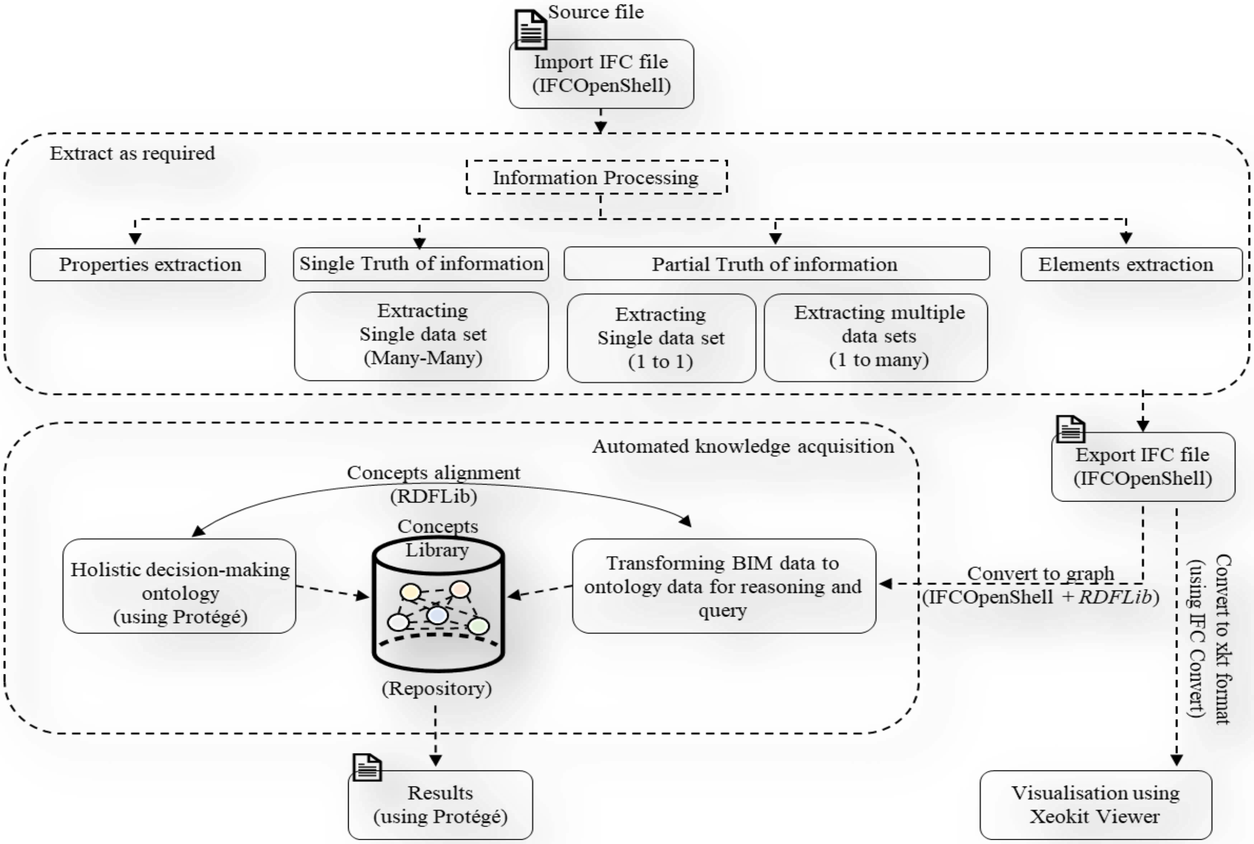

Fig. 10: A theoretical holistic decision-making framework

The theoretical foundation of the proposed framework is linked to the concept of single truth of information and partial truth of information. This framework will understand each model's specific data (partial truth of information) and leverage these models' common data as a common layer via a "single truth of information". Identifying a "single truth of information" that can be shared among different domains and throughout the lifecycle can help developers use the same mapped data set to create their idea and extend this mapped data set to fit their specific use case, eliminating the time wasted on rebuilding this common information again and improve consistency. Moreover, these data sets will be based on the IFC schema. However, IFC was not designed to deduce new information from a BIM model. Consequently, using technologies such as the semantic web can help to support BIM models with a holistic decision-making system.

$$Single\ truth\ of\ information = \text{Truth of information} - \text{Partial truth of information}$$

The use case scenario proposed in this paper was designed as close as possible to reflect a real-life situation. It involves three authorised users: structural engineer, cost engineer and client, and one unauthorised user, **Fig. 11**. After passing the authentication and authorisation check carried by the server associated with the project's user role, the participants will log into the web-based platform. Using this approach can deliver a platform that understands what information is required for the logged-in user by showing only the required information. Hence, it can realise significant time reductions during design. Once the appropriate member is directed to the associated pages, the user can upload a BIM model using the IFC format.

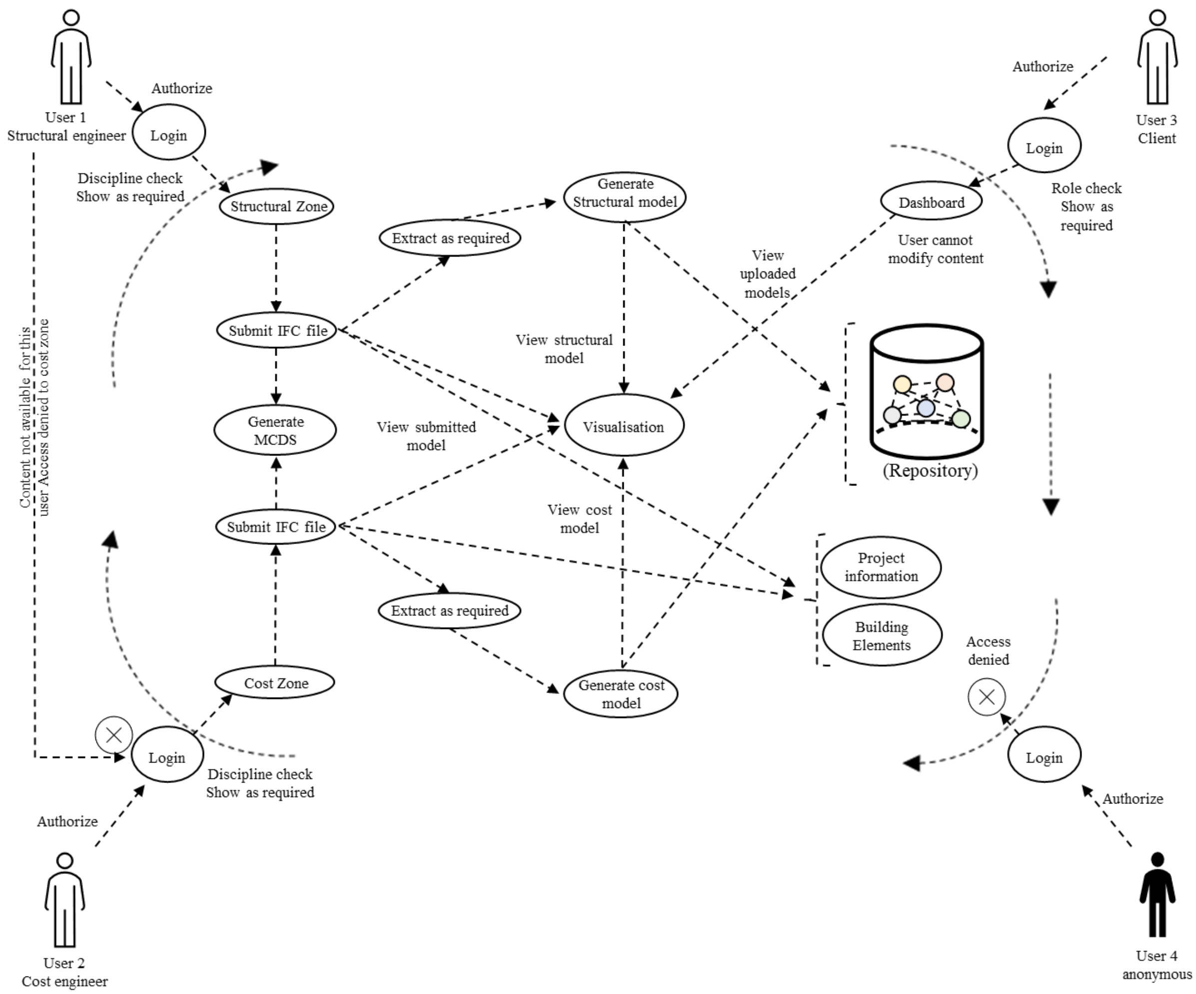

Fig. 11: Use case diagram for the proposed platform

The users will have various options: users can extract information as required, which include various sets such as structural data set, cost data set and MCDS, **Fig. 10** and **Fig. 11**. In other words, the proposed system can automatically generate one model from another model. After the data sets are extracted and saved in the appropriate IFC format using IfcOpenShell Library, which is an open-source software library that helps users and software developers to work with the IFC file, the framework will provide the users with a visualisation option via a web browser using Xeokit viewer, which is an open-source 3D graphics SDK built to view huge BIM models in the browser. Moreover, users can view related information according to the project's user role. A format such as JSON will be used to view the data stored in the uploaded file by transforming the IFC file into a JSON data format. This transformation will be supported by IFCOpenShell Library to filter the necessary information.

On the other hand, the exported IFC file will be converted into a graph representing the BIM model using semantic web, python language and IfcOpenShell, **Fig. 10**. Moreover, a multi-dimensional knowledge base using protégé, which is a free, open-source ontology editor and framework for building intelligent systems, will be used to design the holistic decision-making knowledge base that considers different types of data together, including cost, sustainability, design condition, and safety for collective design making. The converted graph will be further aligned with the developed multi-dimensional knowledge base. Concepts alignment typically occurs by comparison and mapping based on the structure of the knowledge base and the similarities among the concepts used in it. By following this framework, different professions can make a collective decision by putting everything together to produce a joint decision at the early design stage.

To easily implement the proposed framework in an isolated environment that can be easily deployed on any operating system, Docker will be used to host the different web-based services. Docker is an alternative to virtual machines, which are much less resource-intensive [62] since containers share a common kernel, reducing the total overheads in multi-container systems. Services can also be distributed amongst a cluster of nodes through the use of Docker Swarm, which allows for the potential development of easily deployable and high-performance cloud computing systems [63]. This research will use several container images in its architecture, **Figure 12**, such as miniconda3 for developing the Django frontend, the official Postgres image to store information supporting the Django app, a dockerised version of Xeokit viewer to visualise IFC models and parse the model tree, and IFC Convert will be wrapped into a microservice container using the Python Hug library. These images will be deployed as a single stack using a single compose file, which configures the network settings automatically, allowing for requests between the services on the virtual Docker network. Ports will also be exposed to the host machine, allowing connections to the web services via a browser. Volumes will be bind-mounted to local directories on the host machine so that IFC and other data can be immediately inspected.

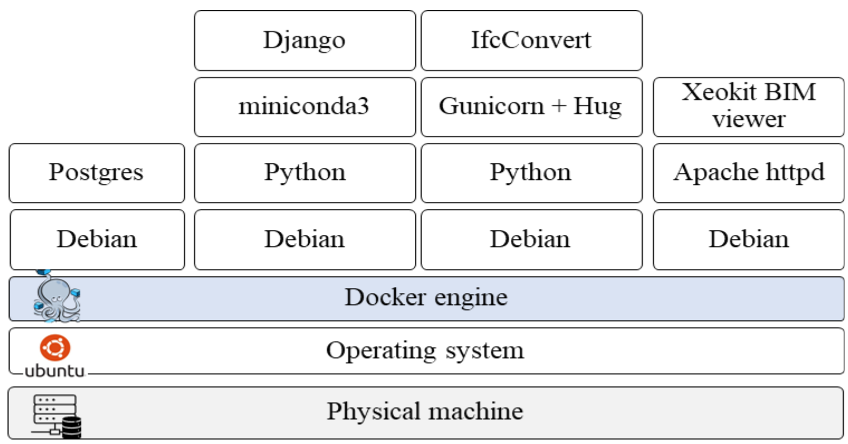

Fig. 12: Stack diagram for Docker environment used in this study

8. Conclusion

In order to eliminate inefficiencies in data sharing and improve the decision-making process in the early design stage, this paper presented a theoretical holistic decision-making framework using combined data extraction and a semantic web approach. Along with the development of this framework, this research found out:

First, this study found that despite the different use of BIM domain-specific partial model, they share some commonalities that are not exclusive to a specific domain. This study found that the more commonalities exist within two systems, the less data loss will exist between the two systems, and the flow of data is not always bidirectional. It flows from the more informed data sets to the less informed data sets. Secondly, most investigations have concentrated on individual areas such as the architectural design and the structural analysis domains. Hence, a CDA referencing various concepts such as the standardised IDM, MVD and the concept of the semantic intersection was designed to conclude a “single truth of information” and “partial truth of information” data sets that form the basis for the theoretical holistic decision-making framework from a data processing perspective. Three BIM models were created: the architectural model was considered as the source model, whereas the structural and cost models represent the models delivered to the end-users. This study aims to focus on data exchange requirements to understand for each profession what sort of data is required and what information needs to be exchanged to improve the data exchange process.

Thirdly, data mapping is the process of matching a requirement to the equivalent entity that exists in a given schema. This process can differ from one developer to another. However, identifying a “single truth of information” that can be shared among different domains and throughout the lifecycle can help developers use the same mapped data set to create their idea and extend this mapped data set to fit their specific use case, eliminating the time wasted on rebuilding this common information again. Thus, it could be valuable to deliver the foundation for holistic decision-making from a data processing perspective. Finally, IFC was not designed to deduce new information from a BIM model. Most of the research was mainly focused on data exchange without providing a holistic decision-making system. There is still a lack of multi-dimensional knowledgebase for holistic decision-making within a BIM workflow that considers the non-geometrical information.

The current proposed framework is in the “proof of concept ” stage and requires further improvement. The developed framework is semi-automated, and the knowledge base covers the most basic building elements and aspects, such as design conditions. Future work will include fully automating the system and providing a web-based platform that can host both the extraction algorithm and the developed knowledge base, where they can communicate. The developed knowledge base requires further enrichment by adding and aligning various aspects. Moreover, in this paper, the focus was mainly on the design stage. Further work will include the investigation of more models from different stages.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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