TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Civil Engineering Institute of Construction Informatics

MASTER THESIS

Investigation of data sharing in the Structural Engineering domain

By
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Matriculation Number: 4748050

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Faculty of Civil Engineering, Technische Universität Dresden
In partial fulfilment of the requirements for the
Degree of Master of Science
In
Advanced Computational and Civil Engineering Structural Studies

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TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Bauingenieurwesen Institut für Bauinformatik

Master Thesis (Masterarbeit) Task Sheet

Name: Mr Rafeequl Islam (Matrikel Nr.: 4748050)

Study Course: ACCESS

Topic: **Investigation of data sharing in the Structural Engineering domain**

(Untersuchung des Datenaustauschs im Bereich Tragwerksplanung)

Objective:

Data sharing is one of the key concepts to establish the successful implementation of BIM. The seamless data exchange will provide better collaboration between all fields of the AEC industry and it enables a reduction in time, cost and effort involved in the duplication of the data. The Data transfer efficiency between different process models is depending upon the data sharing requirements related to the project stages. These data sharing requirements depend on multiple aspects, such as the available data quality, the required input parameters, the methodology used to process data, and the expected outcomes of data processing (quality, robustness, precision).

This study focuses on efficient data transfer techniques between different stakeholders in the domain of structural engineering. There are different technical roles (such are architects, mechanical engineers, structural designers, CAD designers, quantity surveyors, electrical engineers, tenderers, etc.) involved in the process of designing building structural components. The efficient data transfer between these stakeholders will enhance the total process in all design stages (some of the sub-stages are concept design, preliminary design, detailed design and developed design) of the project.

The student is expected to analyse all data required to be shared between these stakeholders and similarly the data sharing requirements to perform seamless interoperability between software applications commonly used by them. The focus is majorly on the IFC meta-data model schema as a neutral file format to hold data, exchange and manage the information.

DRESDEN concept

Die besonderen Hinweise für die Anfertigung Masterarbeit des Instituts sind zu beachten.

Even though many BIM tools can exchange the information using IFC, there is some uncertainty about the capabilities of tools, which are used in the structural engineering domain. Therefore, the student need to continue his further investigations on different tools used by stakeholders and their capabilities in exchanging data. The consideration of different stakeholders in the demonstration of data transfer activity is based on the results from this investigation. After a successful selection of different set of tools, the student is expected to perform a demonstration of data sharing activities between these tools. Finally, the student has to evaluate the results for this activity.

The approach of Linked data and Ontologies are gradually evolving techniques in the process of semantic interoperability. Ontologies (i.e. semantically consistent, meta-data dictionaries) are an enabling technology for the integrated, holistic, seamless deployment of attractive toolkits operated as components of a BIM-platform using the linked data paradigm. Complementing to the above task, student is expected to perform a basic investigation on feasibility of Ontology technique over IFC meta-data schema in data sharing processes based on the results from data transfer demonstration.

Assignments:

The below items shall be discussed in the project.

1. Investigate data transfer requirements between stakeholders in the domain of structural engineering based on the Level of Detail (LOD) standardized specifications as per American Institute of Architects (AIA).
2. Verify data sharing requirements defined in meta-data models such as IFC with respect to above investigated information to analyse adaptability and efficiency of the meta-data model schema in the process of interoperability.
3. Identify different tools that support the above identified data sharing requirements between these tools using IFC in the Structural Engineering domain. Perform a demonstration of data transfer activities and evaluate the results. Together with the supervisor, a preferred building will be selected for the verification of your findings.

   (It is recommended using a building made of composite structure for the demonstration)
4. Based on the results, investigate how feasible the Linked data and Ontologies approach is for semantic interoperability.

Supervisor: Janakiram Karlapudi, MSc

Responsible Academic staff and Examiner 1: Prof. Dr.-Ing. habil. Karsten Menzel

Examiner 2: Prof. Dr.-Ing. Raimar J. Scherer

Topic handed over to student: 30.07.2019

Expected Submission Date: 30.11.2019

(Student)

Prof. Dr.-Ing. Raimar J. Scherer
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Declaration of originality

I confirm that this assignment is my own work and that I have not sought or used inadmissible help of third parties to produce this work. I have fully referenced and used inverted commas for all text directly quoted from a source. Any indirect quotations have been marked as such.

This work has not yet been submitted to another examination institution – neither in Germany nor outside Germany – neither in the same nor in the similar way and has not yet been published.

Dresden, 20-Jan-2020
Place, Date

____
Signature

Acknowledgements

I express sincere gratitude to Prof. Dr.-Ing. habil. Karsten Menzel and Prof. Dr. Ing. Raimar Schrer for giving me the opportunity to do my Master Thesis in the Institute of Construction Informatics, Faculty of Civil Engineering and for providing immense support throughout the process.

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List of Abbreviations and Symbols

BIM	Building Information Modeling
AEC	Architecture, Engineering and Construction
AEC/FM	Architecture, Engineering and Construction/Facility management
IFC	Industry Foundation Classes
IAI	International Alliance for Interoperability
LOD	Level of Detail

1. Introduction

1.1 Building Information Modeling

Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering and construction (AEC) industries. BIM is a process supported by various tools and technologies involving the generation and management of digital representations of physical and functional characteristics of civil engineering structures. These digital models contain precise geometry and data needed for the design, construction and maintenance. BIM accommodates all the information and functions needed to model and support the life cycle of structures (refer to figure 1.1) resulting in better quality at lower cost and reduced project duration. The term 'Building Information Model' first appeared in a 1992 paper by G.A. van Nederveen and F. P. Tolman [1]. The US National Building Information Model Standard Project Committee defines BIM as: [2]

"Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition"

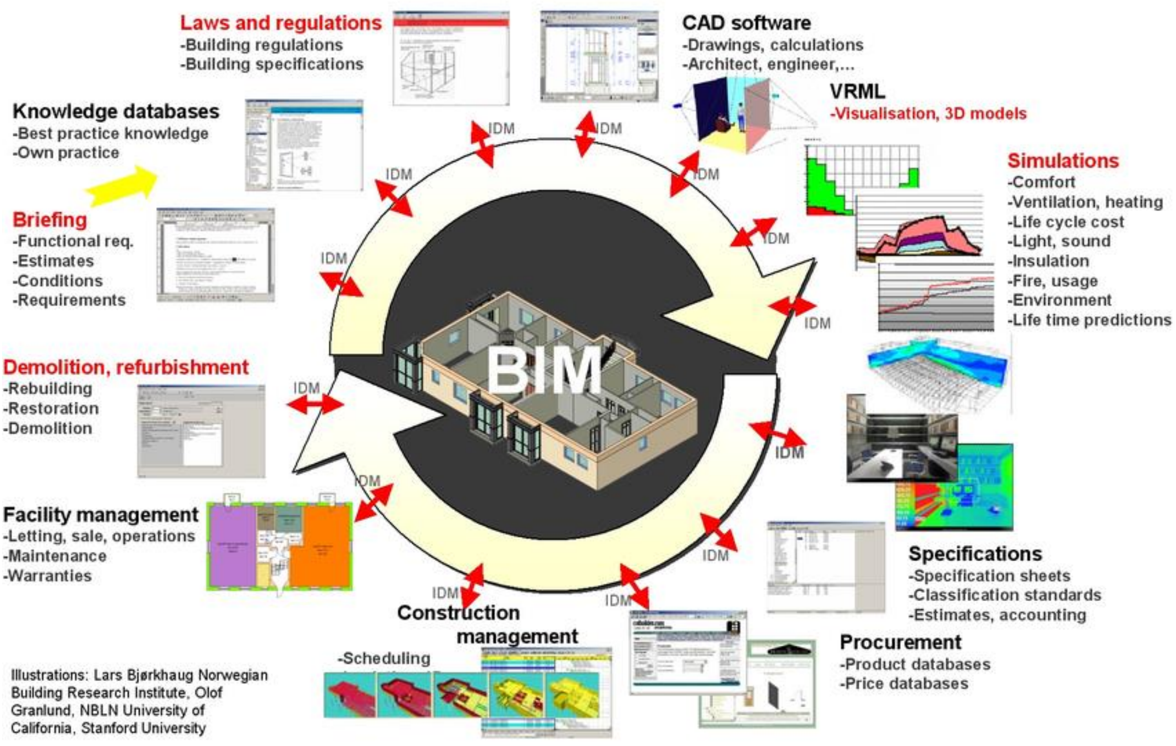


Figure 1.1: Graphical representation of BIM concept and its possible by products *[3]*.

Traditional building design and construction was largely dependent on 2D technical drawings (Plans, Elevations and Sections) but BIM extends this beyond 3D, augmenting the three primary spatial dimensions (width, height and depth) with time (Planning and Scheduling) as the fourth dimension, cost (Estimating) as the fifth, environmental and sustainability as sixth and facility management as seventh dimension [4]. Figure 1.2 shows the different dimensions of BIM.

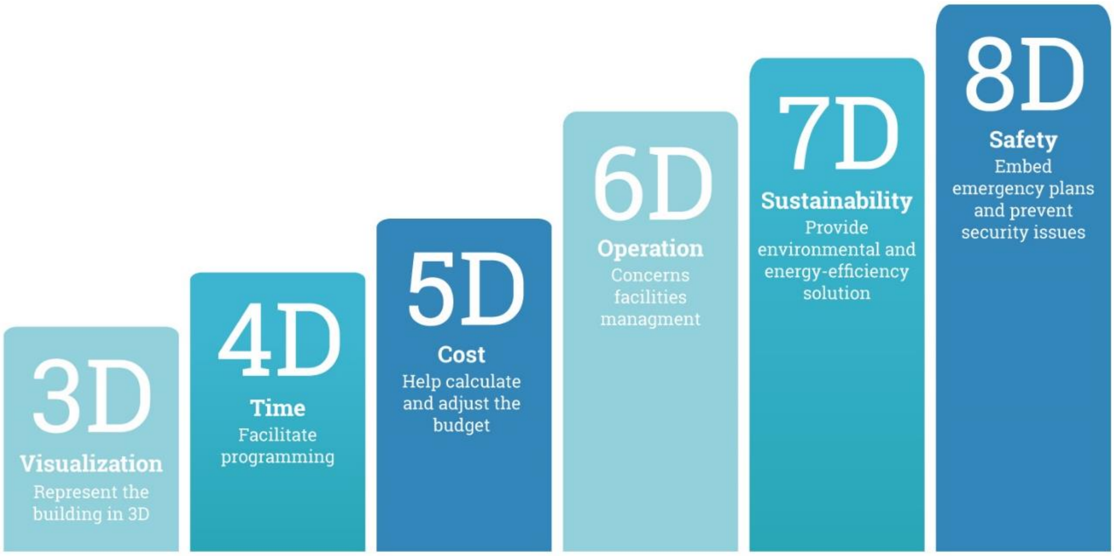


Figure 1.2: Dimensions of BIM

BIM enables virtual information model to be shared with different stake holders in the construction industry such as from design team (architects, landscape architects, surveyors, civil, structural and building services engineers) to the main contractor (planning, procurement and fabrication) and sub-contractors (quality control, safety etc.) and then to the owner/operator. All professionals work on their own different specific software tools and add specific data to the single shared model. The data exchange between them is one of the key concepts for successful implementation of BIM.

Different stakeholders in the AEC industry use diverse software tools according to their specific need (to support large and complex project at various stages of design and construction) and then collaborate with other users for interoperability, the seamless data exchange between them is a crucial issue. Interoperability among these software packages is a big task and is necessary to ensure a seamless sharing of information models. Here comes the data sharing techniques to analyze the data required to be shared among them and the data sharing requirements for better collaboration. Seamless interoperability can help in minimizing the delays and cost overruns by elimination of re-modeling in the construction project. There are several open BIM metadata models or data exchange schemas for interoperability and each of these has their own specific use in terms of need, type of information to be shared and type of project. One such popular schema is Industry Foundation Classes (IFC) developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) to facilitate interoperability in the AEC industry.

1.2 Description of Research Statement

There are several stakeholder in the domain of structural engineering with different technical roles such as architects, structural engineers, CAD designers, quantity surveyors, planners, tenderers, mechanical engineers, electrical engineers, HVAC team etc. Some are responsible for individual component (Architectural, structural, Mechanical, etc.) modeling while others role may vary from integrating all structural components modelled into virtual model to perform overall structural, energy, HVAC, etc. analysis. The efficiency of data sharing and data transfer between them will enhance the overall design process (from concept design to detailed design).

This thesis is about the analysis of the data sharing by different stakeholders in the domain of structural engineering. The focus is on IFC meta-data model schema as a vendor neutral data format to hold exchange and manage the information. The focus is on capability of different software tools used in the structural engineering domain to perform data exchange using IFC format.

1.3 Research Objective and Approach

The objectives of this research work are:

1. Identification of the data transfer requirements between different stakeholders in structural engineering domain at various stages of design as described in different Level of Detail (LOD) specifications by American Institute of Architects (AIA).
2. To investigate the current IFC meta-data model for efficient interoperability with respect to the above identified data transfer requirements.
3. Identification of different software tools used in the domain of structural engineering that support IFC data sharing.
4. Demonstration of data sharing between these tools and analysis of results for feasibility data sharing requirements.

For analysing the semantic interoperability, a suitable building model (Composite structure) is modelled in Revit (Architectural, structural and MEP modelling software) at LOD 300. This model is then exported as IFC file from Revit software. The exported IFC file is then analysed using FZK viewer (IFC model viewer) for data quality, modelling errors and geometrical representation of building components. Now, this IFC file is imported to SCIA Engineer (Structural Analysis and design software). After importing the IFC file, SCIA converts IFC models to internal models and the structural analysis is performed.

1.4 Thesis Layout

Part 1 gives the overview of BIM and its dimensions. It then focus on the need for data sharing in structural engineering domain and interoperability issues between them. Furthermore, this part describes the research statement and its objective and approach used.

Part 2 gives a broad literature study review and discusses the interoperability issues between various software tools used in the structural engineering domain. It summarizes the previous works done by various researchers in this field. It discusses the different Level of Detail (LOD) as defined by American Institute of Architects. (AIA). It also discusses the data transfer requirement at different LODs required by different stakeholders in design stage.

Part 3 discusses the IFC data sharing model, its concept and architecture. Then it analyses how the structural data is represented in IFC file format. Structural elements. Part 4 provide a demonstration of data sharing with a suitable building model. Revit and SCIA engineer is used as software tools.

Lastly, the results obtained from part 4 are then analyzed and investigated for the feasibility of data transfer for semantic interoperability. The interoperability issues are addressed. And the work is concluded with further studies.

2. Literature Studies

Building design process typically involves two separate phases, architectural design and structural design with distinct objectives. Architectural design is focused on defining the space arrangement and geometric information of various architectural elements (Input for structural design), while structural design focus on analyzing the mechanical properties of building elements and structure. Structural design involves several consultants and engineers performing structural analysis and design utilizing different software tools. Software interoperability is necessary to ensure a seamless sharing of information models. Due to multiple disciplines, data sharing and exchange between diverse software tools become an inevitable need, and a public and rich data format is necessary for data interoperability. Consequently, IFC schema was developed by buildingSMART to support data sharing and exchange. IFC is an open data schema and most widely used schema for data sharing among all the disciplines of AEC industry and across the entire life cycle of building. Currently 68 software application have finished buildingSMART certification process and IFC4.2 is the latest version.

2.1 Interoperability Issues

Interoperability is the ability to transfer data between applications, and for multiple applications to jointly contribute to the work at hand. It is a seamless data exchange at the software level. National Institute of Standards and Technology study estimated that inadequate interoperability for the capital facilities industry led to $15.8 billion in annual unnecessary costs in USA in 2002 [5]. Interoperability is achieved by mapping parts of each participating software's internal data structure to a universal data model and vice versa. If the employed universal data model is open (such as IFC), any application can participate in the mapping process and thus become interoperable with any other application that also participated in the mapping. Interoperability eliminates the costly practice of integrating every application (and version) with every other application (and version) and regeneration of models with specific details [6]. Figure 2.1 describes interoperability with and without universal Meta data model such as IFC.

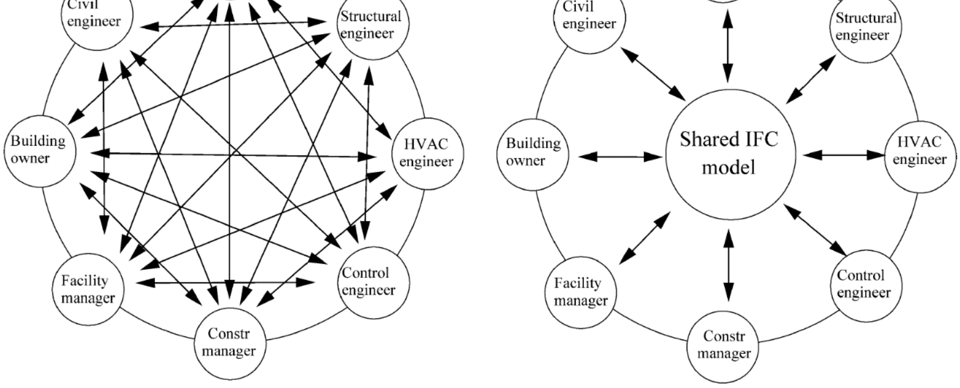


Figure 2.1: Interoperability between various software tools

Lai and Deng studied interoperability issues during bidirectional data exchanges using IFC. They conducted a data interoperability experiment, including architectural, structural and MEP models from a practical project, to analyze issues in the process of data import and re-export between heterogeneous software. The results are summed as: (a) software tools cannot well interpret several objects belonging to other disciplines due to the difference in domain knowledge; (b) software tools have diverse methods to represent the same geometry, properties and relations, leading to inconsistent model data. They also suggested a method for improving the existing bidirectional data sharing and exchange: BIM software tools export models using IFC format, and these IFC models are imported into a common IFC-based BIM platform for data interoperability [7].

Y.-S. Jeong et al. conducted test for data exchanges of precast concrete. They tested a small but complex building model and have shown that despite progress in developing and implementing IFC, much work is still needed to achieve fully effective interoperability. Imperfect exchanges arose from the lack of uniformity in the way the internal object schemas were mapped to IFC objects and properties. Their tests showed clearly the need for a mutually agreed upon standard that defines how precast architectural facades should be modeled and mapped to the IFC schema [8].

A BIM model is to be shared between different software applications which are used by the different stakeholders in the BIM process. Thus it is crucial for the data information model to have seamless sharing among the various software's. To achieve successful data sharing or data interoperability it is necessary that each part of the participating data structure must map itself with the universal data structure such as IFC, without any exceptions. Various researches has been carried out to test the data exchange using IFC and concluded much work is still needed to achieve fully effective interoperability.

2.2 Level of Details (LOD)

BIM presents information in the form of 3D graphical representation which is further associated with more characteristic features of elements. The Level of Detail (LOD) specification is a reference tool intended to improve the quality of communication among the users of BIM about the details of elements in model. The LODs provide five snapshots of the progression of an element from conceptual to actual design [12].

The term LOD was first introduced in 2004 by Vico Company. In 2008, it was further developed by the American Institute of Architects (AIA) releasing their first BIM contract document - *AIA E202 Building Information Modeling Protocol Exhibit*, by describing it as '*level of completeness to which a model element is developed'*. They outlined five levels of detail (LOD 100-500) for defining the amount of detail in a particular BIM model. In 2013 a group called BIMForum published *Level of Development Specification*, they explained all the terms by providing definitions and illustrations of BIM elements of different building systems at different stages of their development and use in the design and construction process.

Level of Detail is essentially how much detail is included in the model element while Level of Development is the degree to which the element's geometry and attached information has been thought through. The table below gives the comparison of AIA's Definitions of LOD with BIMForum Interpretation.

	AIA's Definition (Level of Detail)	**BIMForum Interpretation (Level of Developemnt)**
LOD 100	*The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.*	LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate.
LOD 200	*The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.*	At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate.
LOD 300	*The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.*	The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin.
LOD 350	*The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.*	Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
LOD 400	*The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size,*	An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component.

	shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.	The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
LOD 500	*The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non graphic information may also be attached to the Model Elements.*	Since LOD 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non-graphic information, this Specification does not define or illustrate it.

Table 2.1 Comparison of American Institute of Architect's Definitions of Level of Detail with BIMForum's Level of Development Interpretation *[13] [14]*.

At **LOD 100,** the structure is roughly sized and a basic site layout may exist. The element are graphically represented as a symbol or other generic representation but does not represent actual shape, size, or precise location. LOD 100 enable to approximate conceptual cost based on cost per square foot, tonnage of HVAC, etc. in a model consisting of nothing more than floors, and then to quickly derive overall costs and capacities as the model is changed [15] [16].

LOD 200 is the schematic design and design development stage. The elements are represented with an approximate geometry (size, shape, location, and orientation) and may also include non-graphic information such as cost, thermal characteristics of envelope components, weight of an object, manufacturer/model data, and operation & maintenance manuals. The elements at this stage are useful for comparison of options, such as relative effects of building orientation on HVAC load [15] [16].

LOD 300 elements are specific assemblies, such as, engineered structural members, system components, etc. Columns, beams, slab, joists etc. are represented at their actual engineered sizes, shapes, and locations however flanges, bases and joist webs can be relied upon for spatial coordination with other elements such as piping and ductwork, but the data such as steel tonnage and concrete volume can be derived precisely. No space claims should exist for any future object and major hard clashes should be resolved. The accuracy is sufficient to perform detailed analyses such as structural simulation and HVAC load determination [15] [16].

LOD 350 include connection details such as gusset plates, bolts, stiffeners and bracing which can impact coordination, is modeled at this level. If there is overcrowding near a connection, that connection should be resolved in order to assure proper coordination [15] [16].

LOD 400 is mainly related to fabrication process, it provides detail that is traditionally provided in shop drawings. Structural connections, slab- edge embeds, curtain wall details, and other items requiring special fabrication fall into this category. In case of structural steel element, it includes details such as bracing, stiffeners, masonry supports, lintels, etc. For column, beam, slab element it includes rebar etc. [15] [16].

LOD 500 is the 'as-built' stage and the model is finally handed over to the building's Facility Manager. Elements will contain all the actual quantity, cost, purchase documentation, commissioning data, maintenance requirement as well as any other data required for the life cycle management of building [15] [16].

2.3 Data transfer requirement

Table 2.2 represents the information required for various structural elements at different LOD. As the LOD gets higher the granularity of data also increases.

Structural Element	**Information Required**				
	LOD 100	**LOD 200**	**LOD 300**	**LOD 350**	**LOD 400**
Foundation	Type Dimensions (approx.)	Type Dimensions Elevation Classification Materials	Type Dimensions Elevation Classification Materials Reinforcement degree	Type Dimensions Elevation Classification Materials Reinforcement Concrete strength Environmental class Blinding layer Concrete	Type Dimensions Elevation Elevation Tolerances Classification Materials Reinforcement Concrete strength Environmental class Blinding layer concrete Water proofing Density Manufacturer / Supplier
Concrete Slab	Type Dimensions (approx.)	Type Dimensions Elevations Classification	Type Dimensions Elevations Classification	Type Dimensions Elevations Classification	Type Dimensions Elevations Elevation tolerances

		Material	Material	Material Main reinforcement Concrete strength Environmental class	Classification Material Reinforcement Concrete strength Environment class Weight Drying Protection Manufacturer / Supplier
Concrete Beam	Type Dimensions (approx.)	Type Dimensions Elevations Classification Material	Type Dimensions Elevations Classification Material	Type Dimensions Elevations Classification Material Main reinforcement Concrete strength Environmental class	Type Dimensions Elevations Elevation tolerances Classification Material Reinforcement Concrete strength Environmental class Drying protection Reinforced joints Concrete joints Manufacturer / Supplier
Concrete Column	Type	Type Dimensions (approx.) Elevations Classification	Type Dimensions Elevations Classification Reinforcement degree Material	Type Dimensions Elevations Classification Main reinforcement	Type Dimensions Elevations Elevation tolerances Classification

		Main reinforcement		Material Concrete strength Environmental class	Reinforcement Material Concrete strength Environmental class Drying Protection Manufacturer / Supplier
Steel Beam	Type Dimensions (approx.)	Type Dimensions Elevations Classification Material	Type Dimensions Elevations Classification Material Fire requirements	Type Dimensions Elevations Classification Material Fire requirements Surface treatment Steel Strength	Type Dimensions Elevations Classification Material Fire requirements Surface treatment Steel Strength Corrosion protection Mounting Tolerance Adhesive Anchor Manufacturer/supplier
Steel Column	Type Dimensions (approx.)	Type Dimensions Elevations Classification Material	Type Dimensions Elevations Classification Material Fire requirements	Type Dimensions Elevations Classification Material Fire requirements Surface treatment Steel Strength	Type Dimensions Elevations Classification Material Fire requirements Surface treatment Steel Strength

					Corrosion protection Mounting tolerance Adhesive anchor Semi/drilling depth Manufacturer/Supplier

Table 2.2: Information required for various structural elements at different LOD

3. Data sharing model

Data interoperability is a key to achieving worldwide standardization of BIM methods and usage. An open-source approach based on open standards and workflows is called OpenBIM. Open data standards achieve common language and empower the exchange of relevant data between software applications and thus an efficient communication among project members. Every standard is based on 3 main components - Terminology, Process and Digital storage.

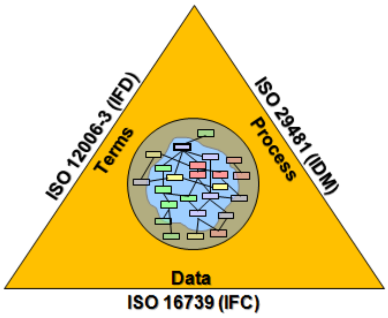


Figure 3.1: buildingSMART standards triangle

buildingSMART has developed an open standard for BIM, known as IFC and is registered as ISO 16739. The standard deals with data models, processes and terms. buildingSMART has also published some other types of open standards to support IFC, they are

- IFD: International Framework for Dictionaries (ISO 12006-3, 2007)
- IDM: Information Delivery Manual (ISO: 29481 – Part 1 &2, 2016)
- MVD: Model View Definitions
- BCF: BIM Collaboration Frame-work

IFC is a standardized, digital description of the built environment, including buildings and civil infrastructure. It is a vendor-neutral and usable across a wide range of hardware devices and software platforms. The schema specification describes how a facility or installation is, used, constructed and operated. IFC can define physical components of buildings, manufactured products, mechanical/electrical systems, as well as more abstract structural analysis models, energy analysis models, cost breakdowns, work schedules and many other things. IFC can also be used as a means of archiving project information, whether incrementally during the design, procurement, and construction phases, or as an "as-built" collection of information for long-term preservation and operations phases [17].

3.1 IFC Schema

A schema is ‘a collection of entities (or classes), attributes, and relationships between entities’. The IFC specification includes terms, concepts and data specification items that originate from use within disciplines, trades, and professions of the construction and facility management industry sector. The IFC specify a data schema and an exchange file format structure. The data schema is defined in

- EXPRESS data specification language as defined in ISO 10303-11
- XML Schema definition language (XSD) as defined in ISO 10303-28

The IFC data schema architecture is defined in four conceptual layers, each individual schema is assigned to exactly one conceptual layer.

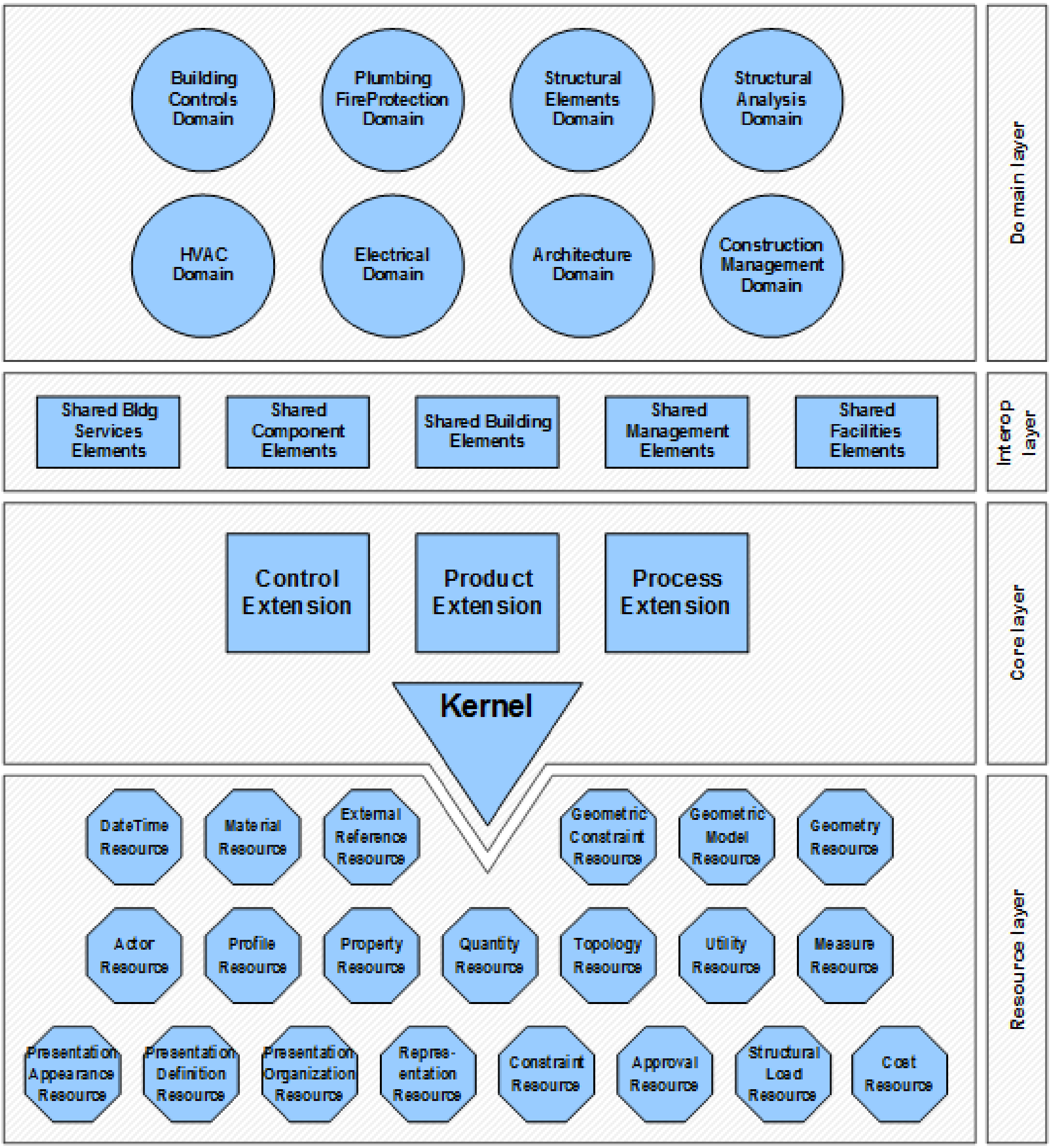


Figure 3.2: IFC data schema conceptual layer

1. **Resource layer**: It is the lowest layer which includes all individual schemas containing resource definitions, these definitions do not include a globally unique identifier and shall not be used independently of a definition declared at a higher layer.
2. **Core layer**: This layer includes the kernel schema and the core extension schemas, containing the most general entity definitions, all entities defined at the core layer, or above carry a globally unique id and optionally owner and history information.

3. **Interoperability layer**: This layer includes schemas containing entity definitions that are specific to a general product, process or resource specialization used across several disciplines, those definitions are typically utilized for inter-domain exchange and sharing of construction information.
4. **Domain layer**: This is the highest layer includes schemas containing entity definitions that are specializations of products, processes or resources specific to a certain discipline, those definitions are typically utilized for intra-domain exchange and sharing of information.

In Ifc schema all the data item names for types, entities, rules and functions start with the prefix "Ifc" while the attribute names within an entity has no prefix; the property set definitions start with prefix "Pset_" and the quantity set definitions start with the prefix "Qto_". All the Ifc entities originate from IfcRoot, the common super type of all IFC entities, except those defined in an IFC resource schema. It is the most abstract and root class for all entity definitions that roots in the kernel or in subsequent layers of the IFC specification. All entities that are subtypes of IfcRoot can be used independently, whereas resource schema entities, that are not subtypes of IfcRoot, are not supposed to be independent entities. The three fundamental sub types of IfcRoot are IfcObjectDefinition, IfcPropertyDefinition and IfcRelationship.

IfcObjectDefinition is the generalization of any semantically treated thing or process, which can be either a type or an occurrence. Object definitions can be named by means of the inherited Name attribute, which should be a user recognizable label for the object occurrence. The principle sub types of IfcObjectDefinition are IfcContext, IfcObject and IfcTypeObject.

IfcPropertyDefinition defines the generalization of all characteristics (i.e. grouping of individual properties), that may be assigned to objects. At present, sub types of IfcPropertyDefinition include property set occurrences, property set templates, and property templates. IfcPropertySetDefinition and IfcPropertyTemplateDefinition are sub types of IfcPropertyDefinition.

IfcRelationship is essentially the abstract generalization of all objectified relationships in IFC. Objectified relationships has the priority when it comes to handling relationships among objects. This allows to keep relationship specific properties directly at the relationship and opens the possibility to later handle relationship specific behavior. IfcRelAssigns, IfcRelAssociates, IfcRelConnects, IfcRelDeclares, IfcRelDecomposes and IfcRelDefines.

3.2 Model View Definition (MVD)

MVD is a subset of the overall IFC schema to describe a data exchange for a specific purpose or workflow as it narrows the broad scope depending on the need of the receiver. MVDs are data-centric rather than application-centric. Not every domain expert in a project need all the same information delivered or received. So, there's a need to clarify which subset of all the data, and its format, is needed to exchange for a particular use. A MVD will describe which objects, representations, relationships, concepts, and attributes are needed for the receiving stakeholder and their software application to accomplish a desired task. In a MVD, the following is defined for the replacement process of an IFC model:

- How information is exchanged
- The data standard
- Required configurations for the standard

buildingSMART developed 6 MVDs for specific purpose within the AEC industry and 4 more are in draft stage. Some examples of MVDs are
Architectural Design to Structural Design: The architect provides the structural engineer a model "background" that can be referenced for the placement and design of structural elements.
Architectural Design to Quantity Takeoff: The architect provides the general contractor a model that has accurate element placement extents for extracting quantities and assigning costs.
Building Envelope Design to Energy Analysis: The architect provides the energy consultant a model with specific construction types and material thermal values, as well as thermal comfort values for internal spaces to determine building performance
Construction Operations Building Information Exchange (COBie): The contractor provides as-built data to the owner and facility manager for operations [18].

3.3 Structural data in IFC

This section describes the information and entities required to represent the structural data in the IFC schema and establishes relation with each other using relationship entities. The Information required to develop the open BIM data model for structural engineering domain (Lead designer to specific task members) is divided into 7 essential parts as shown below

1. Static analysis
2. Dynamic analysis
3. Probabilistic analysis
4. Finite element analysis
5. Pre-Stressed Concrete
6. Steel connection design
7. Reinforcement detailing

Static Analysis: The *IfcStructuralAnalysisDomain* describes the structural analysis model in order to tightly integrate the structural engineering domain. It reuses the existing building element and spatial structure element definition and associates the structural assumptions to it. The focus is to ensure that structural engineering information is captured and made visible to other related domains.

Dynamic analysis, Probabilistic analysis, Finite element analysis and Pre-Stressed Concrete: There are no entities in IFC that describe parameters for the above analysis methods. These analysis methods can be added as an extension of an IFC model using Property Sets. A Property set is used to define dynamically expandable attributes. It is a container class that represents the attributes within a schema includes. The interpretation of the attributes is done according to their name. Suitable entity would be *IfcStructuralLoad* for load effect.

3.3.1 Structural elements

The schema *IfcStructuralElementsDomain* provides the ability to represent different kinds of building elements and parts which in general are of structural in nature. In addition to commonly used building elements defined in *IfcSharedBuildingElements* schema, it contains entities for foundation parts such as footings and piles. It also contains some important structural subpart such as different kinds of explicit reinforcement parts, and manufactured features and treatments.

IfcFooting: A footing is a part of the foundation of a structure that spreads and transmits the load to the soil. A footing is also characterized as shallow foundation, where the loads are transferred to the ground near the surface.

IfcReinforcingBar: A reinforcing bar is usually made of steel with manufactured deformations on the surface, and used in concrete and masonry construction to provide additional strength. A single instance of this class may represent one or many of actual rebars, for example a row of rebars.

The building element comprises all elements that are primarily part of the construction of a built facility, i.e., its structural and space separating system. Building elements are all physically existent and tangible things. An element is a generalization of all components that make up an AEC product. Elements are physically existent objects, although they might be void elements, such as holes/recesses. They can either remain permanently or temporarily such as formwork and they can be either assembled on site or pre-manufactured. An element can have material and quantity information which can be assigned through *IfcRelAssociatesMaterial* and I*fcRelDefinesByProperties* relationship. Elements are a sub set of *IfcBuildingElement* which is a sub set of *IfcElement*. The various structural elements in Ifc are

IfcBeam: An *IfcBeam* is a horizontal, or nearly horizontal, structural member that is capable of withstanding load primarily by resisting bending. It represents such a member from an architectural point of view. It is not required to be load bearing.

IfcColumn: *IfcColumn* is a vertical structural member which often is aligned with a structural grid intersection. It represents a vertical, or nearly vertical, structural member that transmits, through compression, the weight of the structure above to other structural elements below. It represents such a member from an architectural point of view. It is not required to be load bearing.

IfcSlab: A slab is an element that may enclose a space vertically. The slab may provide the lower support (floor) or upper construction (roof slab) in any space in a building. Only the core (Structural part) is considered as slab, the upper finish (flooring, roofing) and the lower finish (ceiling, suspended ceiling) are considered to be coverings. There is also a representation of slabs for structural analysis provided by a proper subtype of IfcStructuralMember being part of the *IfcStructuralAnalysisModel*. An arbitrary planar element to which this semantic information is not applicable shall be modeled as *IfcPlate*. A slab may have openings, such as floor openings, or recesses. They are defined by an *IfcOpeningElement* attached to the slab using the inverse relationship *HasOpenings* pointing to *IfcRelVoidsElement*.

3.3.2 Geometry and placement

The schema *IfcGeometryResource* defines the resources used for geometric representations. The primary application of this resource is for representation of the shape or geometric form of an element. The geometric representation items can also be used to describe geometric models within the schema *IfcGeometricModelResource*.

The schema *IfcGeometricConstraintResource* is used to determine the placement of the shape representation of a product within the geometric representation context of a project. It also contains resource definitions to be assigned to product connectivity definitions to determine the connection geometry constraints between those products.

The primary application of this resource is to:

- determine the object placement used for the shape representation of the object
- determine the constraints applied to the connectivity between two shapes of objects

The placement of a product's shape is given by the IfcObjectPlacement, used by the attribute *ObjectPlacement* of IfcProduct. The object placement defines the local object coordinate system in which all shape representations of that product are defined. It is given either as

Absolute placement: It is specified by using *IfcLocalPlacement* and omitting the *PlacementRelTo* attribute.

Relative placement: It is specified by using *IfcLocalPlacement* and pointing the *PlacementRelTo* attribute to an IfcObjectPlacement used in another IfcProduct instance.

Placement relative to a grid: It is specified by using *IfcGridPlacement* pointing to one (or two) virtual intersections of *IfcGridAxis*. If two virtual intersections are references, than the second virtual intersections specifies the orientation of the object placement. Alternatively the direction can also be provided explicitly by ifcDirection.

An IfcStructuralConnection represents a structural connection object (node connection, edge connection, or surface connection) or supports. There are 3 types of Connections supported

- Point connections: Defined by IfcStructuralPointConnection
- Curve connections: Defined by IfcStructuralCurveConnection
- Surface connections: Defined by IfcStructuralSurfaceConnection

3.3.3 Loads definitions

The entity *IfcStructuralActivity* represents the definition of actions (such as forces, displacements, etc.) and reactions (support reactions, internal forces, deflections, etc.) which are specified by using the basic load definitions from the *IfcStructuralLoadResource*.

The differentiation between actions and reactions is realized from the subclasses *IfcStructuralAction* or *IfcStructuralReaction* respectively. They inherit commonly needed attributes from the abstract superclass IfcStructuralActivity, notably the relationship which connects actions or reactions with connections, analysis members, or elements (subtypes of *IfcStructuralItem* or *IfcElement*).

The entity *IfcStructuralLoadGroup* is used to structure the physical impacts. By using the grouping features inherited from *IfcGroup*, instances of *IfcStructuralAction* (or its subclasses) and of *IfcStructuralLoadGroup* can be used to define load groups, load cases and load combinations.

3.3.4 Material definitions

IfcMaterial is a homogeneous or inhomogeneous material that can be used to form elements (physical elements or their components). *IfcMaterial* is the basic entity for material designation and definition; this includes identification by name and classification as well as association of material properties (isotropic or anisotropic) defined by subtypes of *IfcMaterialProperties*. An instance of *IfcMaterial* may be associated to an element or element type using the *IfcRelAssociatesMaterial* relationship. The assignment might either be direct as a single material information, or a material in layer, profile and constituent sets.

An *IfcMaterial* may also have presentation information associated. Such presentation information is provided by *IfcMaterialDefinitionRepresentation*, associating curve styles, hatching definitions or surface coloring/rendering information to a material.

3.3.5 Structural Results

The entity *IfcStructuralResultGroup* is used to group results of structural analysis calculations and to capture the connection to the underlying basic load group. The basic functionality for grouping inherited from IfcGroup is used to collect instances from *IfcStructuralReaction* or its respective subclasses.

A structural reaction is a structural activity that results from a structural action imposed to a structural item or building element. Examples are support reactions, internal forces, and deflections. Structural reactions are grouped into *IfcStructuralResultsGroups* via the inverse relationship *HasAssignments* and an *IfcRelAssignsToGroup* relationship object.

It is also possible to establish relationships between reactions in one analysis model and actions which they cause into another analysis model. For example, a support reaction from one structural system may be taken over as a load onto another supporting structural system. This is expressed by means of the inverse relationship *HasAssignments* of the reaction and an *IfcRelAssignsToProduct* relationship object.

4. Demonstration of data sharing

To demonstrate the data sharing between a BIM tool and a structural engineering software for structural analysis and design using IFC as an interoperable file format, a suitable composite structural model is selected. The purpose is to investigate the following,

- Level of data sharing (Data Quality) between BIM tool and a structural engineering software based on the data requirements for structural analysis and design.
- Adoption or implementation of meta-model data schemas in a BIM tool (Revit) for data export.
- Capability or adaptability of structural engineering software to import the data from IFC file format.
- Aanalysis and identification of modelling errors in the BIM model by using Model Viewer tools.

The BIM model is created using Autodesk Revit 2018 and this model is then imported to structural engineering software (SCIA Engineer Version 18.1) which supports import of IFC4 data schemas. The following steps are carried out for demonstration of data sharing and to investigate the information mentioned above,

1. A detailed description of data transfer methodology.
2. A complete description of modelled data in Revit.
3. Verification of exported data from Revit to IFC using model view checkers.
4. Guidelines for the successful implementation of data transfer to SCIA Engineer.
5. Investigation of data in SCIA Engineer, which is imported from IFC.

4.1 Research Methodology

The work flow adopted is explained as follows:

1. Firstly, the model is created using the Autodesk Revit 2018 software (Student version). Revit is chosen as a BIM modelling tool as it supports export of data in IFC4 format. The generated model is then exported to IFC file formats (meta-data model schemas). In this work IFC4 – Addendum 2 (IFC4 ADD2) version of OpenBIM standards published in July-2016 is used.

2. Then the model is exported as IFC file format from Revit software. Now, before importing the IFC file to SCIA Engineer, the model is checked by model checkers (In this work FZKViewer-5.2_Build-992 is used, developed by Karlsruhe Institute of Technology which is available freely). In the model checker, the model is investigated for any error or missing entities or issues. In case of any bug, the findings are reported and the model is sent back to Revit for further modifications. This helps the user to rectify the modelling errors in the initial stage of the data sharing process.

3. Now, the IFC file (verified by model checker) is imported to SCIA Engineer software for structural analysis and design. Further verifications regarding the data quality and correctness are performed in SCIA.

Figure 4.1 represents the methodology (the sequence of operations) for data sharing between Revit and SCIA.

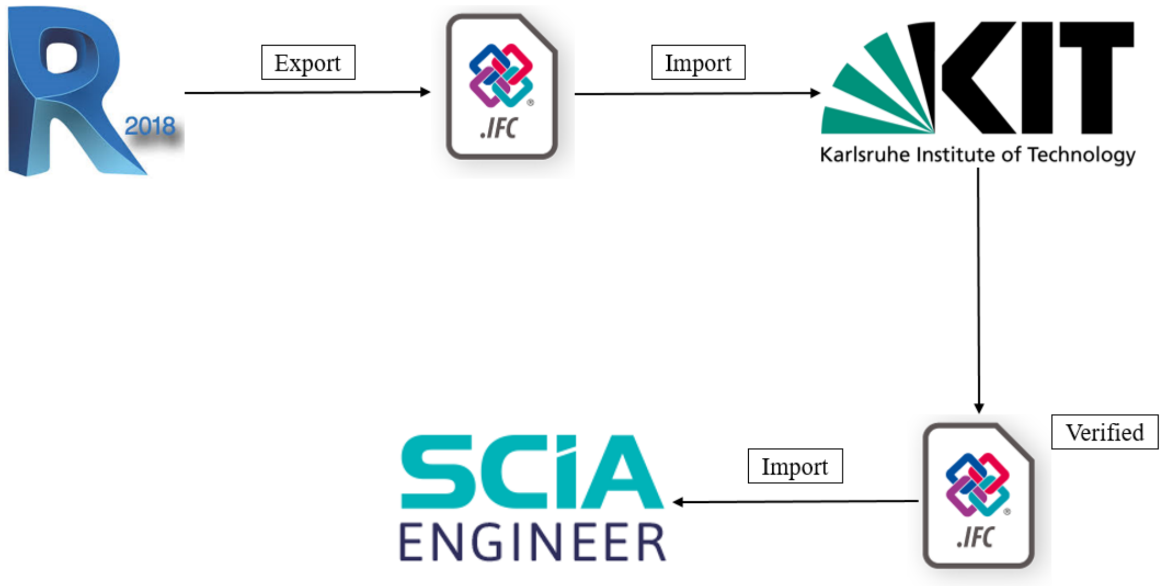


Figure 4. 1: Sequence of operations for demonstration of data sharing

4.2 Revit Model

A three-storey composite structural model is considered for the demonstration of data transfer between Revit and SCIA. The structure is modelled in Revit and geometry is assigned to all structural elements like foundations, beams, columns and slabs. The foundations and first storey is made up of concrete (foundations, beams, columns and slab). The second and third storey is made up of steel (beams, columns and slab). Rectangular steel tube is used for column and I-Sections is used for beams and solid steel plate is used for slab. The structure consists of three bays, the first two consist of floor slabs along with cantilever on one side, while the last one is for stair case hosting. The model is constructed in Revit by using different Revit families. Relevant or similar families are used to construct different building components like beams, columns, slabs, etc. and all these components are interconnected to avoid gaps and overlaps. Revit provides a number of default constructions for each building component, but it also allows the user to define own material, properties, layers and thickness. Figure 4.2 shows the model developed in Revit.

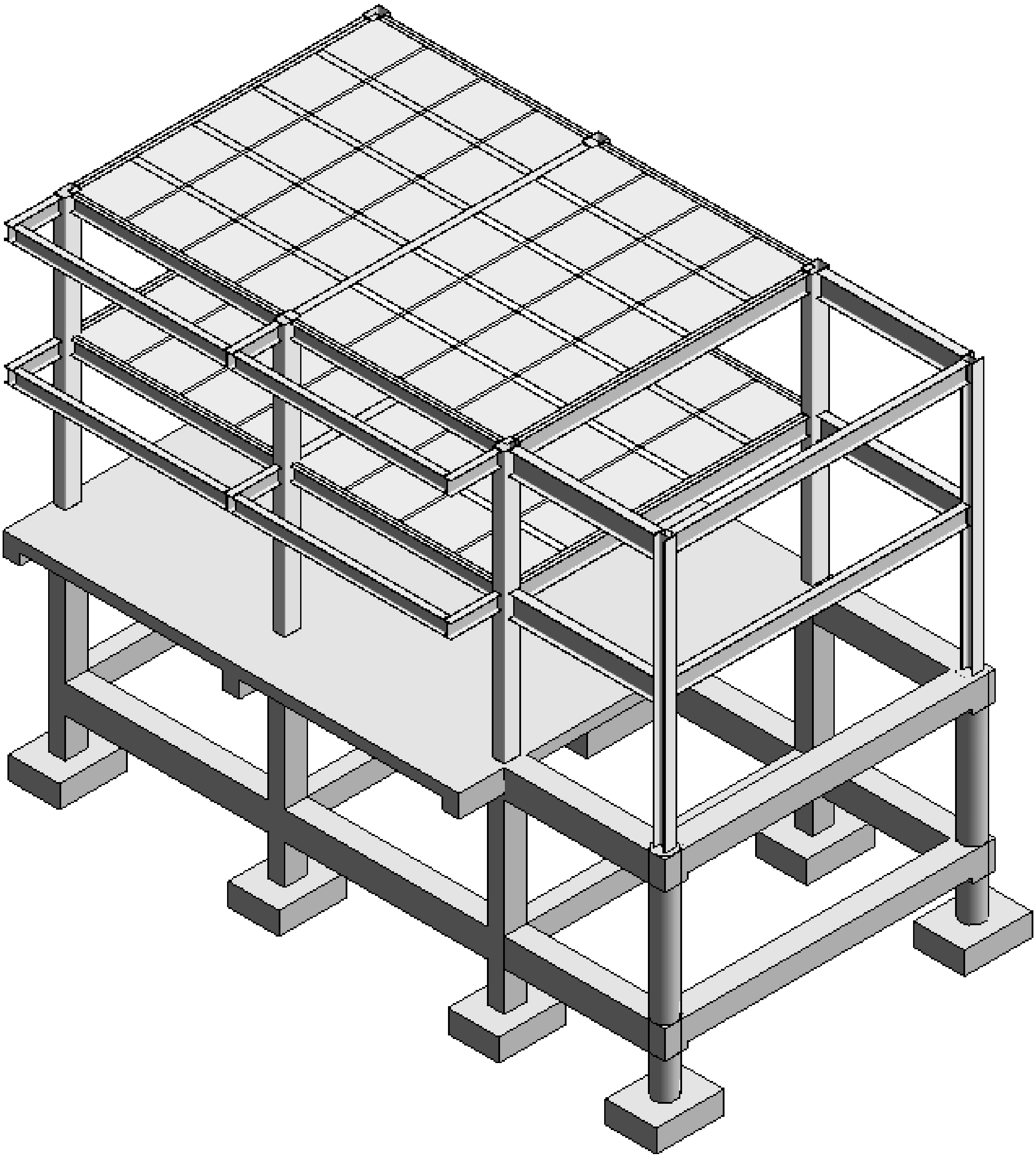


Figure 4. 2: Three Storey composite structure - Revit model

The model is composed of both rectangular and circular columns and beams of various depths are incorporated into the model. A cantilever is also used in the model. The model takes into account the shape and dimensions of various structural elements. Table 4.1 provides a summary of various structural elements modelled in Revit.

Structural Element	Dimention (L×B×H/D in mm)	Material
Foundation	1200×900×400	Concrete (25 Mpa)
Beam - 01	300×400	Concrete (25 Mpa)

Beam - 02	400×500	Concrete (25 Mpa)
Beam - 03	400×400	Concrete (25 Mpa)
Beam - 04	300×500	Concrete (25 Mpa)
Beam - 05	ISMB 250	Steel (345 Mpa)
Beam - 06	ISMB 300	Steel (345 Mpa)
Beam - 07	ISMB 400	Steel (345 Mpa)
Cross Beam (Steel Angle)	50×50×6	Steel (345 Mpa)
Column -01	400×300	Concrete (25 Mpa)
Column -02	300×200×7 (Rect. Hollow Sec.)	Steel (345 Mpa)
Column -03	200×200×14.2 (I Sec.)	Steel (345 Mpa)

Table 4. 1: Construction details of structural elements

4.2 IFC export

Revit offers customized IFC export setup options. Figure 4.3 represents the export parameters mentioned in Revit for IFC export. Based on this parameters Revit will export the modelled data to IFC file. The export parameters are divided into different categories. They are as follows

- General
- Additional content
- Property sets
- Level of detail
- Advanced

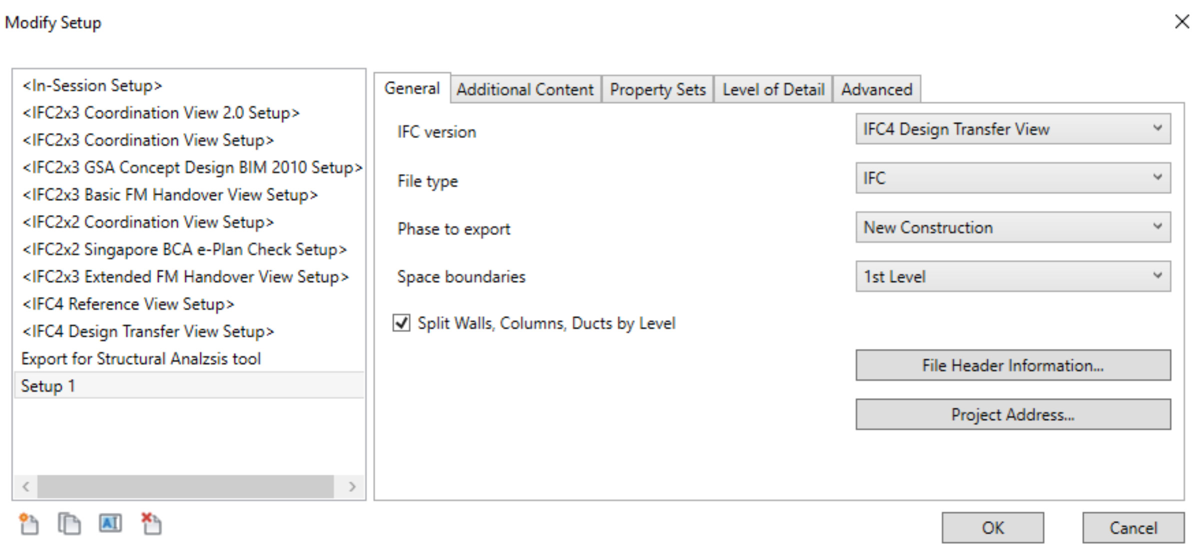


Figure 4. 3: Export parametres in Revit for IFC

Each category has its own importance in the export process, but the General category plays a key role in the export process because it contains information regarding model view, space boundary, and project location and construction phase details. Generally, IFC 4 is equipped with two View Definitions, Design Transfer View (DTV) and Reference View (RV). Design Transfer View allows more entities (such as frame and lining de-tails for doors and windows) for transfer between tools when compared to Reference View, and DTV supports the editing of the IFC file. For IFC export process, Design Transfer View (DTV) is used as Model View Definition.

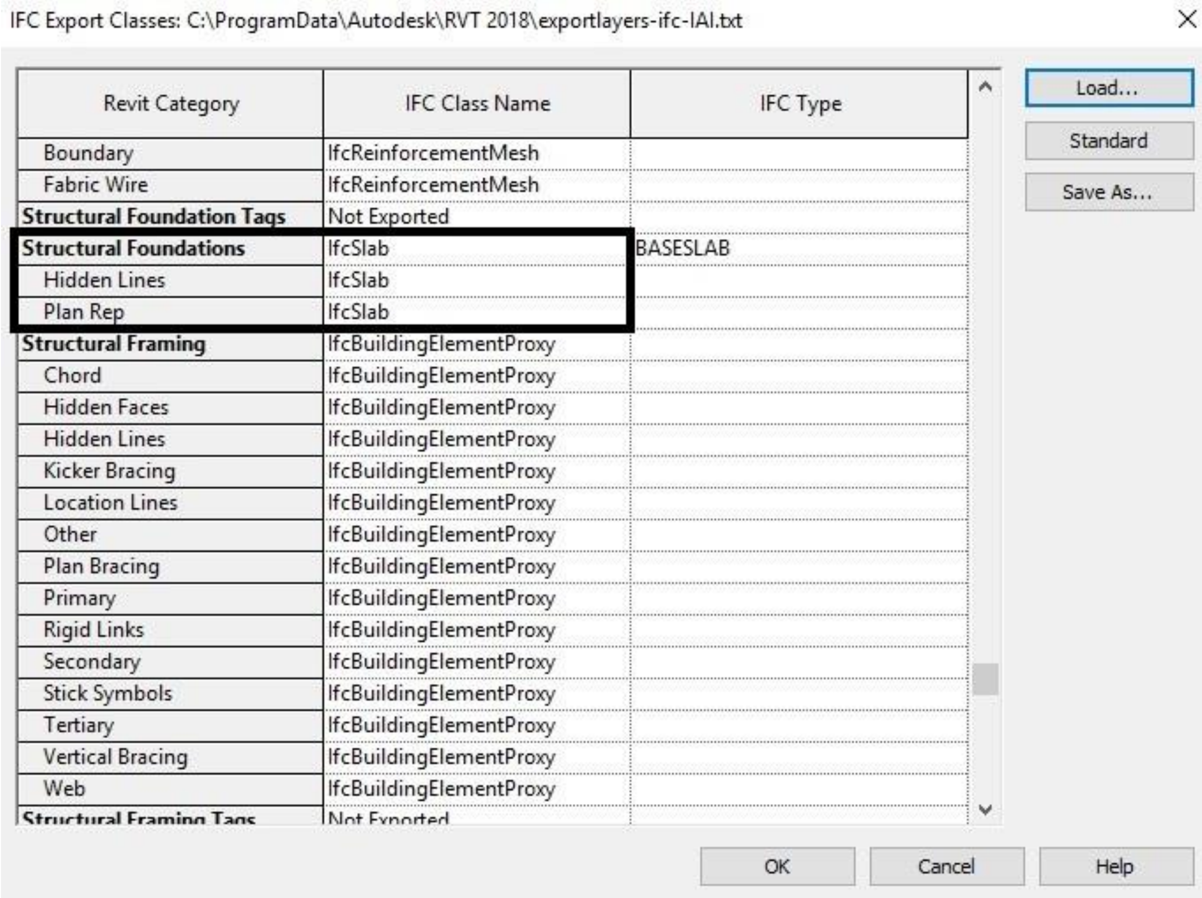
Table 4.2 describes export specifications settings for IFC export.

<table>
<tr><th colspan="2">Export Parameter</th><th>Specification or Value</th></tr>
<tr><td rowspan="4">General</td><td>IFC version</td><td>IFC4 Design Transfer View</td></tr>
<tr><td>File type</td><td>IFC</td></tr>
<tr><td>Phase to export</td><td>New Construction</td></tr>
<tr><td>Space boundary</td><td>1st Level</td></tr>
<tr><td colspan="2">Split Walls, Columns, Ducts by level</td><td>Checked</td></tr>
<tr><td rowspan="3">Additional content</td><td>Export 2D plan view elements</td><td>Disabled</td></tr>
<tr><td>Export linked files as separate IFCs</td><td>Disabled</td></tr>
<tr><td>Export only elements visible in view</td><td>Disabled</td></tr>
<tr><td rowspan="6">Property Sets</td><td>Export Revit property sets</td><td>Enabled</td></tr>
<tr><td>Export IFC common property sets</td><td>Enabled</td></tr>
<tr><td>Export base quantities</td><td>Disabled</td></tr>
<tr><td>Export schedules as property sets</td><td>Disabled</td></tr>
<tr><td>Export user defined property sets</td><td>Disabled</td></tr>
<tr><td>Export parameter mapping table</td><td>Disabled</td></tr>
<tr><td>Level of Detail</td><td>Level of detail for element geometry</td><td>High</td></tr>
<tr><td rowspan="8">Advanced</td><td>Export parts as building elements</td><td>Disabled</td></tr>
<tr><td>Allow use of mixed “Solid Model” representation</td><td>Disabled</td></tr>
<tr><td>Use active view when creating geometry</td><td>Disabled</td></tr>
<tr><td>Use family and type name for reference</td><td>Disabled</td></tr>
<tr><td>Use 2D room boundaries for room volume</td><td>Disabled</td></tr>
<tr><td>Include IFCSITE elevation in the site local placement origin</td><td>Disabled</td></tr>
<tr><td>Store the IFC GUID in an element parameter after export</td><td>Disabled</td></tr>
<tr><td>Export bounding box</td><td>Disabled</td></tr>
</table>

Table 4. 2: IFC export specifications

Revit consists of default export layers, which consist of the data regarding the IFC classes with respect to the Revit element categories modelled in the file. The initial step in the export process is to load the export layers into Revit. Figure 4.4 represents the default IFC export layer file in Revit 2018. Note that Structural foundation is mapped to IfcSlab, this is changed to IfcFooting during export process to IFC.

After finishing the IFC-export set up the process, the modelled data has been exported to IFC (STEP – physical file format) file and the same file imported to the Model viewer tool to verify the data quality and modelling errors. The exported IFC file is attached in Appendix A for reference.

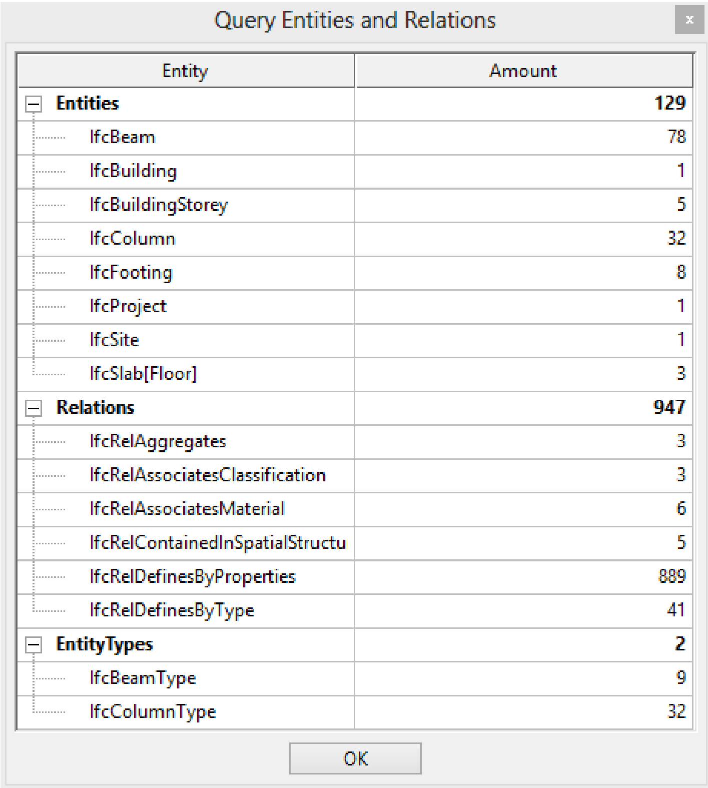


Revit Category	IFC Class Name	IFC Type
Boundary	IfcReinforcementMesh	
Fabric Wire	IfcReinforcementMesh	
Structural Foundation Tags	Not Exported	
Structural Foundations	IfcSlab	BASESLAB
Hidden Lines	IfcSlab	
Plan Rep	IfcSlab	
Structural Framing	IfcBuildingElementProxy	
Chord	IfcBuildingElementProxy	
Hidden Faces	IfcBuildingElementProxy	
Hidden Lines	IfcBuildingElementProxy	
Kicker Bracing	IfcBuildingElementProxy	
Location Lines	IfcBuildingElementProxy	
Other	IfcBuildingElementProxy	
Plan Bracing	IfcBuildingElementProxy	
Primary	IfcBuildingElementProxy	
Rigid Links	IfcBuildingElementProxy	
Secondary	IfcBuildingElementProxy	
Stick Symbols	IfcBuildingElementProxy	
Tertiary	IfcBuildingElementProxy	
Vertical Bracing	IfcBuildingElementProxy	
Web	IfcBuildingElementProxy	
Structural Framing Tags	Not Exported	

Figure 4. 4: IFC export Layers mentioned in Revit 2019

4.3 Verification (FZKViewer)

After successfully exporting the model from Revit into IFC format. The IFC file is checked into model viewers for modelling errors. Figure 4.4 gives a summary of entities and relations exported in to IFC file format. It can be seen that there are a total number of 8 footings, 78 beams, 32 columns and 3 slabs are exported. Figure 4.5 shows the model as interpreted by FZK model viewer. On examining the entities it can be seen that there is some problem with beam connected to circular column. Figure 4.6 shows the zoomed view of the problem. Other geometry and dimension of structural elements are found to be exported correctly. The beam to circular column connection error is noted and the circular column is replaced with rectangular column. Now, the model is modified with rectangular column in place of circular column in Revit and is again exported to IFC and checked into FZK model viewer (Figure 4.7) and found correct.



Query Entities and Relations

Entity	Amount
Entities	**129**
IfcBeam	78
IfcBuilding	1
IfcBuildingStorey	5
IfcColumn	32
IfcFooting	8
IfcProject	1
IfcSite	1
IfcSlab[Floor]	3
Relations	**947**
IfcRelAggregates	3
IfcRelAssociatesClassification	3
IfcRelAssociatesMaterial	6
IfcRelContainedInSpatialStructu	5
IfcRelDefinesByProperties	889
IfcRelDefinesByType	41
EntityTypes	**2**
IfcBeamType	9
IfcColumnType	32

OK

Figure 4. 5: Summary of entities and Relations

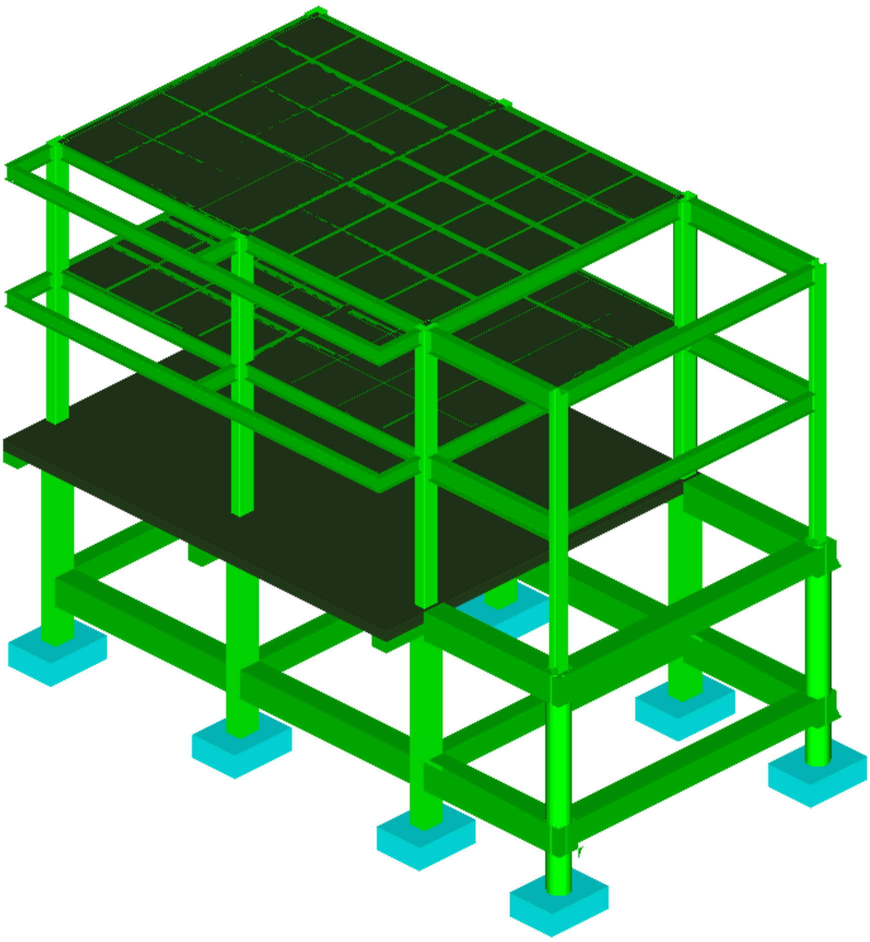


Figure 4. 6: IFC model in FZK viewer

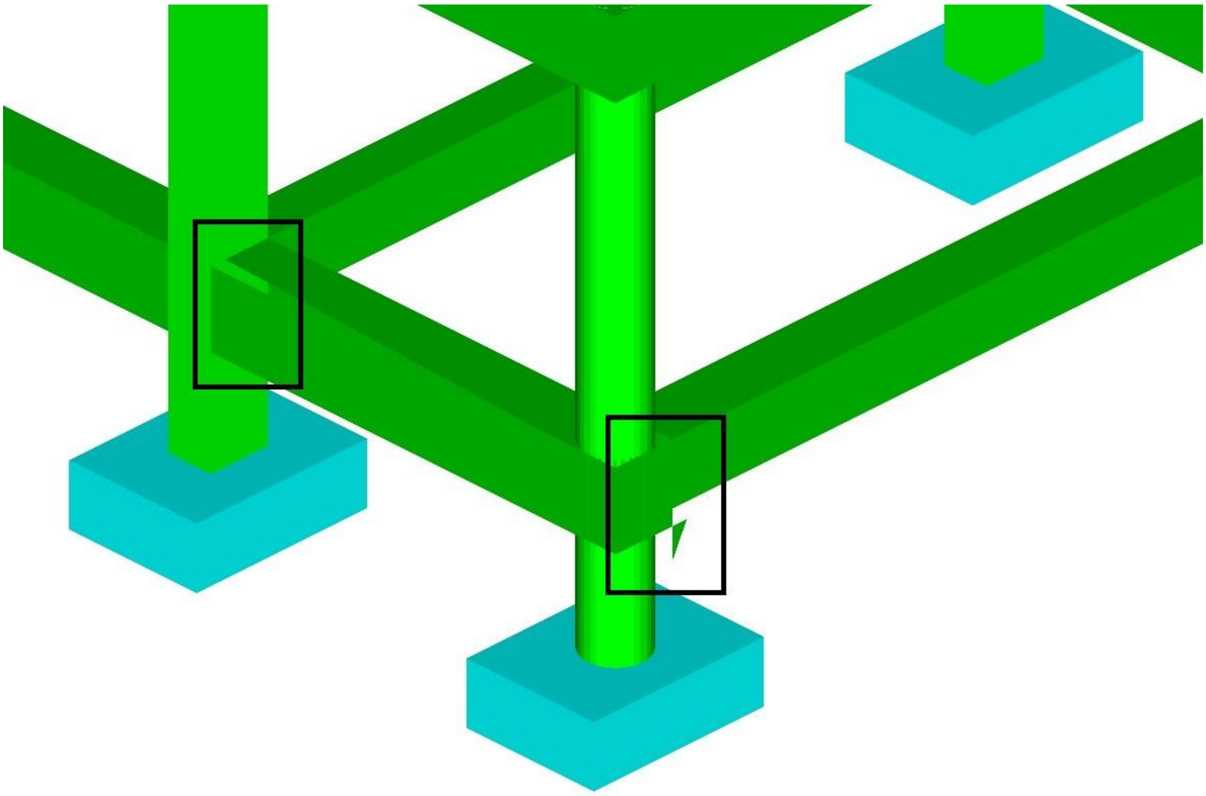


Figure 4. 7: Connection of beam to circular column error

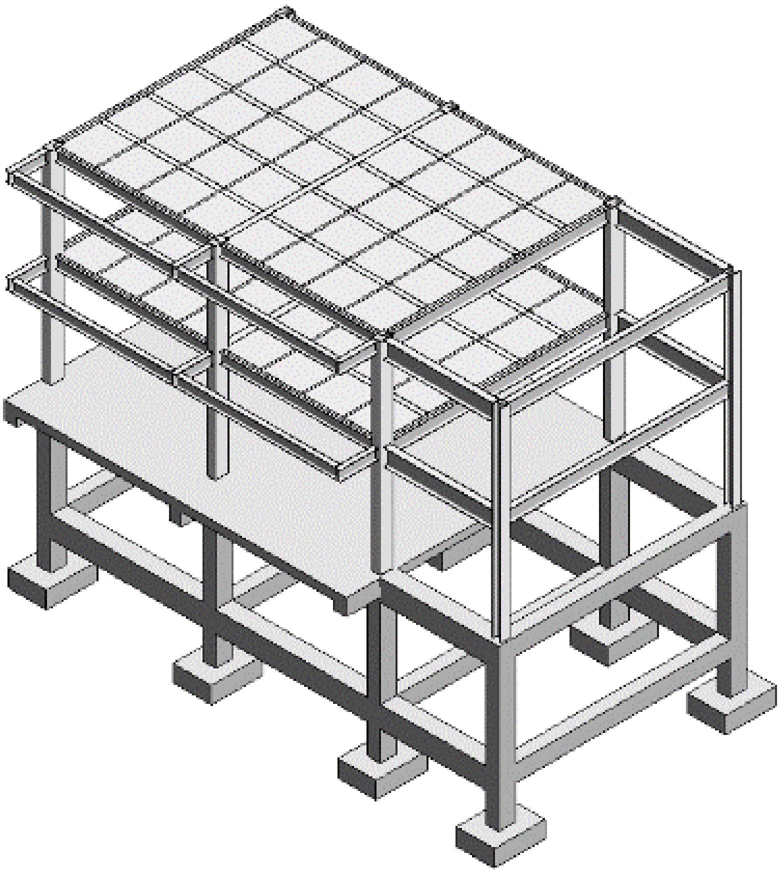


Figure 4. 8: Circular column is replaced with rectangular column - Revit Model

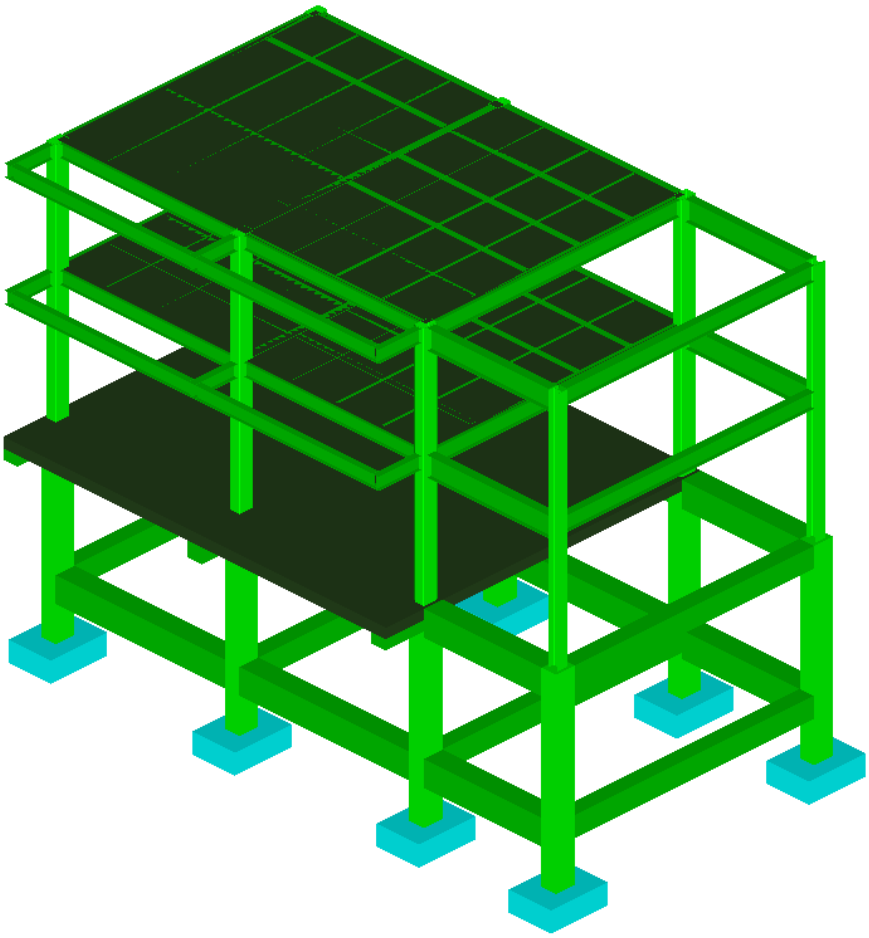


Figure 4. 9: Circular column is replaced with rectangular column - FZK Viewer

4.4 Import to SCIA Engineer

After verification of the quality of input data using Model Viewer tool, the data has been transferred to SCIA Engineer. This section investigates the data import capabilities of SCIA from IFC and the quality of imported data. SCIA gives an import statistics after every successful import IFC file. When the IFC file is imported with circular columns it is unable to read beams connecting to that column, SCIA shows the error as missing or unsupported geometry.

After replacing circular columns with rectangular columns, the model is again imported into SCIA software. Figure 4.9 shows the import statistics of SCIA engineer with rectangular columns. Note that SCIA has replaced Revit exported materials with their default one. However there is no error with import of any entities.

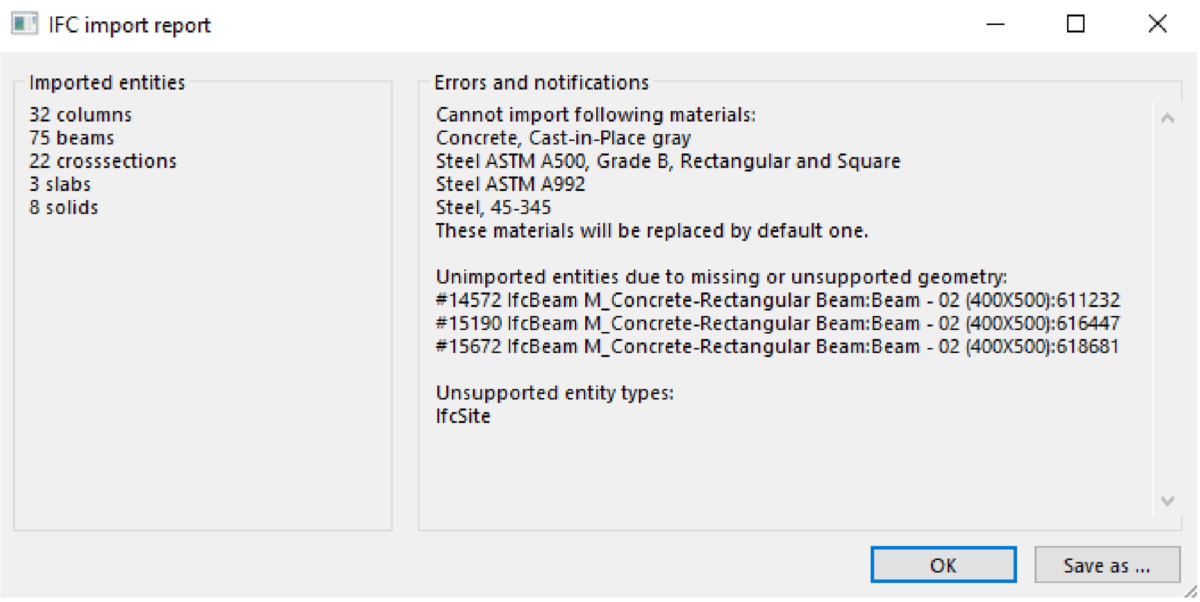


Figure 4. 10: Import statistics of SCIA engineer (With circular columns)

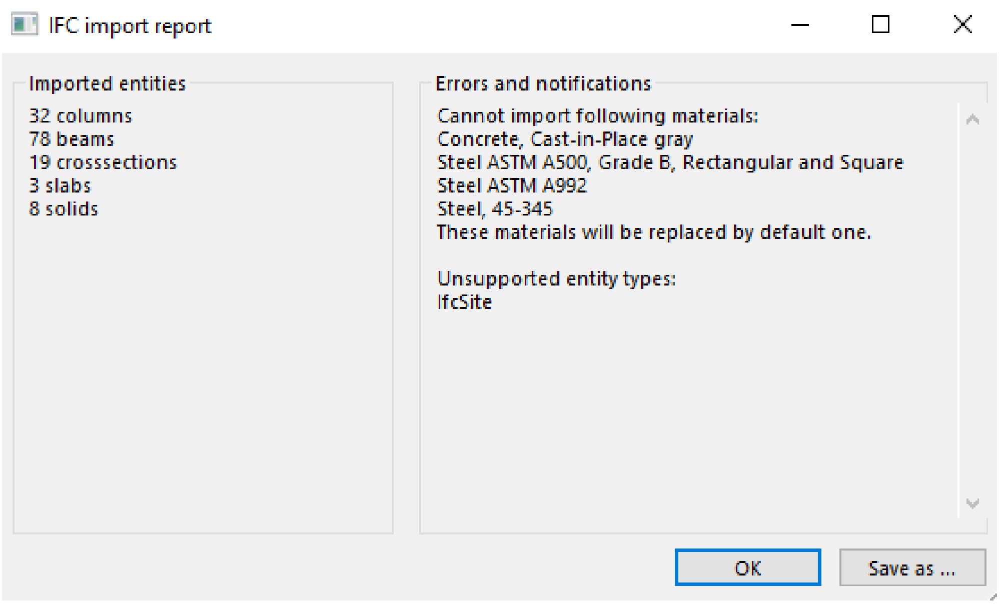


Figure 4. 11: Import statistics of SCIA engineer (With rectangular columns)

The structural analysis in SCIA is carried out using analytical model. Figure 4.10 shows the model imported into SCIA. It can be seen that SCIA has converted into analytical model. The nodes can be seen disjointed. When load is applied over the structure and stability analysis is carried out it gives the result, that structure is unstable in vertical direction. This is due to the fact that nodes are not joined at one point.

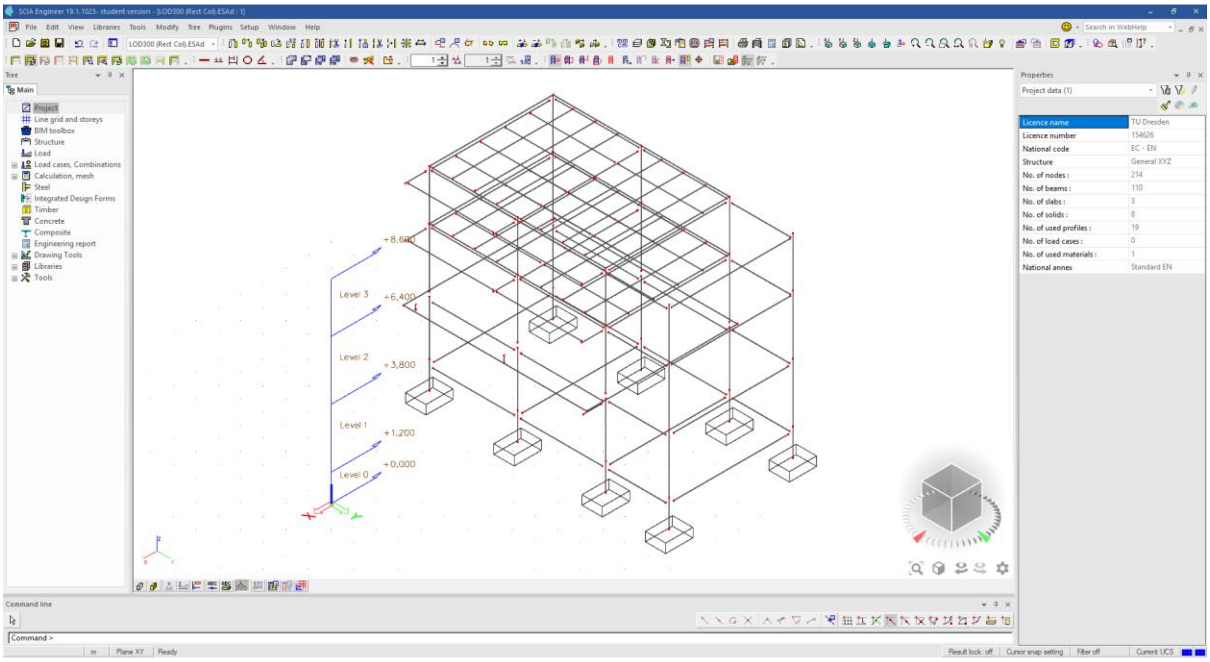


Figure 4. 12: Imported model into SCIA (Analytical Model)

5. Results and Discussions

The results analysis is carried out to explain the data quality and the interoperability problems between the BIM tool and structural analysis software.

The first problem was found in default export layers of Revit for IFC data transfer, the Revit element structural foundation was mapped to IfcSlab by default in export layer, which was modified to IfcFooting.

The second problem was found in connection of rectangular concrete beam to circular concrete column. Revit IFC manual describes three basic possibilities for Geometric representation of three-dimensional IFC objects as:

- extrusions
- solid body representation using a sweep, and
- representation using B-reps

B-rep: The method known as boundary representation (B-rep) can also be described as a boundary surface model. The surfaces of a component are represented using coordinates and together form the actual solid, allowing even complex forms to be represented.
B-rep objects use complex calculations to represent individual surfaces in detail.

NURBS and other smooth surfaces
In the IFC4 schema, it is possible to generate B-rep objects as advanced B-reps using NURBS (non-uniform rational B-splines) surfaces. The bodies are represented more accurately.

The IFC4 documentation describes an entity called IfcAdvancedBrep under IfcGeometricModelResource in the Resource definition data schemas. The entity is defined as, an advanced B-rep is a boundary representation model in which all faces, edges and vertices are explicitly represented. It is a solid with explicit topology and elementary or free-form geometry. The faces of the B-rep are of type IfcAdvancedFace. An advanced B-rep has to meet the same topological constraints as the manifold solid B-rep. The advanced B-rep has been introduced in order to support the increasing number of applications that can define and exchange B-rep models based on NURBS or other b-spline surfaces.

In our model, on examining the ifcxml file it was found to use IfcAdvancedBrep for model geometry. Note that typically software supporting IFC only implement model view definitions a subset of IFC. So, the shape representation we are trying is not recognizing as it's beyond the model view definition, or perhaps they just don't recognize IfcadvancedBrep at all in IFC4 ADD2 DTV. Also there is no documentation available for IFC4 DTV to verify for IfcadvancedBrep. DTV is summarized as on building smart website as “Advanced geometric and relational representation of spatial and physical components to enable the transfer of model information from one tool to another. Not a "round-trip" transfer, but a higher fidelity one-way transfer of data and responsibility". However, the documentation available for IFC4 RV doesn't contain IfcadvancedBrep.

The third problem was found in SCIA software. SCIA uses analytical models for structural analysis. After importing the model into SCIA the nodes are found to be disjointed. This is due to SCIA has taken end to end distance as centre line of member for creating analytical model. Due to this at junctions all member ends doesn't joins at one point. And when structural analysis is carried out it give the result the structure is unstable.

Figure 5.1 explains how nodes can be joined at one point, if the SCIA allow some overlapping geometry of structural elements. If we don't allow overlapping in 3D model then we cannot achieve joining of nodes at common point.

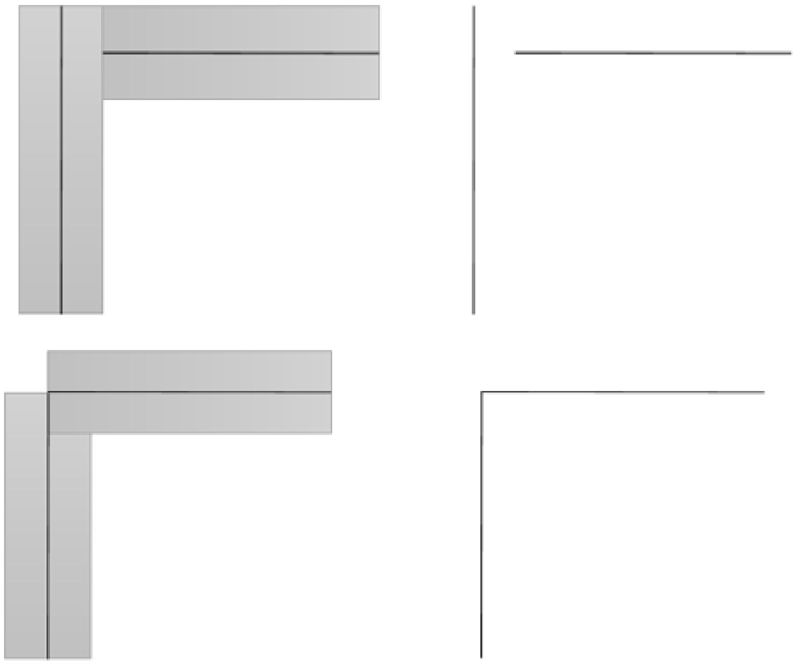


Figure 5. 1: Nodes dislocation due to non-overlapping members (Above) and nodes are joint at one point due to overlap of members (Below)

6. Conclusions and Outlook

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