TECHNISCHE UNIVERSITÄT DRESDEN

FakultätBauingenieurwesen Institut für Bauinformatik

An approach to Open-BIM based Construction Project Management.

Master Thesis

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Topic for the Master Thesis

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Title: An approach to Open-BIM based Construction Project Management

Entwicklung methodischer Ansätze für open-BIM-basierte Anwendungen im Baubetriebswesen

Goal:

Adding construction project management parameters to a BIM model would mean adding an extra dimension to the BIM model. To exchange and share data between different departments and to effectively use this data is one of the crucial challenges the AEC industry is facing. Hence, it is necessary to find a method to optimize the process of data management for integrated project delivery.

This Thesis aims to investigate the current IFC meta-data model and to propose methods to integrate construction project management data in a flexible, parametric way.

The student is expected to conduct research on IFC modelling methods, and to develop a concept and method to integrate construction project management data to the IFC model structure. This will include methods to import data from a project management platform into a BIM model in IFC format.

Finally, the student is expected to study and analyse the existing IFC meta data model and to analyse the flexibility of the IFC meta data model to support the integration of construction project management data in a flexible, parametric way.

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

Scope of the Work:

The below items shall be discussed in the Thesis.

1. Develop an overview of IFC-modelling methods. Implement a logical and relational data model based on IFC relevant for construction project management.
2. Analyse the construction project management information sharing between multiple organizational units, i.e. to specify what kind of data should be provided to whom. This shall include an analysis of how to import data from a Project Management tool into a BIM model constantly evaluating the quality of data and propose methods to improve the quality of data.
3. Analyse the degree of flexibility for the integration of construction project management data into the existing IFC data model.
4. Develop a demonstration for integrating construction project management data into a BIM model and managing the data in IFC format.
5. It is recommended to use REVIT, Dynamo for REVIT, SQL Developer Data Modeler and Oracle as tools for the implementation.

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Declaration

I hereby declare that the Master Thesis work entitled “An approach to Open-BIM based Construction Project Management ”(Entwicklung methodischer Ansätze für open-BIM-basierte Anwendungen im Baubetriebswesen) which is being submitted in partial fulfillment of the requirements for Masters of Science in Advanced Computational and Civil Engineering Structural Studies in Technische Universität Dresden, is carried out by me. I confirm that the report has been independently written and the sources used have been specified.

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

Dresden, 07.01.2019

Signature

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Abstract

Construction Project Management (CPM) is a vast and complex discipline in Architecture, Engineering and Construction industry. The virtue of complexity in construction projects demands extensive research and efforts in formulate new organizational structures, techniques and other important methods towards the efficient management of construction activities. Moreover, there is a pressing need to devise new ways to integrate the construction management disciplines into Building Information Modeling (BIM) as BIM holds the key to the future of seamless interaction of the various participants in a construction project. One such innovation comes with the introduction of Integrated Project Delivery. This is geared towards integration of people, resources and business practices that can translate into a more efficient version of the existing ones.

As a part of ongoing research, this Master thesis aims to integrate the Cost Schedule Information and Time Schedule Information with BIM since these are deemed to be one of the most challenging and dynamic aspects in construction project management. In an attempt to achieve successful integration, two methodologies were designed to add Time Schedule Information and Cost Schedule Information separately to the generated open BIM models. From the two methodologies adopted, no difficulties were recorded in the model generation phase of 3D,4D and 5D data. However, there were limitations in 4D and 5D models in terms of exporting the model data in the open BIM format. Ultimately, it was found that the Model Definition View and the software's compatibility in mapping MVD with the existing 4D or 5D data in software's are crucial in successful generation of 4D and 5D models in open BIM format.

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Nomenclature

3D Three Dimensional

4D Fourth Dimension

5D Fifth Dimension

AEC/FM Architecture, Engineering, Construction/Facility Maintenance

AECO Architecture, Engineering, Construction and Operation

AIA American Institute of Architects

BIM Building Information Modeling

CIB Construction Industry Board

CIC Construction Industry Council

CM Construction Management

CPM Construction Project Management

DB Design-Build

DBB Design-Bid-Build

ER Exchange Requirement

ERM Exchange Requirement Model

FP Functional Part

GML Geographic Markup Language

GPP Generic Process Protocol

HOAI Honorarordnung für Architekten und Ingenieure

IDM Information Delivery Manual

IFC Industry Foundation Classes

IPD Integrated Project Delivery

ISO International Organization for Standardization

LOD Level of Development

MDS Model Development Specification

MVD Model View Definition

NBIMS National Building Information Modeling Standard

OGC Open Geo-spatial Consortium

PACE Property Advisers to the Civil Estate

PM Project Manager

RIBA Royal Institute of British Architects

STEP Standard for the Exchange of Product Data

UK United Kingdom

1 Introduction

In the beginning of 1950's project management came into picture to use it on large defense projects at first time[20]. Later on, small and large scale industries adopted the methodology project management. The complexities of construction projects always demand new organizational structures, techniques and procurement methods to manage the construction works.

The Architecture, Engineering, Construction/Facility Maintenance (AEC/FM) industry is fragmented due to the many participants and stages involved in construction projects. Program Evaluation and Review Technique, the Critical Path Method technique gave great control over construction projects to managers. Later the AEC/FM industry started using traditional procurement methods and information technology in the construction process. It increase the quality of work and reduced documentation errors. But these methods failed to increase labor efficiency and decrease productivity problems. According to statistics, 70 percent of construction projects are over budget and delivered late[21].

Recently, a new method called Integrated Project Delivery(IPD) is used to manage projects in the AEC/FM industry. This method aims to integrate people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction. To achieve this goals, IPD is adopting another new process called Building Information Modeling.

Building Information Modeling (BIM) is process of identifying players, their requirements, deliverable's with the help of distinctive layers of analysis with interaction of policy and technology fields, generating the building data which have ability to perform tasks and managing it in a usable digital format throughout the life cycle of a built artefact. Therefore, this work explores current project management methods and BIM. It proposes Open-BIM methodology for Construction Project Management (CPM).

The thesis is structured as follows:

The first chapter provides an introduction to project management, organizational structures and the different stages involved in CPM according to standard and local protocols, project delivery methods and case studies. The case studies and literature review on CPM are elaborated. In addition to this problem statement, possible solution is proposed for thesis work. It further explains the thesis objectives and conclusion statements for each chapter.

The second chapter gives a brief introduction to BIM and the Industry Foundation Classes(IFC) frame work. It also explains Open-BIM data models.

The third chapter addresses information required to develop Open-BIM data model and explains logical relationships between them.

The fourth chapter describes the methodology to integrate project management parameters into BIM architectural models and to implement this methodology using BIM tools.

The fifth chapter lists and describes the results of the thesis. Especially, it focuses on interoperability problems between different BIM tools to share information between them.

The sixth chapter concludes the thesis work and summarizes the result.

1.1 Construction Project Management

The aim of this section is to present the main concepts related to Construction Project Management. First, the definition of Construction Project Management is given. Life cycle of construction project management is discussed. Moreover, the other sections are dedicated to the traditional project delivery methods and innovative project delivery methods and its differences. Finally, the possibilities and challenges related to CPM with BIM are presented.

1.1.1 Definition

The term project management or construction project management has various definitions depends on the nature and type of project. Irrespectively, project management is management of a project from its inception stage to demolition stage. Some well known definitions are listed as follows.

"The project management is the application of knowledge, skills, tools, and techniques to project activities to meet project requirements"[11].

"The planning, co-ordination and control of a project from conception to completion (including commissioning) on behalf of a client requiring the identification of the client's objectives in terms of utility, function, quality, time and cost, and the establishment of relationships between resources, integrating, monitoring and controlling the contributors to the project and their output, and evaluating and selecting alternatives in pursuit of the client's satisfaction with the project outcome."[27].

1.1.2 Life cycle of construction project management

The project considers specific activities for the completion of construction projects. The activities take or place in the project will vary widely from project to project. So, every project needs fundamental structure to manage the whole project irrespectively of specific work involved. This can be achieved by project life cycle methodologies.

A life cycle of construction project management is "a collection of generally sequential project phases whose name and number are determined by the control needs of the organization or organizations involved in the project. A life cycle can be documented with a methodology"[25].

The project life cycle is categorized into phases or stages. This depends upon project size, type, risk...etc. Stages are sub divided into sub stages. The following section provides the information regarding the stages of project life cycle.

1. **Project Stage**

For the purposes of developing a basis for subsequent definitions of roles, it is important to develop a terminological structure for the names of distinctive stages through which a project typically progresses. This will enable participants' roles to be developed in relation to the output of each stage. Project stages are "a collection of logically related project activities, usually culminating in the completion of a major deliverable"[25, 15]. The completion of project stages are done sequentially and in some situations it can overlap. Phases can be sub divided into sub phases and then into components. A project stage is a component of the project life cycle and it is not a management process group of a project[15]. The RIBA plan of work 2013 project stages are shown in Fig. 1.

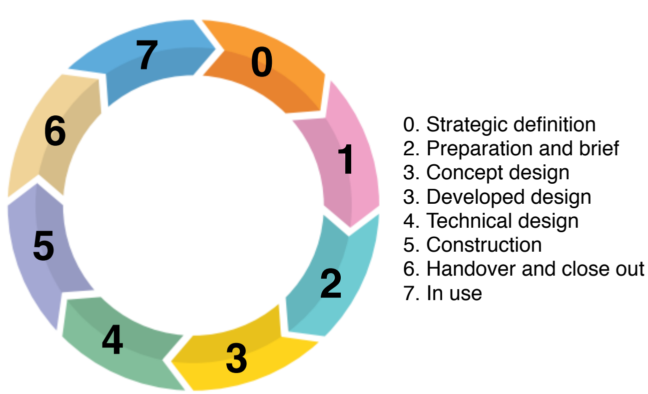


Figure 1: Project stages for RIBA plan of work 2013[22]

a) Standard life cycle stages:

Standards give world-class specifications for processes to ensure quality, safety and efficiency. They are instrumental in facilitating consistency in the process.

Life cycle stages should always be defined on a common basis. For the purpose of primary reference to identifying life cycle stages in any project, ISO 22263 suggests the six principal life cycle stages as follows[25]:

- Inception
- Brief
- Design
- Production
- Maintenance
- Demolition.

For the purposes of information delivery manual standards, the principal stages identified in ISO 22263 are further divided. This set of stages will be used to develop the process maps and exchange requirements for the building information modeling process. The decomposed stages are shown in table 1 with a cross reference to ISO 22263 stage name.

Table 1: Standard life cycle stages[25]

Reference Number	International Standard Stages	GPP Project Stages
1	Inception	Portfolio requirements
2	Brief	Concept of need
		Outline feasibility
		Substantive feasibility
3	Design	Outline conceptual design
		Full conceptual design
		Coordinated design
4	Production	Production Information
		Construction
5	Maintenance	Operation and maintenance
6	Demolition	Disposal

b) Local life cycle stages:

Project life cycle stages differ from one place to another place. So, identification of life cycle stages will be done according to local process protocols. These are called local life cycle stages. For example, project development is often organized according to the RIBA Plan of Work within the UK and according to the HOAI protocol in Germany[25].

Some of similar local life cycle stages practiced in United Kingdom and Germany are compared in the table 2.

Table 2: Local protocol stages[8][13]

Reference Number	CIC	CIB	PACE	HOAI
1	A & B Appraisal and Strategic briefing	Getting started	Stage 1	Programming

Reference Number	CIC	CIB	PACE	HOAI
2		Defining the project		
3	C Outline proposals	Assembling the team		Planning for preliminary design
4	D Detailed proposal		Stage 2	Planning for conceptual design
5	E Final proposals			Planning for submission and permission
6	F1 Production information			Planning for execution documents
7	F2 Production information			
8	G Tender documentation			Prepare tendering
9	H Tender action		Stage 3	
10	J, F2 & K Mobilization, post production information and construction			
11		Designing and constructing	Stage 4	Participate contract agreement
12			Stage 5	Control assembly
13		Completion and evaluation		Handover and documentation

c) Mapping between standard project stages and local project stages:

To maintain consistency in the process, it is always recommended to modify a standard process to reflect local process in a localized exchange requirement. That is, the standard life cycle stages can be replaced by a locally defined stages. The exchange requirements in each stage between the participants can be defined according to this local protocol. Where local protocols are used, the mapping between the stages in the local protocol and those within this part of ISO 29481 should be maintained. Either — a single standard stage is decomposed into multiple stages in the local protocol, or — multiple standard stages are composed into a single stage in the local protocol.

Standard stages and local protocol stages should always conform to boundaries such that there is a one:one, one:many or many:one relationship between them. Life cycle stages should not cross boundaries, such that a stage in a local protocol starts part way through one standard stage and ends part way through another standard stage[25].

For Example, mapping between the ISO 29481 standard stages and HOAI Germany local stages are shown in the Fig. 2.

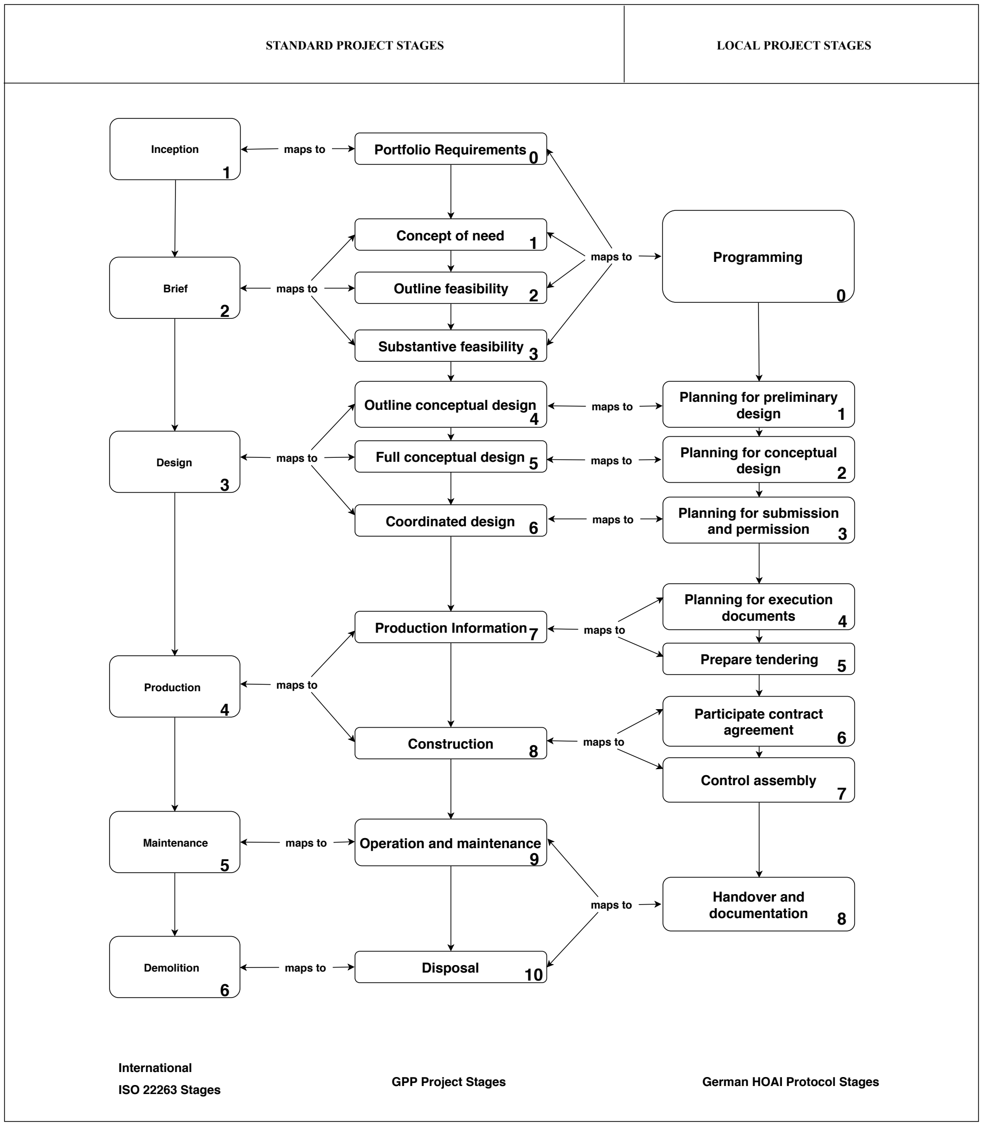


Figure 2: Mapping between standard project stages and local projec stages[13]

1.1.3 Construction project management organization structure

In order to execute construction projects successfully, it is imperative to have organizational structures. Over the last three decades, there have been constant improvements and innovations. Some of which have quite created a breakthrough in the development of new organizational structures. Currently, there are three project management structures which have gained a wide acceptance by organizations which employ them at various levels. These structures are namely :

- Functional
- Project related structures
- Matrix

Functional organizations are marked by a vertical structure with long lines of communication and a long chain of command. The functional structure places the project to be managed inside one of the technical departments of the company. So, the project responsible is the functional manager of this department. In the functional organization, the scope of the project is limited to the boundaries of the function. The schematic representation of functional organizations is shown in the Fig. 3.

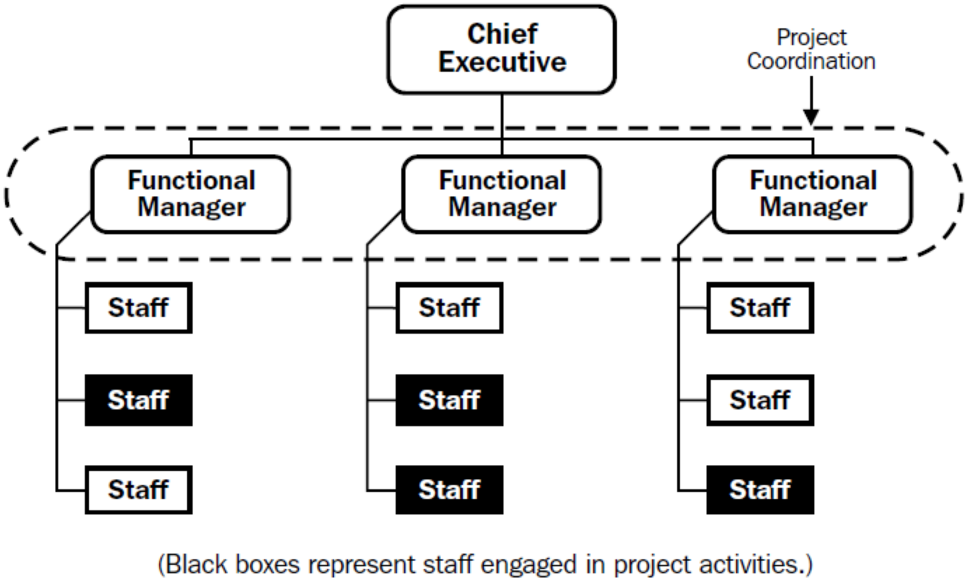


Figure 3: Functional Organization[15]

The projectized organization is that a unique role, the project manager (PM), keeps a complete authority over the project as a whole and team members are often collimated. Besides that, organizational units called departments will report to the PM or assist in the various projects. The typical organizational structure can be seen in the Fig. 4.

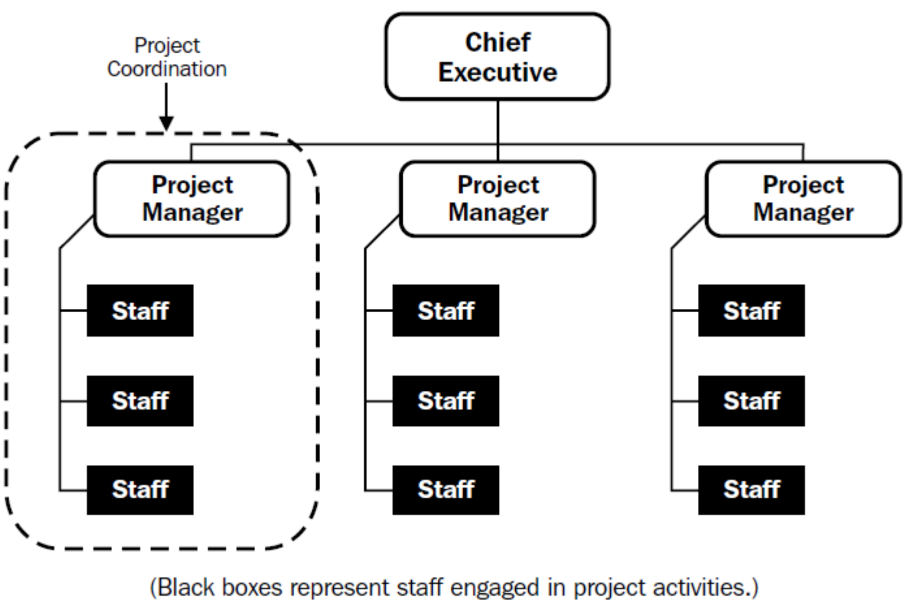


Figure 4: Projectized organization[15]

The matrix structure combines the functional and the project based structure to create a hybrid structure with characteristics of the two mother-structures. In parallel to the functional structure, under the responsibility of the functional managers, project's groups are created under the responsibility of the project managers. The matrix structure could present itself in different formats: weak matrix structure, balanced matrix structure and strong matrix structure. The pictorial illustration of the strong matrix organization is shown in Fig. 5.

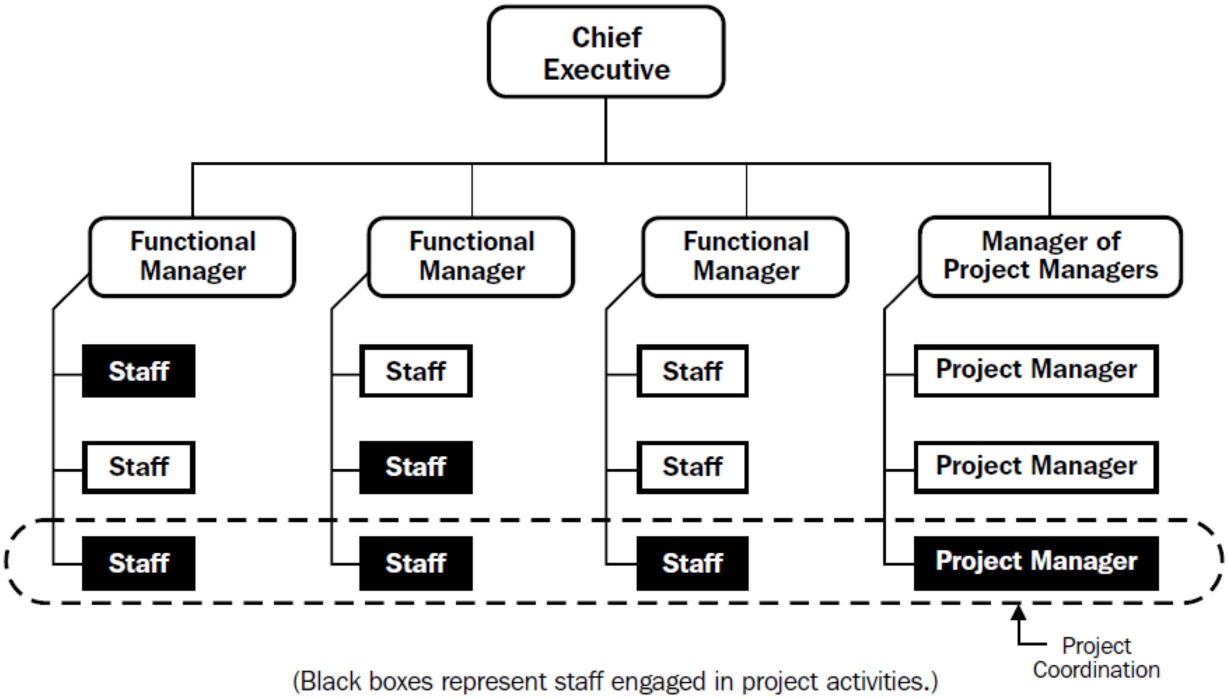


Figure 5: Strong matrix organization[15]

The projects are influenced by organizational structures and these are discussed in Fig. 6.

Project Characteristics \ Organization Structure	Functional	Matrix			Projectized
		Weak Matrix	Balanced Matrix	Strong Matrix	
Project Manager's Authority	Little or None	Limited	Low to Moderate	Moderate to High	High to Almost Total
Percent of Performing Organization's Personnel Assigned Full Time to Project Work	Virtually None	0–25%	15–60%	50–95%	85–100%
Project Manager's Role	Part-time	Part-time	Full-time	Full-time	Full-time
Common Titles for Project Manager's Role	Project Coordinator/ Project Leader	Project Coordinator/ Project Leader	Project Manager/ Project Officer	Project Manager/ Program Manager	Project Manager/ Program Manager
Project Management Administrative Staff	Part-time	Part-time	Part-time	Full-time	Full-time

Figure 6: Organizational structure influences on projects[15]

1.1.4 Typical construction organization chart

Over the recent years, it has been crucial to understand the development, design and implementation of the construction information systems. However, areas pertaining to interactive management systems, resource allocation, advanced database management in the construction industry are still in the nascent stages of development. Consequently, more resources and efforts are underway to address these areas as well as the definition, types and utilities involved in the same. One such effort was made by Kwaku A Tenah where he interviewed the decision makers and non-decision makers of some organizations to understand the hierarchical intricacies and developed a hierarchical system with the aid of the matrix organization structure.

The figure below is the resultant of the proposed solution in the form of a flow chart representing the hierarchical system as well as the flow of information among the various participating members.

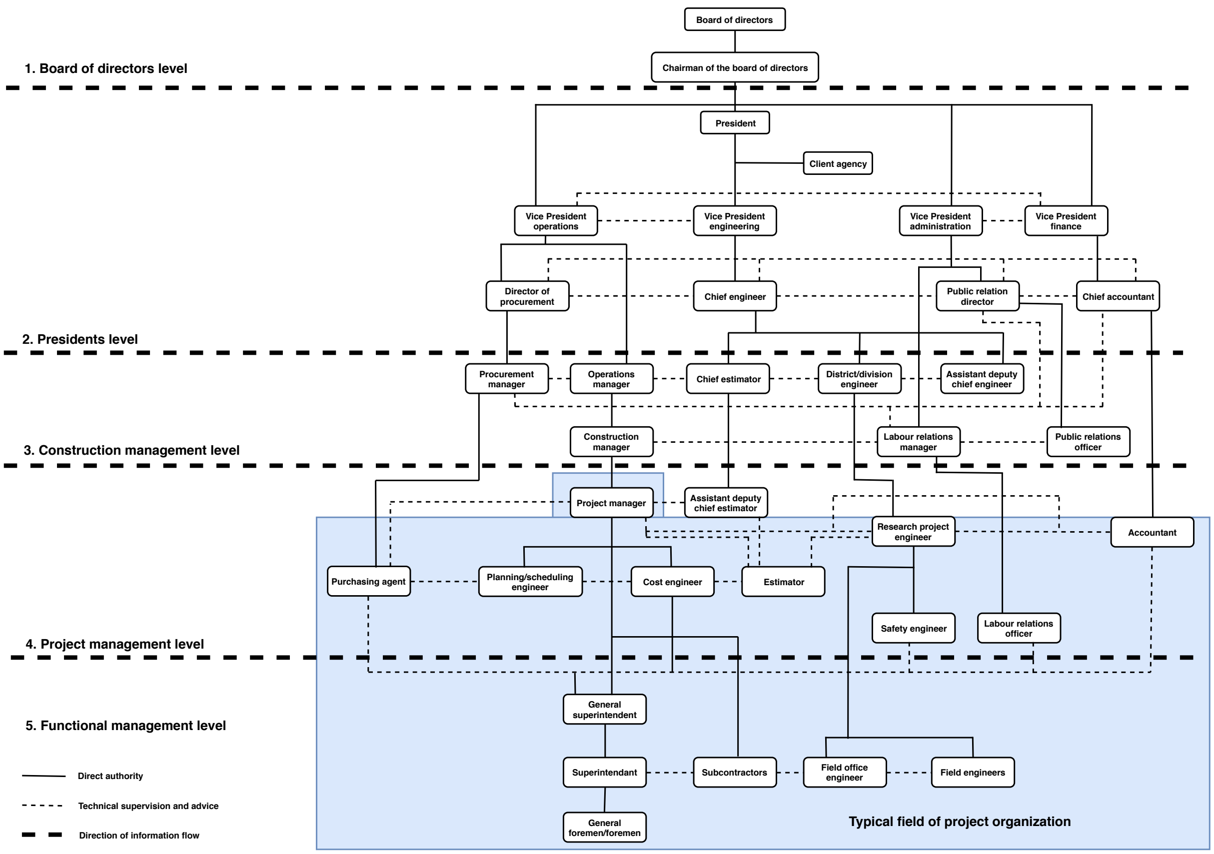


Figure 7: Typical construction organization chart[26].

1.1.5 Traditional Project delivery Methods for construction project management

The number of people involved and the information exchanged in large scale projects are nearly the same according to statistics[6]. So it is not easy to manage such a large number of people and documents without proper project delivery or contractual methods.

Some of the well known traditional contractual methods are listed below. Recently innovative procurement methods are becoming popular to promote the collaboration among the stakeholders(owner, architect, project manager, designer, general contractor and sub contractors...etc.) involved in the process. One of the famous method in this one is Integrated project delivery/ Lean construction.

Design-Bid-Build:

In the DBB model, the owner has contracts separately with an architect and a contractor[14, 6, 2]. In the first stage, the architecture develops a list of building requirements and establishes design objectives of project.The architect proceeds through a series of phases and makes final documents which must fulfill the regulations. Design is completed prior to bids from general contractors.

Stage two involves obtaining bids from general contractors. The owner and architect may play a role in determining which contractors can bid. Each contractor must sent a set of drawings and specifications which are then used to compile an independent quantity survey. These quantities, together with the bids from subcontractors, are then used to determine the cost estimation. Contractor is typically selected based on the bid price. The typical structure of design-bid-build is shown in Fig. 8.

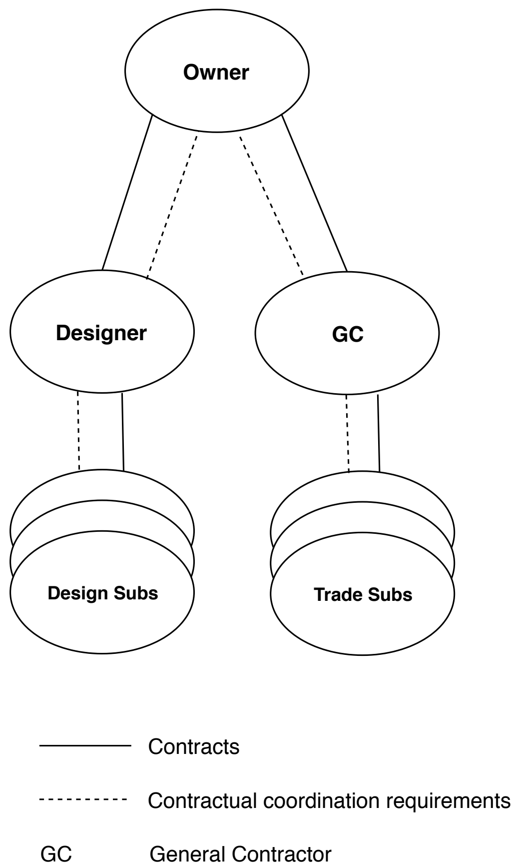


Figure 8: Design Bid Build[6]

Advantages of DBB projects as per[6, 2]:

- Competitive bidding to achieve lowest possible price for an owner.
- Less political pressure to select a given contractor.
- Communication between client and designer is satisfactory.

Disadvantages of DBB projects as per[6, 2]

- Error prone and inconsistent drawings lead to time consuming conflicts in the field.
- Inaccurately and uncertainty in design lead to fabrication of building elements onsite and are not cost effective.
- Ineffective communication between the stakeholders, low bidding than estimated cost leads to disputes and delays. Changes in design are necessary.

Design-Build:

In the Design-Build (DB) method a contractor under a contract with an owner is responsible for the project's design and implementation as a whole.

In this method, first the owner gives contracts to a single contractor. Later, this contractor is responsible for design and construction as a whole, possibly on performance-basis. Design delays or errors do not reduce the contractor's responsibility for impeccable completion of the project.

Secondly, the contractor establishes relationships with design consultants and subcontracts then on the contractual relationship basis . A typical structure for a design build method is shown in Fig. 9.

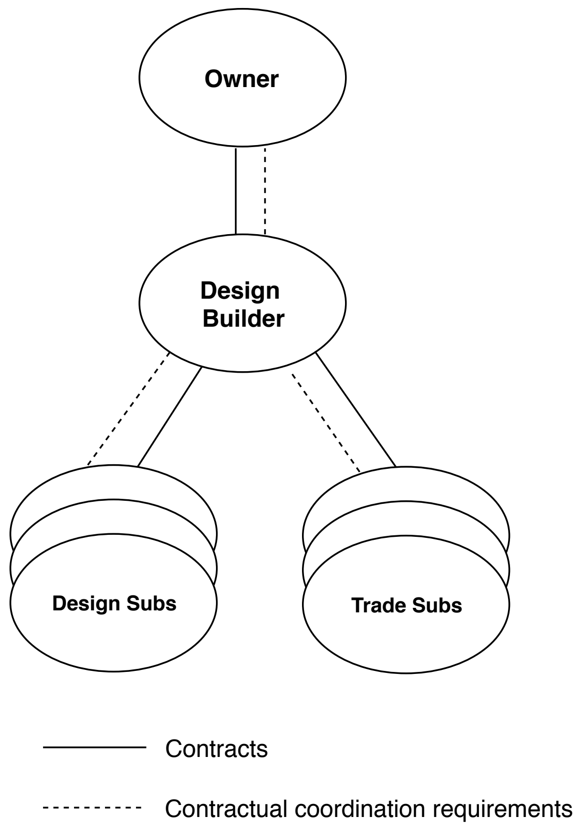


Figure 9: Design Build[6]

Advantages:

- The owner has less risk.
- Possibility to make early changes will help to reduce cost and time in the project.
- Contractor experience will give positive contributions to project.

Disadvantages:

- Less detailed documents in the early design process will lead to disputes between contractor and owner.
- Difficult to compare alternative design offers.
- Unsuccessful tenders lead to more design cost compared to estimated cost.

Construction Manager at Risk:

Construction management at risk (CM@R) is a procurement method in which a client hires a designer and construction manager to manage design services and construction management services for a project throughout all project stages.

Different parties are responsible for design and construction, but the CM organization participates in management of both. These services may include preparation and coordination of bid packages, scheduling, cost control, value engineering, and construction administration. The construction manager is usually a licensed general contractor and guarantees the cost of the project.

The typical CM@R method is shown in Fig. 10.

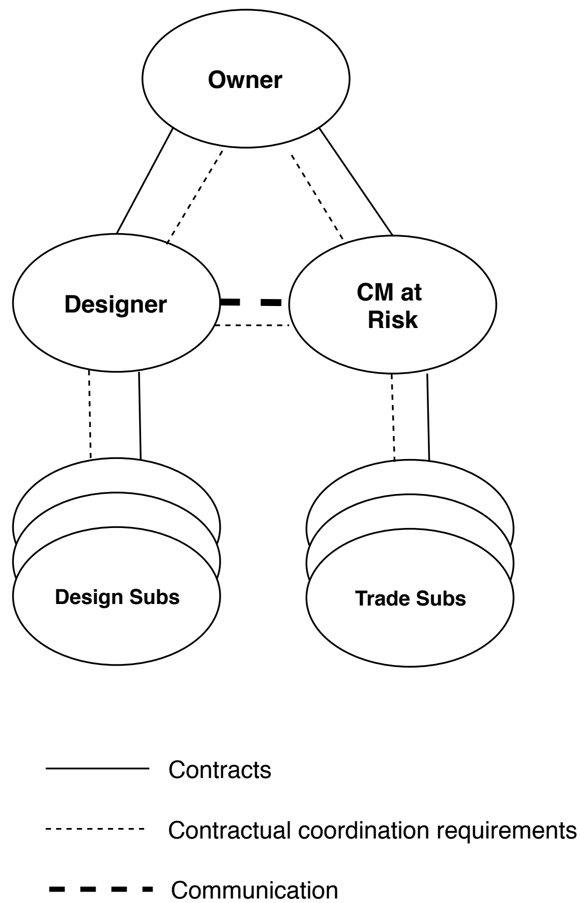


Figure 10: Construction Management at Risk[6]

Advantages[2, 6]:

- CM@R brings the constructor into the design process at a stage where they can have definitive input.
- The value of the delivery method stems from the early involvement of the contractor and the reduced liability of the owner for cost overruns.

Disadvantages[2, 6]:

- Even if the financial risk of the construction manager is small, the risk of loss of reputation is high.
- The client carries more risks than in DBB due to the additional risks coming from interfaces and coordination between multiple contracts and cost plus fee-type contracting.
- Design and construction functions are being performed by separate entities and the possibilities of cooperation are not fully utilized.

1.1.6 Integrated Project Delivery for construction project management

IPD is a relatively new procurement process that is gaining popularity as the use of BIM expands and the AEC facility management (AEC/FM) industry learns how to use this technology and to support integrated teams[6]. In traditional methods identification of how and who does a project is decided after design stage. However, in IPD it will be decided in early stages of the project so that it promotes tight collaboration between the teams.

The essential principles of IPD are mutual respect, mutual benefit, early goal definition, enhanced communication, clearly defined open standards, adoption of appropriate technology, high performance and leadership taken by persons most capable with regard to specific services[2, 18].

The American Institute of Architects (AIA) has developed a guide to give information on principles and techniques of IPD and to explain how to adopt IPD methodologies in designing and constructing projects[2]. The integrated design process using IPD and traditional design process is shown in the figure11.

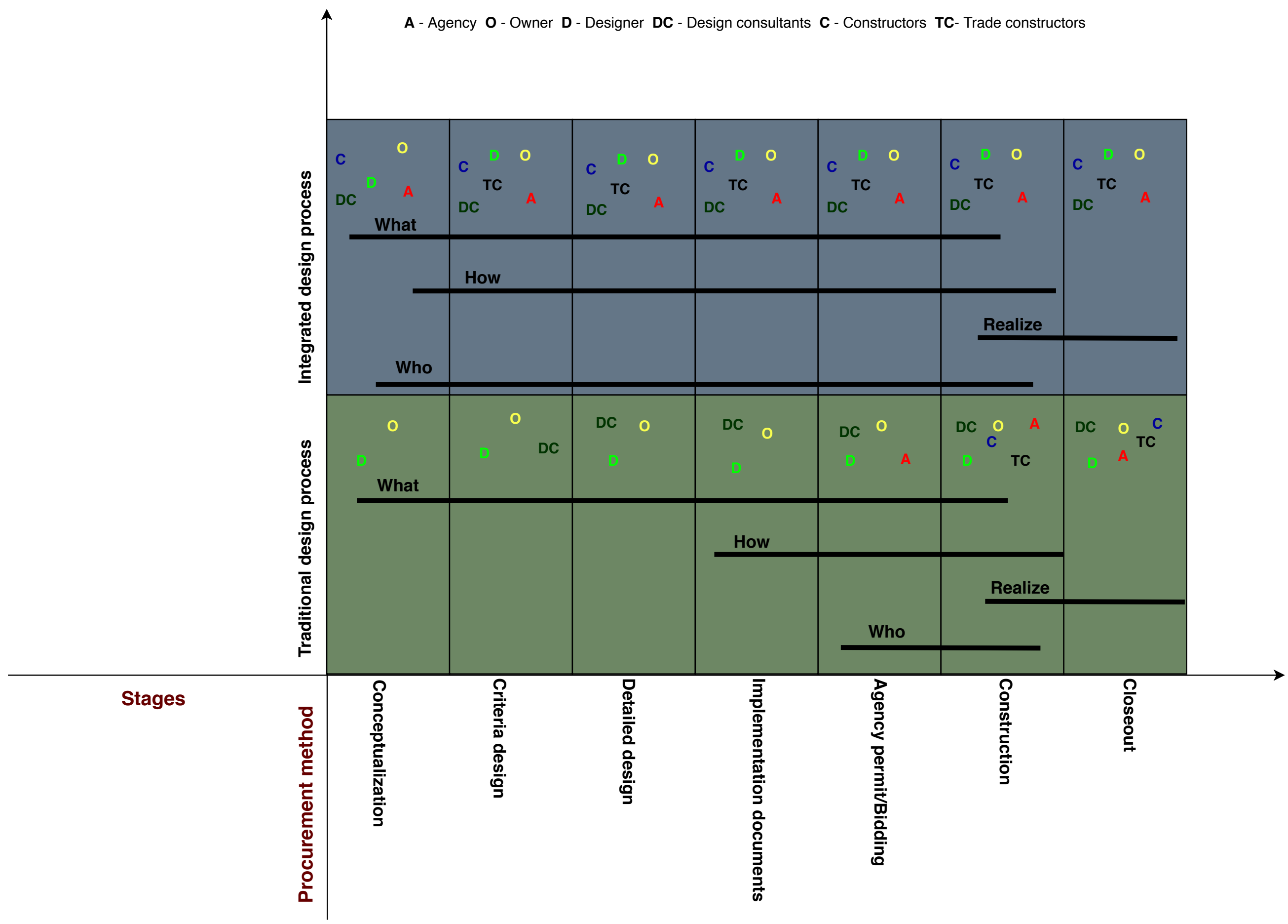


Figure 11: Integrated design process vs traditional design processs[18]

The major differences between the traditional project delivery method and IPD are explained with respect to the characteristics like teams, process, risk, compensation, communication and agreements in the table3.

Table 3: Comparison between traditional project delivery and IPD[10]

Traditional Project Delivery	Characteristic	Integrated Project Delivery
Fragmented, assembled on "just-as-needed" or "minimum-necessary" basis, strongly hierarchical, controlled	teams	An integrated team entity composed key project stakeholders, assembled early in the process, open, collaborative
Linear, distinct, segregated; knowledge gathered "just-as-needed"; information hoarded; silos of knowledge and expertise	process	Concurrent and multi-level; early contributions of knowledge and expertise; information openly shared; stakeholder trust and respect
Individually managed, transferred to the greatest extent possible	risk	Collectively managed, appropriately shared
Individually pursued; minimum effort for maximum return; (usually) first-cost based	compensation/ reward	Team success tied to project success; value-based
Paper-based, 2 dimensional; analog	communications/ technology	Digitally based, virtual; Building Information Modeling (3, 4 and 5 dimensional)
Encourage unilateral effort; allocate and transfer risk; no sharing	agreements	Encourage, foster, promote and support multi-lateral open sharing and collaboration; risk sharing

1.2 Case studies

Case study analysis is carried out by taking three research papers which are explained about the problems of project management companies, current level of BIM adoption to the project management and how the researchers/industry uses BIM in project management and the problems faced in the process.

1.2.1 Case Study 1

As a first step in the research process, literature review was undertaken to identify the project management companies and then a questionnaire on project management service use was sent to construction companies. The types of companies chosen were engineering consultancies, quantity surveyors, contractors and project management companies[28].

Problems	**Number/23**	**%**
Misunderstanding/lack of respect of other professionals Comments *Project managers seen as...* • Unreasonable people with unrealistic expectations • Lacking engineering understanding • Expensive parasites at times • A 'paper pusher' in the middle of a project • Unrealistic goal setters • Having insufficient technical understanding of the project and ending up as a highly paid post box • Knowing very little about civil engineering work • Not appreciating costs of decisions • Too quick to disregard input from building contractors • Failing to identify (and verify) key deliverables • Lacking liability *Other relationship problems...* • Contractor unable to talk to clients • Managing consultant/contractor performance • Controlling the design consultants • Intermittent communication breakdowns • Contractor on site management problems • Division of PM responsibilities • Delegation of work to inexperienced PMs	15	65
Client related problems Comments • Obtaining a client's brief is very difficult • Client's politics • Understanding the client's brief • Poor brief definition/lack of clear brief from client • Managing client expectations • Failure by client to align scope and budget	11	48
Co-ordination/communication problems Comments • Not bought early enough • Communication • Intermittent communication breakdowns • Timing of work on site	4	18
Being paid on time Comments • Getting paid on time • Money	2	8
Other problems Comments • Managing risk • Local authorities • Sub-contractors • Quality • Set fee tends to minimize workload	5	22

Figure 12: Problems faced by project management companies[28]

The results reveal that majority of companies agreed (76% of companies) that a separate project management service should be used to manage construction projects. The convenience of the client is one of the main reasons to adopt for separate project management services. Other reasons are the client having one point of contact with an independent expert and the client receiving advice independent from architect/engineer and consultants. One comment received pointed out that a separate project management company, provides for the client clear definition of roles of parties involved; ensures accurate and adequate supervision of consultants, reduces in-house squabbles and fiddling, provides clear leadership[28].

The problems faced by project management companies are listed in Fig. 12.

To conclude, The problems are seen from the perspective of the project management company and these problems appear to be relationship-based. Problems occur in relationships with the other professionals in the construction team and with the client. As a final word, project management companies internationally need to develop better collaboration strategies for dealing with the problems raised in the process.

1.2.2 Case study 2

In this paper the author examines the utilization of Building Information Modeling (BIM) as a Construction Project Management tool from a theoretical and a practical standpoint. In the first instance, the author collects information about the pursuing of different management approaches and traces the potential output of managing projects with BIM. Secondly, a collection of material from practice by analyzing the market of BIM-related software used for management is compiled. This software is based on either built-in features of BIM authoring tools, extensions or specialized software used aside BIM packages[19].

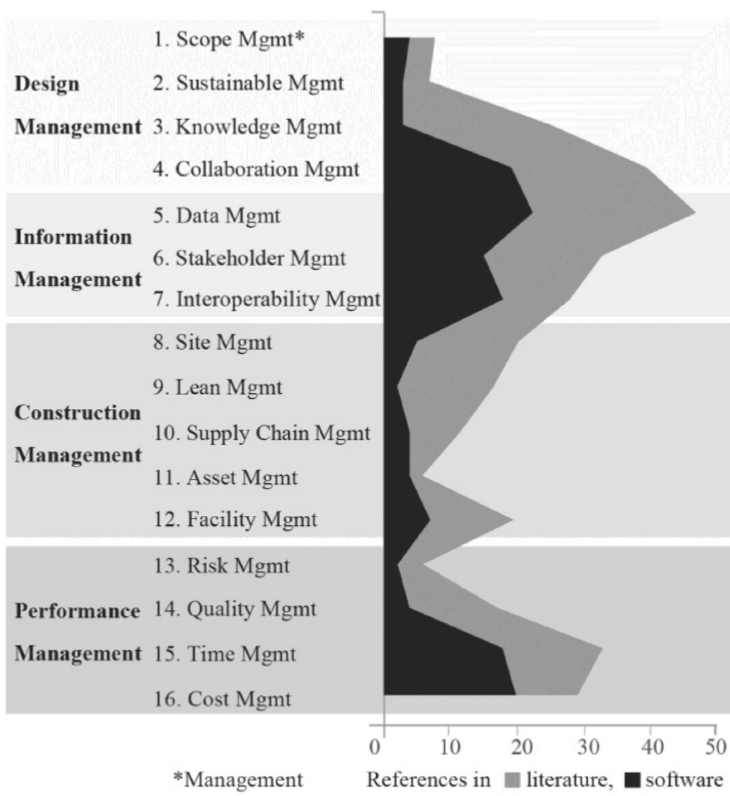


Figure 13: Number of references for PM with BIM in literature and in software developments[19].

The results revealed that the distance between academia and practice confuses the practitioners because they cannot experience all the proclaimed benefits of BIM for CPM. The management approaches currently employed in conjunction to BIM are one-sided, because they focus only in the time-related, cost-related or data-related aspects of the project life cycle, in a static manner. Often, several work-rounds from the practice attempt to approach the CPM more globally. However, still they fail to include all the project stakeholders or aspects such as sustainability or facility maintenance. All these aspects create confusion as how to manage a project with BIM. The diverse nature of AEC projects requires the undertaking of customized management approaches per project. Consequently, there is more than one way to manage a project, according to the project scope and goals[19].

Overall, synthesis between theoretical research and tools development is critical to increase the utilization of BIM as a CPM tool and it is important to develop methodologies in dynamic manner, so that it can adopted globally.

1.2.3 Case study 3

In this paper the author presents the development and implementation of a 4D planning tool which is part of a product model based project database. The proposed system is a web-based 4D planning tool. All project information is kept at a central project database and parties can access the information through the database as and when they want. The database keeps and manages the information as objects, which are created directly from the IFC model[24].

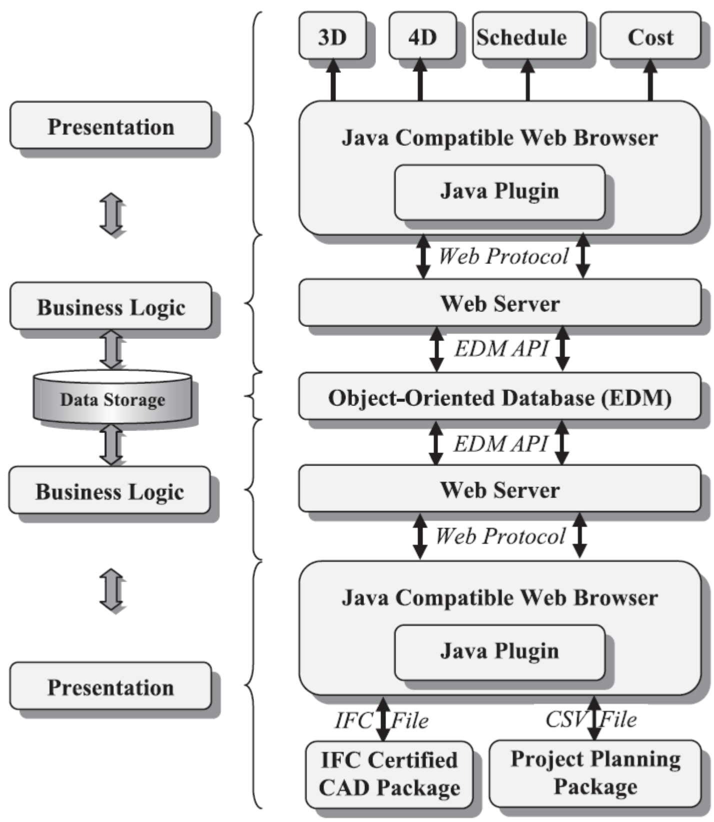


Figure 14: Architecture of the proposed system[24]

In paper[24] the below listed problems are revealed:

- Traditional work practices.
- Level of detail in project deliverable.
- The quality of the IFC file.
- Size of the IFC file.

- Lack of 3D modeling.
- Management of the data in single project database.

The single database approach provided the opportunity to improve the what-if questions as project parties could check different dimensions at the same time. Although this is a great advantage for the project participants, the case study has revealed that the single database approach has its own challenges during the implementation.

1.3 Problem statement

It is evident that traditional procurement methods are not enough to solve the current problems of the AEC/FM industry. BIM gains popularity in AEC/FM industry to overcome the problems. The problems of construction project management with BIM are categorized into 3 types:

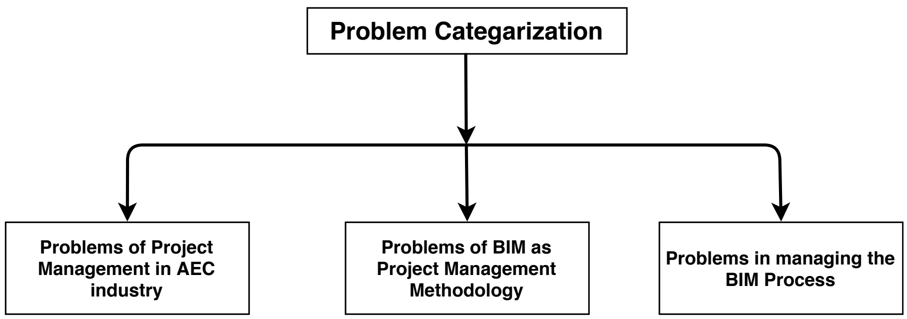


Figure 15: Problem categorization

Firstly, The information generated in the construction process is huge and sharing this information using traditional work practices create many problems because of coordination lack. In the current methods sharing of information is done by drawings and documents. The typical information flow between all the stake holders involved in the construction process as sown in the figure.

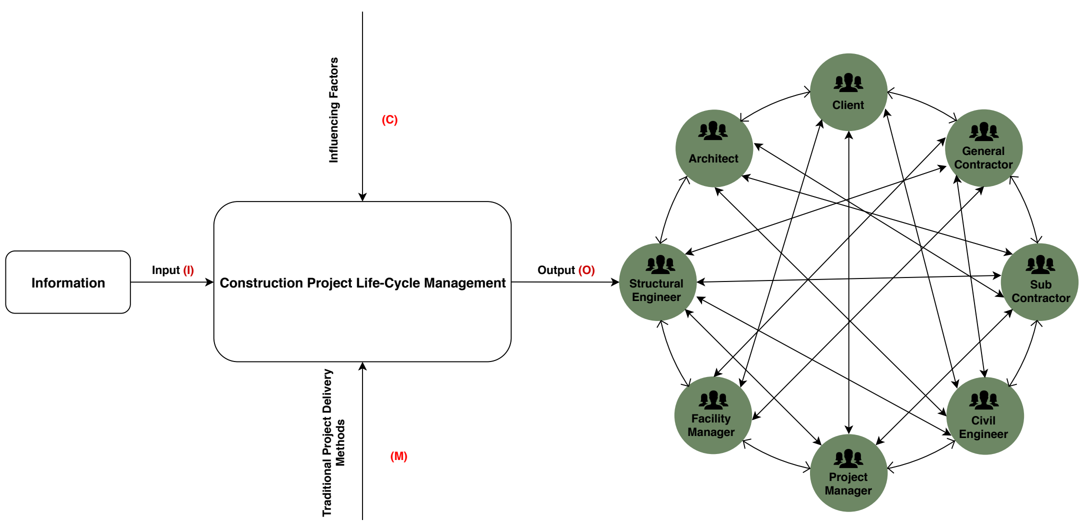


Figure 16: Information sharing between different stack holders using traditional methods

Secondly, Many BIM process are undefined today[5], Because it is new approach and the process depends on the people involved in the project. BIM implementation for project management includes social challenges and obstacles. Some of them are shown in figure17.

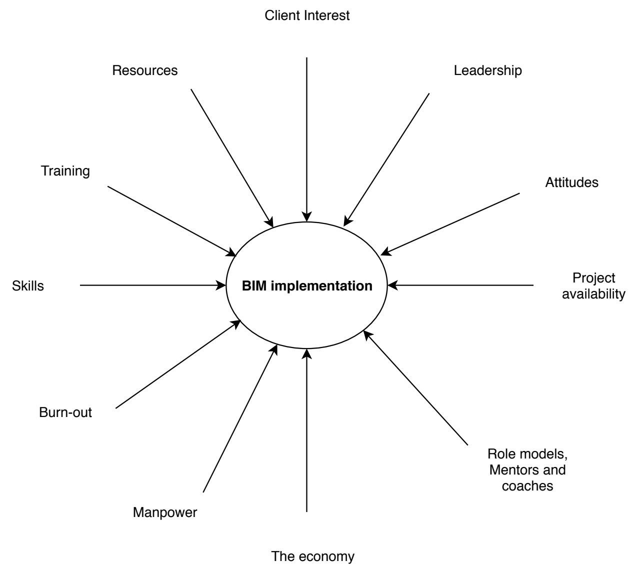


Figure 17: Multiple forces potentially impact the successful outcome of BIM implementation[5]

Thirdly, There are 12 major problems[5] included in the BIM process. Figure 18 shows all the twelve obstacles in BIM adoption.

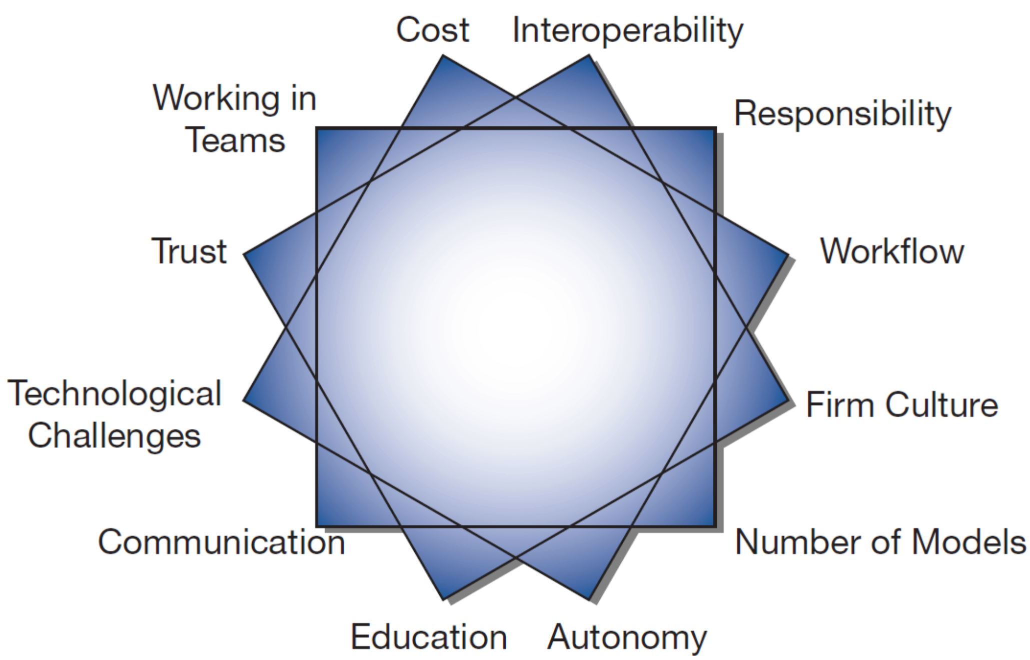


Figure 18: Twelve obstacles to successful adoption of and collaboration in BIM and integrated design[5]

Overall, it is evident that there is a need to generate, optimize and manage the flow of activities across the life cycle in conjunction to BIM. This makes me to focus on effective communication and collaboration techniques, Open-BIM data models, optimization and frame work of CPM work flow activities.

1.4 Possible solution

It has been keenly noted that information sharing between stakeholders, social challenges and obstacles for using integrated design are major problems. To overcome these problems, there is a necessity to modify organizational structures, process optimization using advancements in information technology.

Building Information Modeling is a process change[6] with the help of advancements in information technology. It aims to alter key procedures involved in completing construction projects. In research work, BIM is used to propose new methods to manage projects in an effective way.

One of the major possible solutions to solve the communication and collaboration problems using building information models is shown in Fig.19.

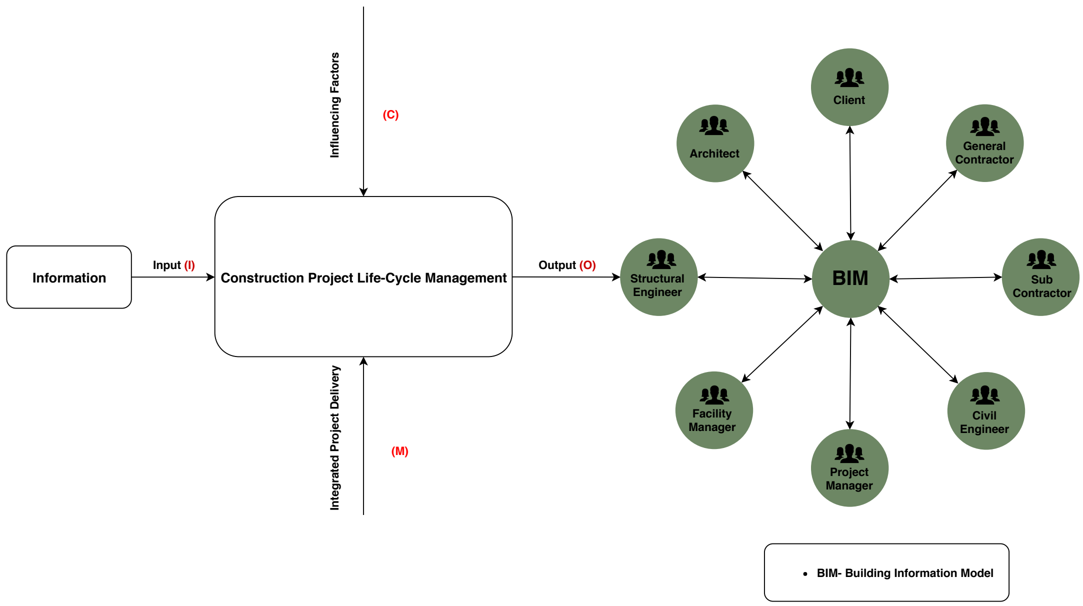


Figure 19: Information sharing between different stack holders using Integrated project delivery with BIM

1.5 Aim and Objective

1.5.1 Aim

The thesis work aims of:

- To investigate the current IFC meta data model and to implement an IFC based logical meta model for Construction Project Management information.
- To propose a method to integrate CPM parameters to the object based model in a flexible way.

1.5.2 Objective

The main objectives of this thesis work is to

- Conduct research on IFC modeling methods and develop an overview of IFC modeling methods.
- Analyze the Construction Project Management Information sharing between multiple organizational units.
- Implement a logical meta data model for Construction Project Management data based on IFC models.
- To propose improvements in method to integrate Construction Project Management data into a BIM model and manage the data in IFC format.

1.6 Conclusion

Management of construction projects has been done using traditional procurement methods still. With significant advancements in the Information and Communication Technologies(ICT) the AEC industry changed the way of managing construction projects. Even though there are greater improvements in the technology, still construction industry is facing the problems like over-budget and late delivery of projects. The labor efficiency and productivity of projects has decreased over the past years. The industry is fragmented.

It is important to redesign the traditional management approaches for managing construction projects, the information sharing, collaboration between the stake holders involved in the project. To overcome the problems of the AEC/FM industry, recently innovative procurement method called integrated project delivery with BIM became a popular emerging method. Taking this as advantage, Building Information modeling is explained briefly in the next chapter.

2 Building Information Modeling and Open Standards

The aim of this chapter is to present the main concepts related to the Building Information Modeling (BIM). First section discusses about BIM definition and process, level of development for information models and interoperability between the software applications. Second part explains about universal data model and its schema structure.

2.1 Building Information Modeling

The National Building Information Modeling Standard (NBIMS) defines BIM is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format usable by all throughout its life cycle"[17, 6].
"Building Information Modeling as a process—as opposed to software, technology, or tool—of generating and managing building data during its complete life cycle, from conceptual design though maintenance and operation of the building." [5]

In the book BIM and construction Management -proven tools, methods and work flow, Brad Hardin defines "BIM is not just software—rather, it is a process and software". Taking that one step further, we now see that successful BIM use requires three key factors: Processes ,Technologies, Behaviors[7].

"Building Information Modeling (BIM) is a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle"[23].

From all the definitions it is observed that BIM is process of identifying players, their requirements, deliverable's with the help of distinctive layers of analysis with interaction of policy and technology fields, generating the building data which have basic ability to perform task and managing it in a usable digital format throughout its life cycle.
Some another meanings of BIM is shown in the Fig. 20.

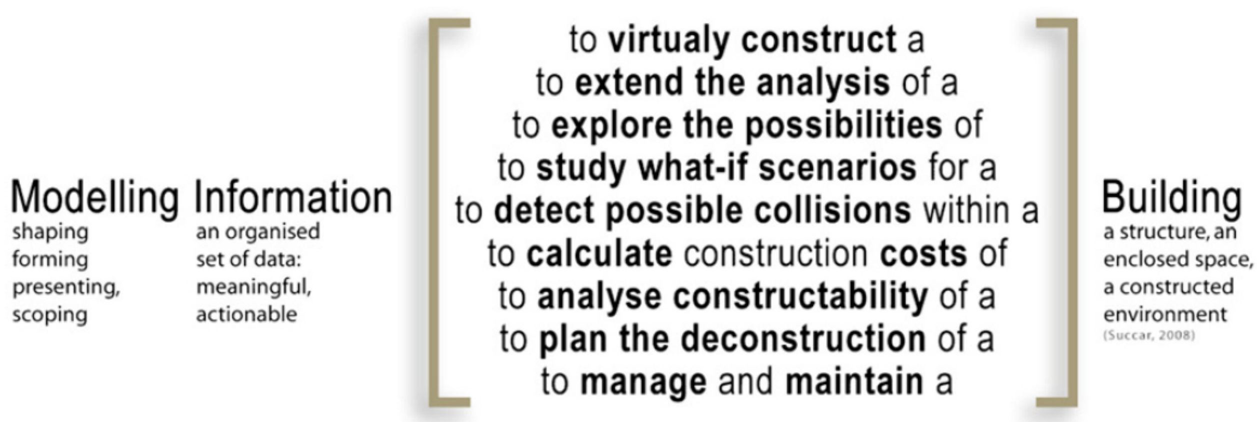


Figure 20: Some common connotations of multiple BIM terms[23]

The model which is generated from BIM process is also called as Building Information Model. It is defined 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 analyzed to generate information that can be used to make decisions and improve the process of delivering the facility"[11].

2.1.1 Overview of BIM

The BIM knowledge domain mainly involves three concepts, which are BIM fields, BIM stages and BIM Lenses. The ontology diagram of BIM knowledge area can be seen in the figure 21.

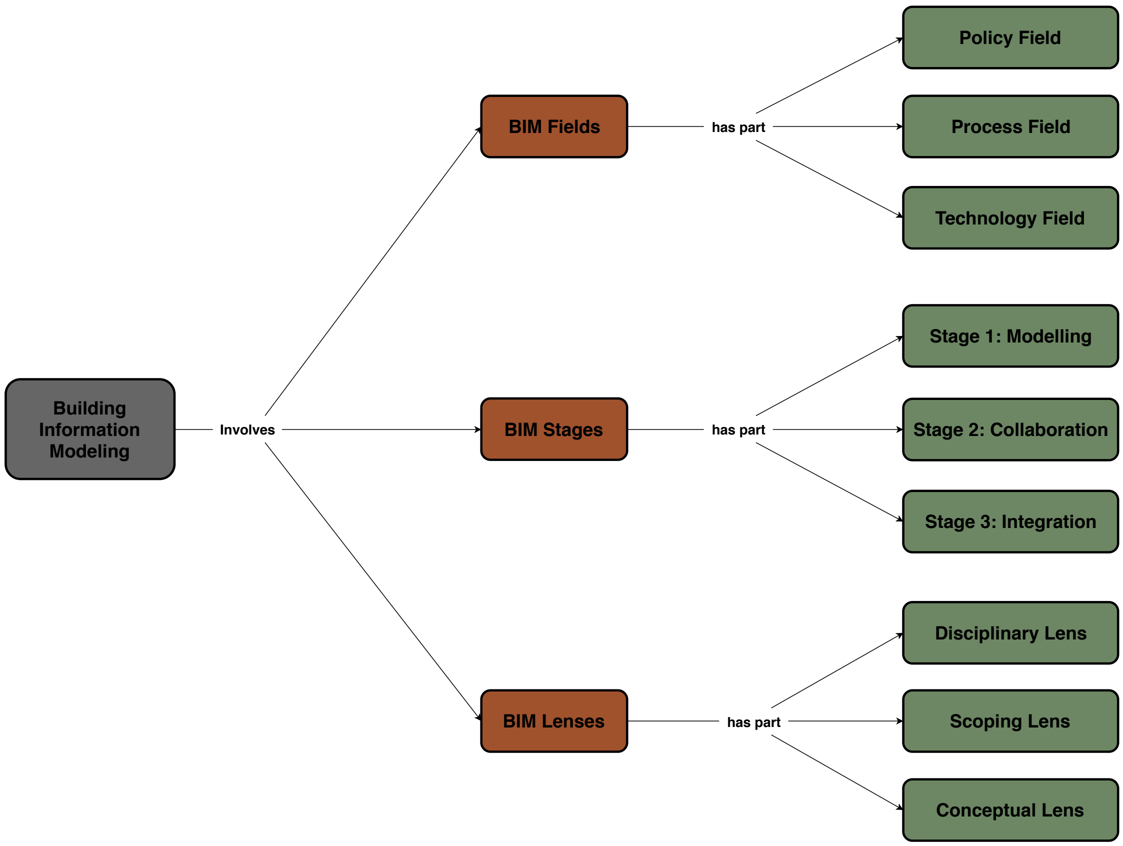


Figure 21: Knowledge view using Concept Maps and BIM Ontology

With the aid of conceptual clustering of knowledge objects available in the Architecture, Engineering, Construction and Operation (AECO) industry, the BIM Fields identified are observed to interact within the AECO industry leading to the inception of new products, services and roles. BIM has three interact fields called technology field, process field and policy field. These three BIM fields are explained in the following three paragraphs.

"The BIM Technology Field Technology is the application of scientific knowledge for practical purposes"[23]. The underlying principle of the Technology Field is grouping of players who specialize in developing software, hardware, equipment and networking systems necessary to expedite efficiency, productivity and inflate the profitability of AECO sectors.

"The BIM Process Field Process is a specific ordering of work activities across time and place, with a beginning, an end, and clearly identified inputs and outputs: a structure for action"[23]. The Process Field essentially gathers a cluster of stakeholders who are involved in the procurement, design, construction, manufacture, use, management and maintenance of the structures.

"The BIM Policy Field Policies are written principles or rules to guide decision-making" [23]. The Policy Field brings together the participants who predominantly focus on conducting research, distribution of benefits, risk allocation and minimization of conflicts within the AECO industry.

BIM Stages explains the Building Information Model capability to perform a task, deliver a service or generate a product which is the core principle of BIM. The process flow in a BIM model is fundamentally comprised of 3 different stages, they are object based modeling, model based modeling and network based modeling. For example an organization to be recognized as object based modeling stage , it is necessary that an object based modeling software tool is deployed . Similarly to consider under model based modeling stage, it is absolutely necessary for an organization to be a part of or share a multidisciplinary model-based collaborative project. To fall under network based modeling stage, it is crucial for an organization that it makes use of network-based solution (like a model server) to share object-based models with at least two other disciplines[23].

BIM Lenses form the third dimension of the Framework with its characteristic function being, to be able to generate results at deep levels of inquiry. BIM Lenses, in essence are distinctive layers of analysis that are applied to Fields and Stages to generate 'Knowledge views'. They (BIM Lenses) 'abstract' the BIM domain and regulate its complexity by discarding inconsequential details. Lenses permit the domain researcher to selectively focus on a chosen aspect of the AECO industry and generate knowledge views that either (a) highlight observable which are in coherence with the research criteria or (b) filter out those that do not comply with. In effect, all knowledge views are nothing but abstractions derived from the applications of one or more lenses and/or filters[23].

Differences between BIM Lenses and Filters:
Lenses and Filters are both analytical tools of inquiry and domain analysis which are oriented towards the discovery of concepts and relations. The difference between Lenses and Filters can be summarized as follows: Lenses are additive and are deployed from the 'investigator's side' of BIM Field observation while Filters are subtractive and are deployed from the 'data side'[23]. Lenses highlight observable that are in part with research criteria and identify their relations. Whereas Filters discard observable that do not meet the research criteria.

2.1.2 Model Development Specification

The primary goal of Model Development Specification (MDS) is to define "the amount, type, and precision of information that is to be included in Building Information Models (BIMs) for specific project milestones and deliverable's as the project progresses from concept to closeout"[12]. It underlies the fundamental processes that clearly inform the project team regarding the content and timing of information that are required vs available to them, increasing the efficiency and reliability and doing away with the unnecessary or redundant work. Thus MDS significantly helps in reducing the cost and increasing the benefit of the BIM process.
The advantages of Level of Details's are[12] :

- The assurance to the owner in getting the models needed to support the necessary processes.
- A significant reduction in the modeling cost by way of accurately scoping to include only the necessary detail.
- The characteristic of the modeling effort being scoped and priced fairly.
- The planning and tracking of the design process so that the necessary information is available when needed.
- Specific definition and regulation of the reliance of the downstream users on the models, making the models much more useful when compared with the common "for reference only" models. Thus making it extremely effective in eliminating coordination errors and avoiding rework.
- The ability of concise definition of Builders' needs in the models thereby allowing design models to be passed on to the builder. This phases out the need for the builder to re-create models consequently leading to huge savings.

The MDS defines the models with the help of widely accepted language − the Level of Development, Level of Detail...etc. The history of MDS can be observed in the appendix A.
The variations of the MDS as illustrated in the Fig .68 have resulted in a great deal of confusion. Below are a few examples[3]:

- The original 'Level of Detail' index was intended to measure the reliability of both geometric and non-geometric data. However, it now focuses primarily on the geometric attributes;
- The 'LOD' acronym is interchangeably used when describing Level of Detail and Level of Development;
- Identical concepts are occasionally referred using different terms. This can be seen when referring to 'Level of Information' and 'Associate Attribute Information'.
- The Level of Development, while intended to be associated with Model Components is sometimes inadvertently associated with BIM models.
- Many BIM documents that these classifications are based on are obsolete.

2.1.3 Role of Interoperability in BIM

It is important that the information models generated or modeled in the BIM process should be shared between the different software applications. Software interoperability is necessary to ensure a seamless sharing of information models.

Interoperability is achieved by mapping parts of each participating application's internal data structure to a universal data model and vice versa. If the employed universal data model is open, 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 with every other application[17].

The National Building Information Modeling Standard (NBIMS) stipulates that for a successful software interoperability in the capital facilities industry, it is essential to accept an open data model of facilities and a corresponding interface to that data model for each participating application. If the adopted data model is industry-wide (i.e. represents the entire facilities life cycle) in its characteristics then the software application of each industry can be made interoperable.

2.2 Industry Foundation Classes

Industry Foundation Classes (IFC) is an open specification, supported by an international, non-for-profit organization called buildingSMART with the goal of defining, promoting and publishing a specification to ensure data sharing throughout the project life cycle, globally, across disciplines and between software applications. It is registered with ISO as ISO16739.

The primary function of IFC is to exchange information about a building, which may include geometry, but is by no means limited to this. Another important feature of IFC is to facilitate linking of alphanumeric information (properties, quantities, classification, etc.) to the building objects and maintaining the relationships among the building objects. It is important note that the content of the IFC exchange is determined by the IFC view definition. So strictly speaking there is no IFC implementation, but several IFC view implementations.

To ensure a better understanding of IFC architecture and its implementation, the IFC specification is forked into 2 divisions. In the first division, the schema or product data model explains how the IFC is structured and specified. The second division attempts to explain the populated data model which essentially bears data about mode of information sharing between the software applications.

2.2.1 IFC Schema

A schema is "a collection of entities (or classes), attributes, and relationships between entities". A schema defines the patterns or templates by which populations of these entities and relationship shall be represented unlike a populated data model[16].

IFC Schema Definition layers:

The data structure of the IFC schema is defined in four layers which fundamentally consists of classes, attributes, rules, functions property sets and quantity sets. These four layers are explained as follows:

- Resource layer : This is the lowest layer which includes all individual schema containing resource definitions. These definitions do not include an globally unique identifier and shall not be used independently of a definition declared at a higher layer[25].
- Core layer : This next layer includes the kernel schema and the core extension schema which contains the most general entity definitions.However all entities defined at the core layer or above, carry a globally unique id with an option of also storing the owner and history information[25].
- Interoperability layer : This layer includes schema containing entity definitions that are specific to a general product, process or resource specialization which find applications across several disciplines. The entity definitions are typically applicable in inter-domain exchange and sharing of construction information[25].

- Domain layer : This layer which is at the highest level which includes schema containing entity definitions that are specializations of products, processes or resources specific to a certain discipline. The definitions are typically utilized for intra-domain exchange and sharing of information[25].

The diagrammatic representation of IFC schema layer is shown in the Fig.22.

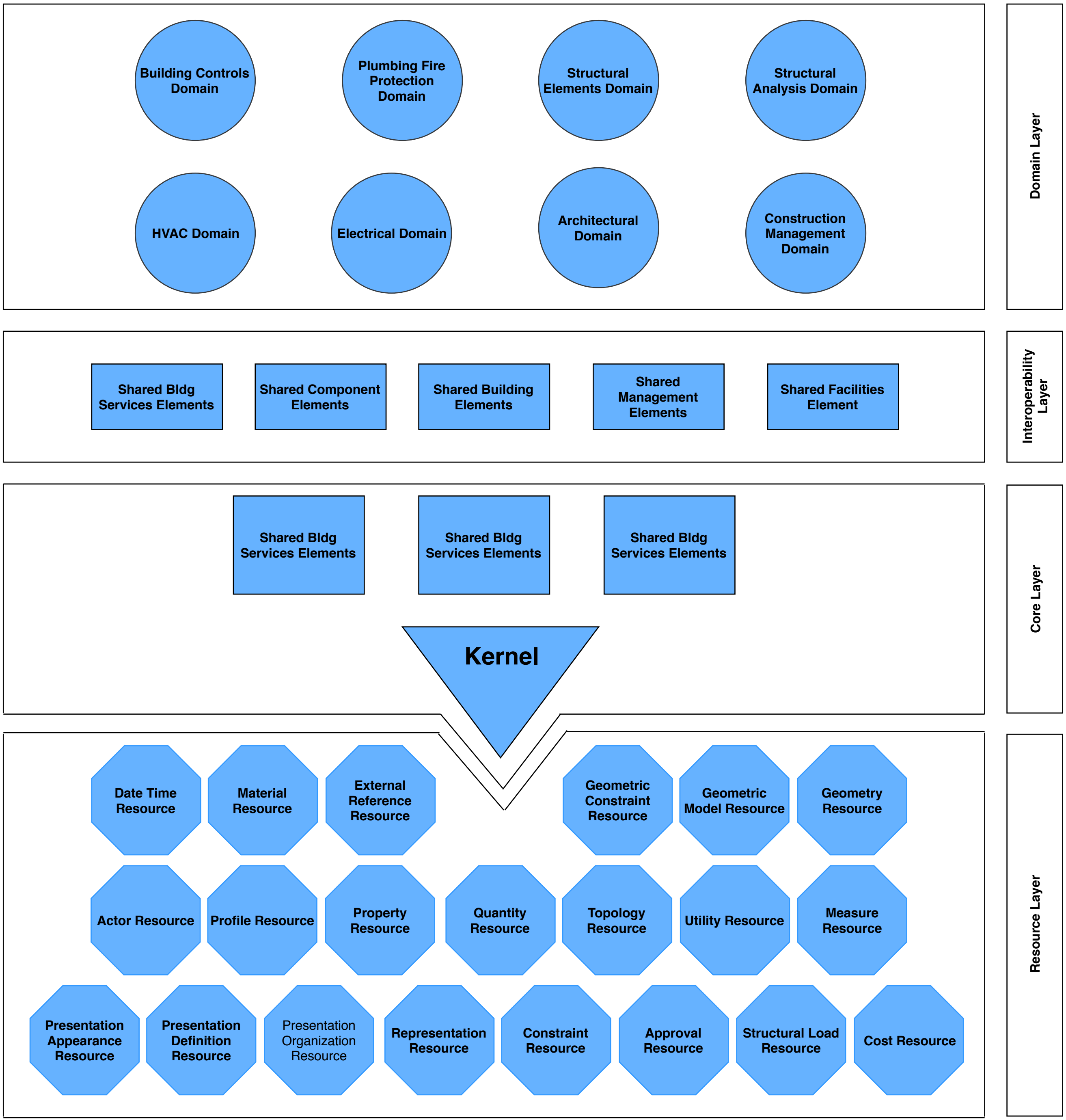


Figure 22: IFC Schema conceptual layers[25]

The IFC schema operates on a ladder principle. In other words, the Resource classes can refer only other Resource classes in the same layer. The ladder principle is applicable within the Core layer wherein the Kernel classes can be referenced by the classes in the Core extension. The ladder principle also applies when the Core classes can interact with the neighboring Core classes within and also while referring within the Resource classes. However, referencing of Core classes with Interoperability or Domain Layer is not applicable. A similar scenario follows with the upper Interoperability layer where the classes in this layer can refer within themselves and also with the Resource and Core layers. Finally, the Domain/Application layer can refer any class in the Resource, Core and Interoperability layer without any limitations[9]. The same can be seen in the Fig. 23.

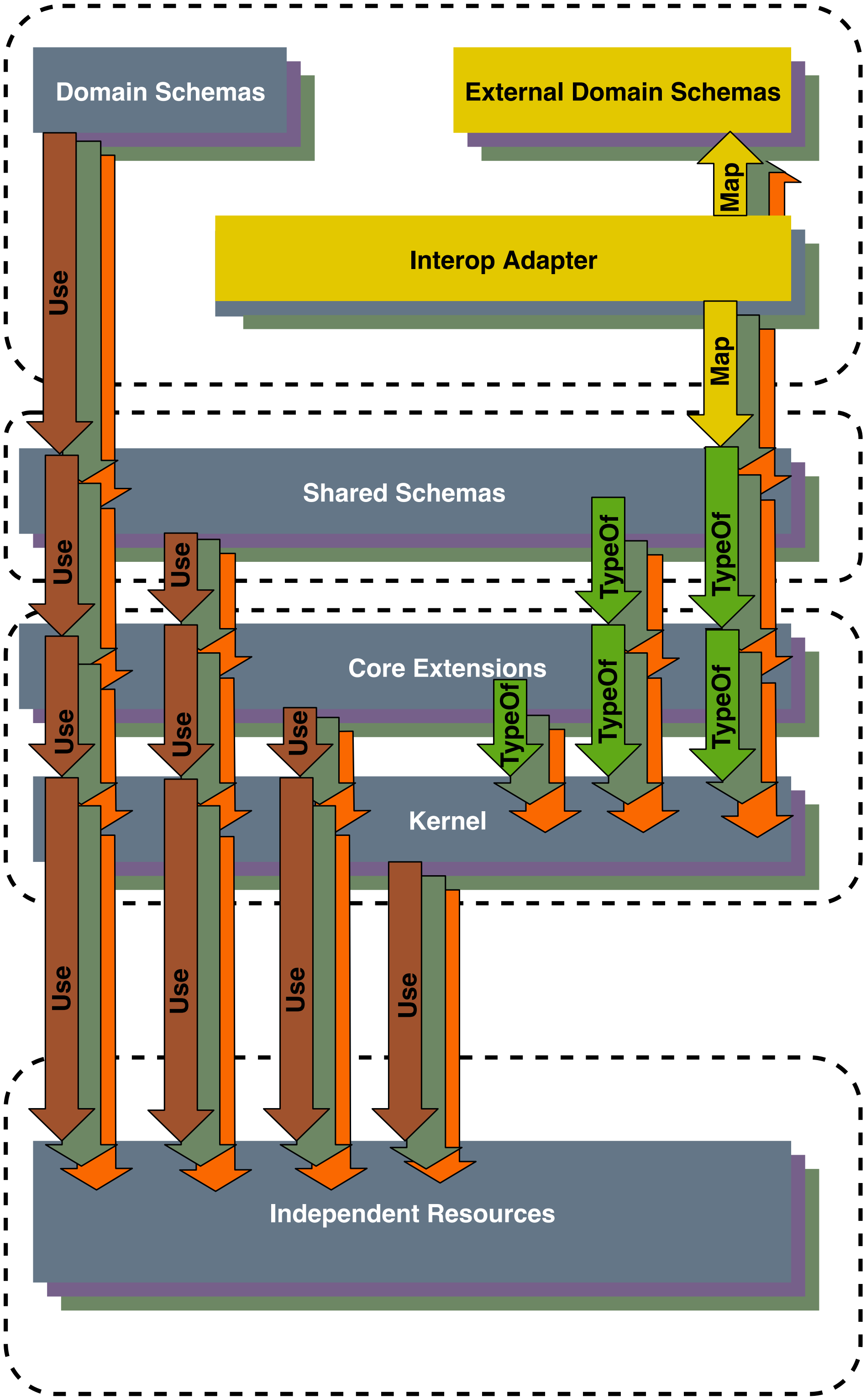


Figure 23: Layering concept of IFC architecture[29]

EXPRESS for IFC Development:

The IFC schema is denoted using EXPRESS. EXPRESS is a data definition standard developed to enable a formal definition of industrial data. It helps in validating a population of data types (the entities and attributes). EXPRESS-G is a notation to denote graphical modeling notation. It is developed within STEP and used for IFC definition. It is used to identify classes, the data attributes of classes and the relationships that exist between classes. EXPRESS-G has direct relationship with the EXPRESS data definition language. That is to say that, everything that is drawn in EXPRESS-G can be defined in EXPRESS. However, the converse is not true. EXPRESS-G notations and the relationships are illustrated in the Fig. 24. Greater details of the EXPRESS language and notations can be found in ISO 10303-11.

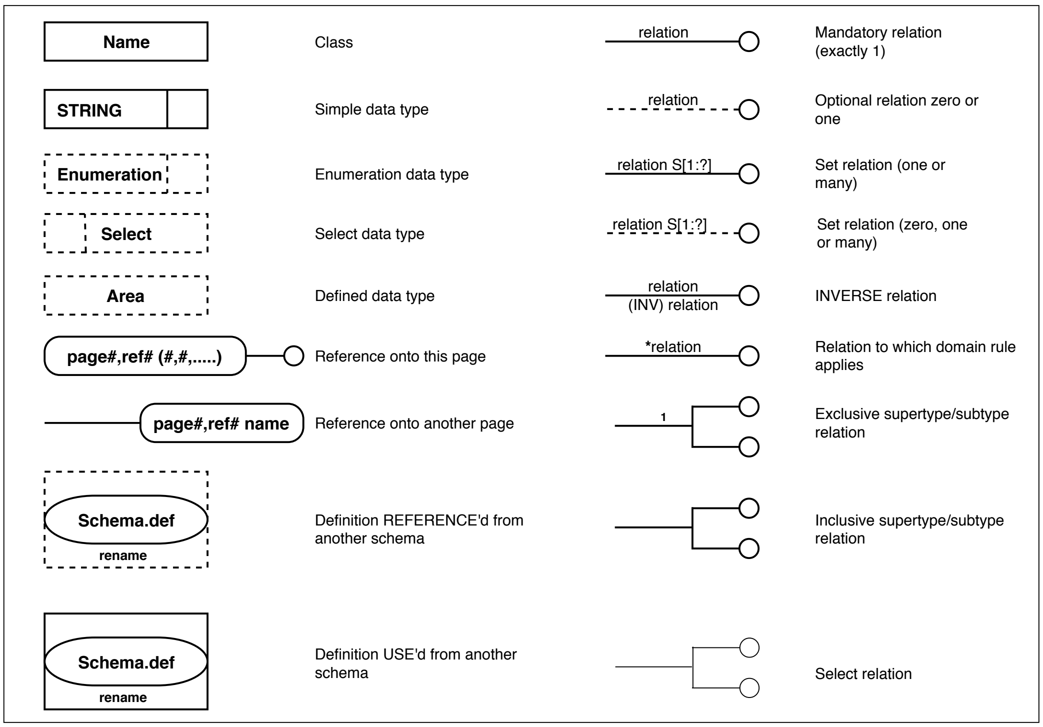


Figure 24: EXPRESS G notation symbols[1]

Fundamental classes in the IFC schema:

This section deals with the brief explanation of the main classes of IFC schema and their purpose.

IfcRoot is the most abstract and also the root class for all entity definitions in the kernel or in subsequent layers of the IFC specification. It is therefore the common super type of all IFC entities, apart from those defined in an IFC resource schema. It is possible to use all entities that are sub types of IfcRoot independently. However it is not possible to attribute those resource schema entities as independent that are not sub types of IfcRoot[25].

Three fundamental sub types of IfcRoot are IfcObjectDefinition, IfcPropertyDefinition and IfcRelationship.

An 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[25].

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[25].

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[25]. Explanation of IFC schema entities and their attributes can be found in ISO 16739.

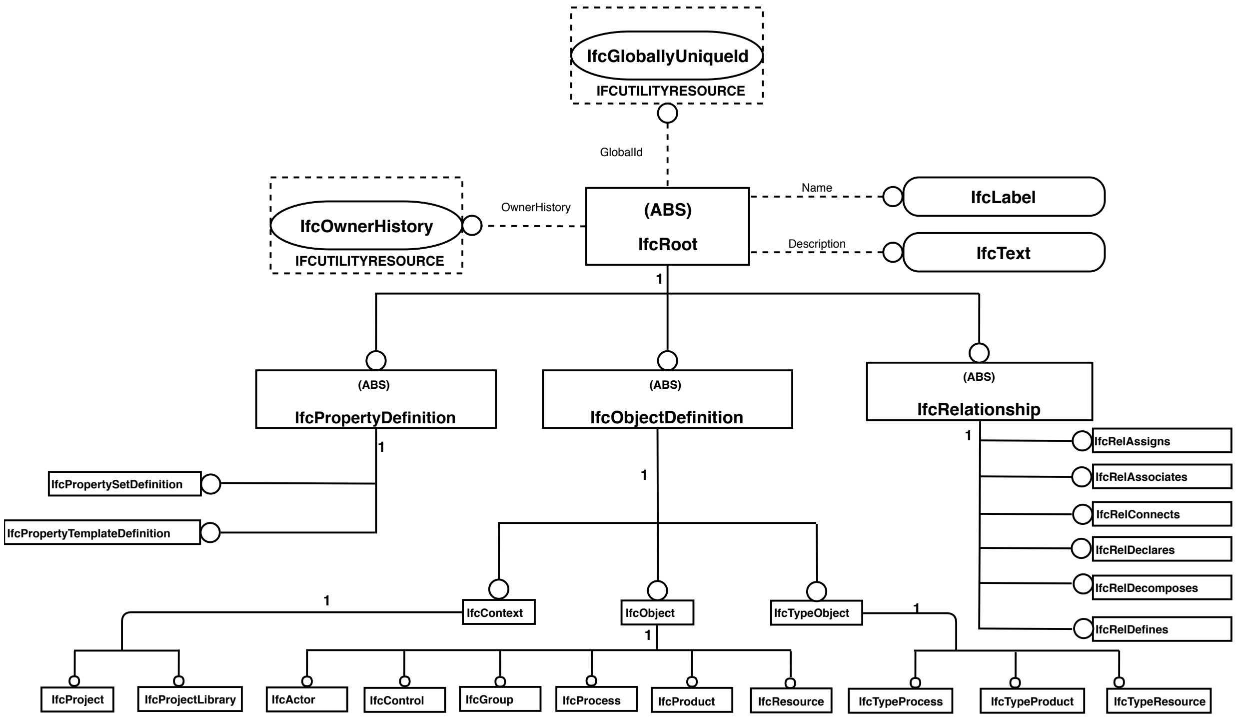


Figure 25: EXPRESS G notation for IFC root entity with its fundamental sub types[25]

2.3 IFC Data Model

A model is a population of a schema, following the patterns, templates and constraints stipulated by the schema. It contains the actual instances of the entities (or classes). Such a model is often called a populated data model, a project data model, a building information model (if content is construction industry specific. An IFC exchange file represents a building (information) model[16].

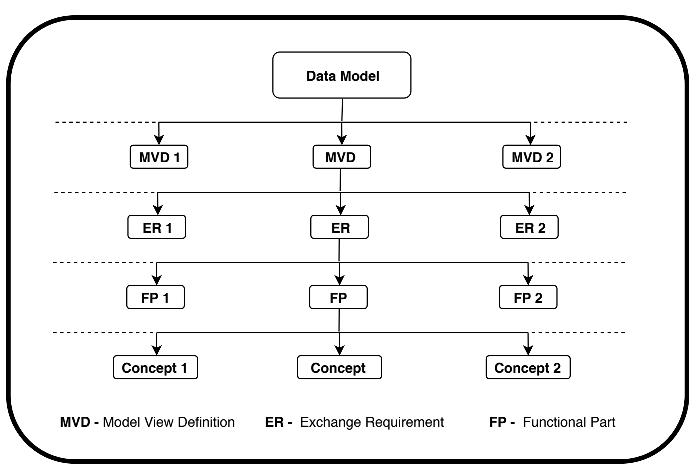


Figure 26: Hierarchy diagram of IFC data model[13]

The hierarchical makeup of the Data model is as follows :
The data model is comprised of Model Definition View (MVD) which in turn comprises of Exchange Requirement (ER) . The ER contains Functional Part (FP) and finally the Concept forms the integral part of the FP. The same can be seen in the Fig. 26.

2.3.1 Model View Definition

A model view definition (MVD) is in principle a set of information from the information model that can be supported by a type of software application[13].

The IDM-MVD approach is derived from the building process point of view to select and specify the appropriate entities from a schema that carry information, attributes of the entities, and rules for selected exchange use-cases. IDMs are defined by domain experts to provide references in the human-readable format which finds relevance in use-case scopes, business processes and Exchange Requirements (ERs) of particular exchange scenarios in use-cases. Hence it follows that, an IFC-based model view is a model subset of the IFC schema with respect to requirements from end users for the IFC implementation purpose. In general, MVD is represented in mvdXML format. Further on ,mvdXML can be denoted 1) in a text file editor using codes 2) using software such as IFCDOC.

The schematic representation mvdXML in the appendix Fig.69 illustrates the scope of the mvdXML document. The representation includes zero-to-many mvd:ModelView and zero-to-many mvd:ConceptTemplate. It is advised to include all concept templates that are referenced by included model view(s), or else to distribute the mvdXML file along with other mvdXML files containing such templates[4].

ConceptTemplate represents the reusable concepts as templates. It consists of zero-to-many mvd:SubTemplates and hence form a tree relationship with the reusable concept templates. By having a tree interconnection it may refer to shared partial concepts. Each mvd:ConceptTemplate has an applicable schema and may have applicable root entities (i.e. concept roots to which the mvd:ConceptTemplate applies)[4]. The Fig.70 represents concept template.

Model View Definition (MVD) is specific to an IFC schema release and contains zero-to-many mvd:ConceptRoot elements. It also includes the reference to zero-to-many applicable mvd:ExchangeRequirement elements. A single file may potentially contain multiple model views from different schema release.However,the set of entities and types to be represented within scope of a model view is not explicitly defined. Rather it is indirectly determined by constructing a graph of mvd:ConceptRoot elements and adhering to the set of rules indicating referenced entities within scope. Thus, describing the set of rules automatically determines the validity of the scope thereby preventing the possible mismatch of missing data structures that are required, or included data structures that are not documented for use[4]. The Fig.71 represents the schematic diagram of a Model View Definition

2.3.2 Exchange Requirements

An Exchange Requirement(ER) contains a bundle of information that needs to be exchanged to support a particular business requirement at a particular stage of a project. It is currently prescribed that for an Information Delivery Manual (IDM), the set of information should be defined within the IFC model. However, the IDM approach will also function with sets of information defined within other industry standard models such as the Geographic Markup Language (GML) as defined by the Open Geo-spatial Consortium (OGC)[13].

The primary task of an exchange requirement is to provide a description of the information in non-technical terms. The principal audience for an exchange requirement is generally comprised of architects, engineers, constructors, etc. It should however be adopted by the solution provider since it is crucial in accessing the technical detail that enables the solution to be provided.

ERs are specified as Exchange Requirement Models (ERM) and Functional Parts (FP) which are mapped to a data model schema (usually IFC) to extract model subsets as “model views”, which can then be implemented in domain applications which are used in the development of translators for mapping software, internal data models to or from model views and to develop export or import routines for target exchange scenarios.

An exchange requirement model is manifested as the technical solution of an exchange requirement. It serves as a support for a software application to enable exchange of information for a particular purpose, at a particular point in time on a project and at a particular location. Thus, it satisfies all the conditions for supporting a project workflow in strict coherence with the rules and methods of working defined for a region, country or framework agreement. However, the exchange requirement model depends on the release version of the information model from which it is derived. Therefore, it is possible for an exchange requirement to have several exchange requirement models as technical solutions, where each technical solution follows a particular release of the information model[13].

The Fig. 27 shows an example ER of wall element for architectural and structural purpose.

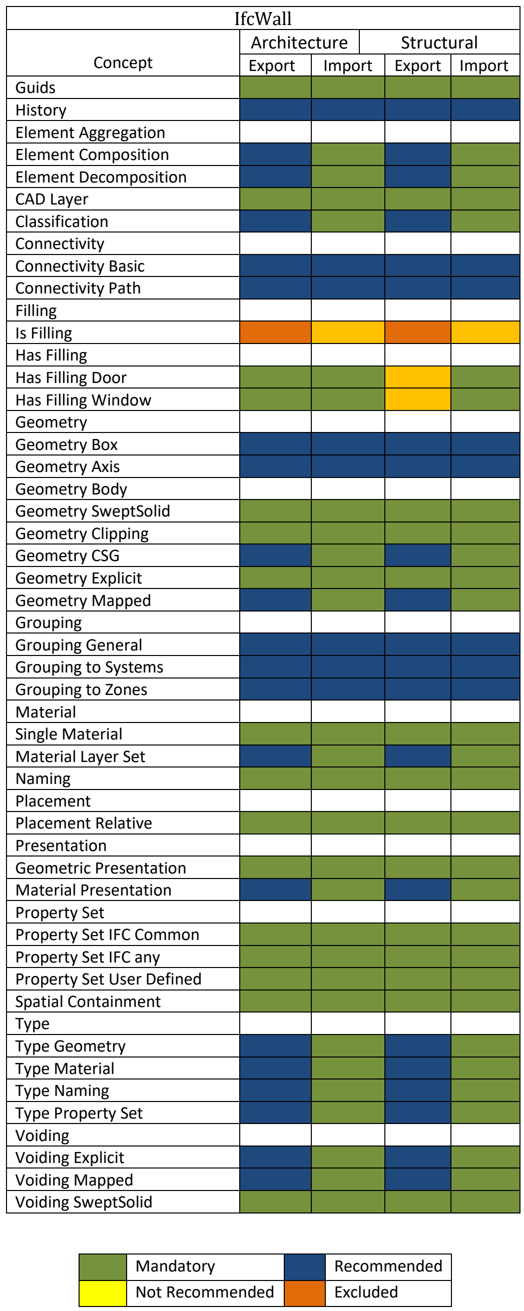


Figure 27: Architectural and Structural exchange requirement of wall

The information required in order to develop ERs in a BIM process is categorized into the following seven groups[17].
1. WHO is requesting the information?
2. WHY is the activity happening?
3. WHEN at what phase is project execution?
4. WHAT define the entities, objects, and properties of the architectural model needed by the estimator to complete the task and also about what is delivered between the parties and the applications?
5. To WHOM is the request being given?
6. HOW generally are the resources used to develop the design and construction of a project that do not become part of the project?
7. INPUTS & OUTCOME data are referenced and utilized during the process of creating and sustaining the built environment.

2.3.3 Functional Parts and Concepts

A functional part is a unit of information, or in essence a single information idea which is used by solution providers to support an exchange requirement. A functional part describes the information in terms of the required capabilities of the industry standard information model which forms the basis. As per the present norms for IDM, the functional parts are based on versions of the IFC model. A functional part is fully described as an information model in its own right as well as being a subset of the information model on which it is based[13].

The functional part emphasizes on the individual actions that are carried out within a business process. An action primarily deals with a particular unit of information within an exchange requirement. For instance, in order to exchange a building model, it is first necessary to model the walls, windows, doors, slab, roof etc. The action of modeling of each of these structural elements is described within a functional part. Each functional part provides a detailed technical specification of the information that should be exchanged resulting from the action. Since it is possible for an action to occur within many exchange requirements, it is evident that a functional part may also relate to many exchange requirements. To account for this , the functional parts are specifically designed to be reusable within many exchange requirements. However, certain functional parts deal with more general ideas and may have frequent participation. For instance, functional parts dealing with relationships such as applying a classification to an element or those dealing with geometric shape representation. An example for functional part is wall, window, roof ...etc.

A concept is a fragment of information that can be used in a functional part (where it is bound to a release of the IFC model) or to an exchange requirement (where it is expressed in generic terms). It can be also applied to highlight the basic functionalities within a model such as naming, identification etc. A concept does not necessarily be simply related to a single entity or even to a whole entity. For example, the concept of a software identifier simply describes how a globally unique identifier attribute is asserted for an entity[13].

2.4 Conclusion

A BIM process is essentially carried out through BIM Fields, BIM Stages and BIM Lenses. The information data models are developed by adopting this three BIM knowledge areas. The amount, type and the accuracy of the intended data to the BIM model is obtained using Model Development Specification. The generated information model has to be shared between the different software applications which are used by the different participants in the BIM process. Thus it is crucial for the data information model to have a 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 without any exceptions. In order to achieve the data sharing between various actors a constraint is put on the data information model by making it open so that it can be shared or used by any software applications throughout the project life cycle. This openness to the model can be achieved by an open data schema called Industry Foundation Classes(IFC).

3 Open BIM data and logical meta models for construction project management

This chapter describes information and entities needed to represent the cost information in the ifc schema and establishes relation with each other using relationship entities. In similar way, meta logical model is developed to time scheduling.

3.1 Open BIM data model for time schedule information by using IFC schema

The Information Requirement to develop the open BIM data model for Time Schedule Information is divided into 7 essential parts as shown in the figure below.

1. Project information
2. Work plan information
3. Work schedule information
4. Work calendar information
5. Task information
6. Resource information
7. Product information

- **Project Information**

In essence ,a construction project contains the details of the design, engineering ,construction or maintenance activities as its core information.IfcProject is used to describe the information based on the context of the project. The context of the project includes details like default units , the project coordinate system , coordinate space dimension and so on. The main function of IfcProject is to provide root instance and context for the information involved in the project.

- **Work Plan Information**

Planning and scheduling of the work form the integral part of Work Plan Information . Planning , at its core , means to prioritize among various works by deciding on the efficient ways to execute them and also to allot the required time necessary for the execution. This information is represented by IfcWorkPlan in IFC schema. Strictly speaking , IfcWorkPlan contains information on set of work schedules.

- **Work Schedule Information**

Scheduling refers to process of arriving decisions on the various works as to when and by whom those works/tasks would be executed. It also provides information on duration necessary to carry out each of those tasks.
An IfcWorkSchedule represents a task schedule of a work plan, which in turn can contain a set of schedules for different purposes.

- **Work Calendar Information**

Work Calendar Information refers to the working and non-working time periods for tasks and resources. In the IFC schema , the Work Calendar Information is represented using IfcWorkCalendar.The IfcWorkCalendar also enables to define both specific time periods as well as repetitive time periods based on frequently used recurrence patterns.

- **Task Information**

The details and specifics about an identifiable piece of work and its associated tasks are contained in the Task Information. The task can generally pertain to the construction activity or installation of products but is not limited to these. A task can also be used in the context of design processes, move operations and other design, construction and operation related activities as well. IfcTask is used to represent the Task Information in IFC schema.

- **Resource Information**

The details or the information necessary to determine the costs , schedule and other impacts resulting through the usage of a resource or a product is defined in Resource Information. For example , the use of contruction equipment or the amount of labor involved in the execution of a work comes under Resource Information .The Resource Information in IFC schema is represented by IfcResource.

- **Product Information**

Product Information represents the abstract information of any object in relation to its geometric or spatial context.It also represents information pertaining to non-physical items such as grid , annotation , structural actions ,etc. The Product Information is represented by IfcProduct in the IFC schema.

The Time Schedule Information is essentially composed of classes and attributes which define the data contained in the Time Schedule Information. The classes and attributes are very important in developing the meta model for Time Schedule Information. The following table explains in detail about these classes and attributes and how they influence the information.

Table 4: Entities to represent time schedule information in IFC schema[25]

Entity	**Attributes**	**Description**	**Type**
IfcWorkCalendar	WorkingTimes	Set of times periods that are regarded as an initial set-up of working times. Exception times can then further restrict these working times.	IfcWorkTime
	ExceptionTimes	Set of times periods that define exceptions (non-working times) for the given working times including the base calendar, if provided.	IfcWorkTime
	PredefinedType	Identifies the predefined types of a work calendar from which the type required may be set.	IfcWorkCalendarTypeEnum
IfcTask	Status	Current status of the task.	IfcLabel
	WorkMethod	The method of work used in carrying out a task.	IfcLabel
	IsMilestone	Identifies whether a task is a milestone task (=TRUE) or not (= FALSE).	IfcBoolean
	Priority	A value that indicates the relative priority of the task (in comparison to the priorities of other tasks).	IfcInteger
	TaskTime	Time related information for the task.	IfcTaskTime
	PredefinedType	Identifies the predefined types of a task from which the type required may be set.	IfcTaskTypeEnum
IfcPermit	PredefinedType	Identifies the predefined types of permit that can be granted.	IfcPermittypeEnum
	Status	The status currently assigned to the permit.	IfcLabel
	Long Description	Detailed description of the request.	IfcText
IfcWorkControl	CreationDate	The date that the plan is created	IfcDateTime

Entity	Attributes	Description	Type
IfcWorkControl	Creators	The authors of the work plan	IfcPerson
	Purpose	A description of the purpose of the work schedule	IfcLabel
	Duration	The total duration of the entire work schedule	IfcDuration
	TotalFloat	The total time float of the entire work schedule	IfcDuration
	StartTime	The start time of the schedule	IfcDateTime
	FinishTime	The finish time of the schedule	IfcDateTime
IfcWorkPlan	PredefinedType	Identifies the predefined types of a work plan from which the type required may be set	IfcWorkPlanTypeEnum
IfcWorkSchedule	PredefinedType	Identifies the predefined types of a work schedule from which the type required may be set.	IfcWorkScheduleTypeEnum

- **Logical meta model for time schedule information**

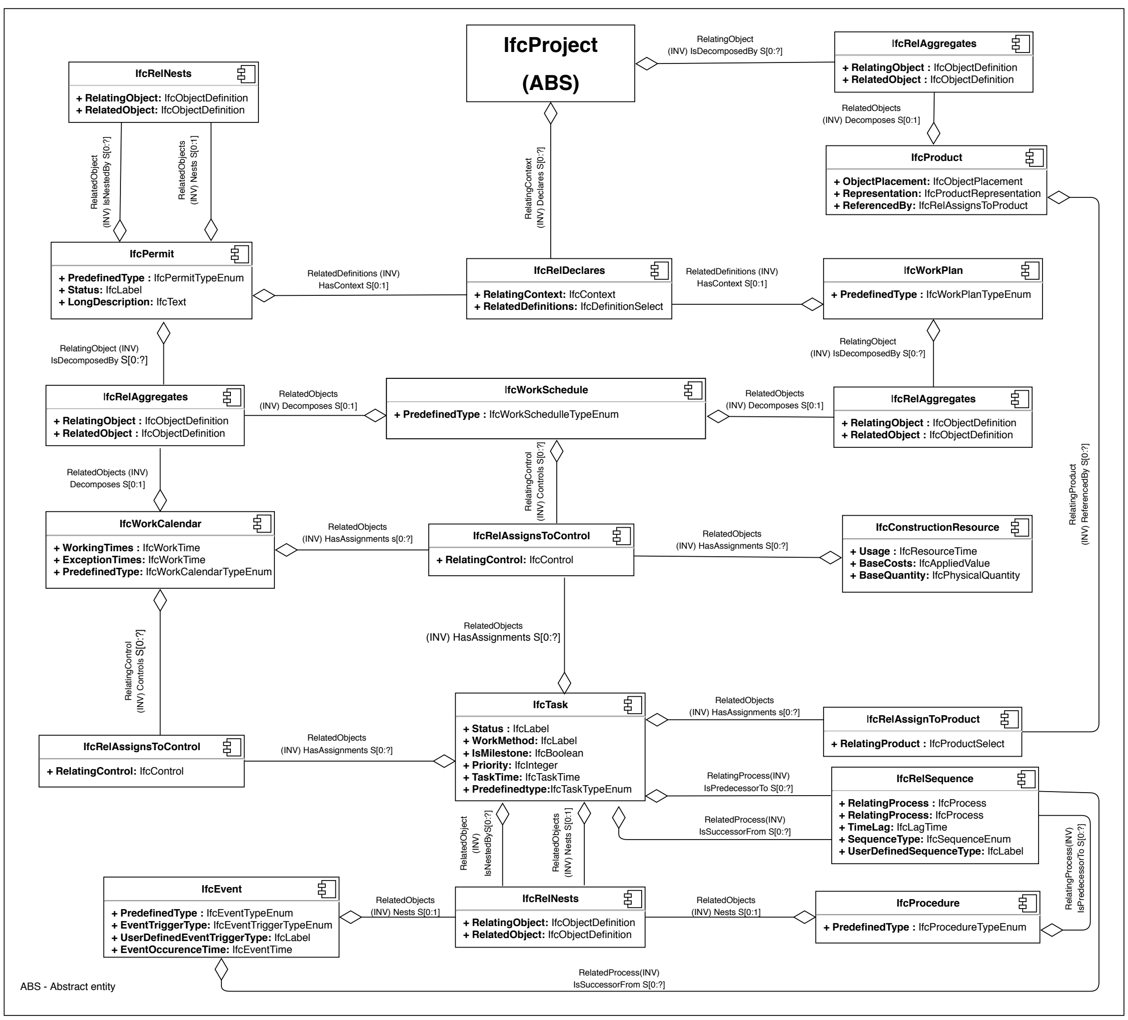


Figure 28: Logical meta data model for schedule information

The information data model for cost estimation using IFC standard is created as shown in figure 28. Scheduling the time in a project is at utmost importance, the model should work in-accordance with the real world time and cost constrains. To implement this, a good model will have multiple layers of entities which controls the whole status of the project. As from the figure below, it is clear that IfcProject is influenced by IfcRelDeclares and IfcRelAggregates. The former also pulls the wire over IfcPermit and IfcWorkPlan but the latter plays an important role in segregating the objects in the IfcProduct to distribute accordingly.

On a side-note, the latter have the control over IfcWorkPlan, IfcPermit and IfcWorkSchedule acting like a feed forward network of interlinked entities. Although IfcWorkSchedule is overseen by IfcRealaggregates, IfcRelAssignsToControl also plays an important role for the same. IfcRelAssignsToControl make a great impact on the whole IfcProject by having a say over IfcTask, IfcWorkCalendar, IfcConstructionResource and IfcWorkSchedule. IfcRelSequence have a greater impact on IfcTask by supervising the whole structure of the IfcProject and also the IfcTask is constantly monitored for the changes in IfcProduct. In the event of multiple objects in IfcPermit and IfcTask, IfcRelNests will control the instances. IfcTask is related to IfcProcedure and IfcEvent using IfcRelNests. IfcEvent and IfcProcedure are connected by IfcRelSequence.

3.2 Open BIM data model for cost estimation by using IFC schema

IFC schema contains entities for cost scheduling data. To define logical meta cost data model, the information related to cost scheduling is divided into 6 categories.

1. Cost schedule information
2. Cost item information
3. Quantity information
4. Price information
5. Product information
6. Resource information

- **Cost Schedule Information**

The primary function of Cost Schedule Information is to solely estimate the construction costs or to combine the cost information with another work order. This information is represented by IfcCostSchedule in the IFC schema.

- **Cost Item Information**

Cost Item Information represents the assignment of a cost or financial value along with the description of the item or a product in the context of being applicable to a cost schedule.It is represented by IfcCostItem in the IFC schema. For example , form work or concrete or steel are those upon which cost item information can be applied.

- **Quantity information**

Qunatity information represents a set of derived measures of an element qunatity. IfcElementQuantity represents this information in the IFC schema. IfcQuantitySet is the the abstract super type for all quantity sets attached to objects. The quantity set is a container class that holds the individual quantities within a quantity tree. These quantities are interpreted according to their name attribute and classified according to their measure type. Length, area, volume and time ...etc. are examples for quantities.

- **Price Information**

The price information represents the rates or costs declared in the bill of quantities or cost schedule. IfcAppliedValue and IfcCostValue represents this price information in the IFC schema.

Product and Resource information has same meaning as explained in the section 3.1.

The table 5 explains about the attributes related to cost information in the IFC schema.

Table 5: Entities to represent cost schedule information in IFC schema[25]

Entity	Attributes	Description	Type
IfcAppliedValue	Name	A name or additional clarification given to a cost value.	IfcLabel
	Description	The description that may apply additional information about a cost value.	IfcText
	AppliedValue	The extent or quantity or amount of an applied value.	IfcAppliedValue-Select
	UnitBasis	The number and unit of measure on which the unit cost is based.	IfcMeasureWith-Unit
	ApplicableDate	The date on or from which an applied value is applicable.	IfcDate
	FixedUntilDate	The date until which applied value is applicable.	IfcDate
	Category	Specification of the type of cost used.In the absence of any well defined standard, it is recommended that local agreements should be made to define allowable and understandable cost value types within a project or region.	IfcLabel
	Condition	The condition under which a cost value applies. For example, within the context of a bid submission, this may refer to an option that may or may not be elected.	IfcLabel
	ArithmeticOperator	The arithmetic operator applied to component values.	IfcAirthematic-OperatorEnum
	Components	Optional component values from which AppliedValue is calculated.	IfcAppliedValue
	HasExternalReference	Reference to an external reference, e.g. library, classification, or document information, that is associated to the IfcAppliedValue.	IfcExternal-ReferenceRelationship
IfcConstructionresource	Usage	Indicates the work, usage, and times scheduled and completed.	IfcResourceTime
	BaseCosts	Indicates the unit costs for which accrued amounts should be calculated.	IfcAppliedValue
	BaseQuantity	Identifies the base quantity consumed of the resource relative to assignments.	IfcPhysical-Quantity
IfcProduct	ObjectPlacement	Placement of the product in space, the placemnet can be absolute,relative or constraint.	IfcObject-Placement

Entity	Attributes	Description	Type
IfcProduct	Representation	Reference to the representations of the product, being either a representation or as a special case a shape representations.	IfcProduct-Representation
	ReferencedBy	Reference to the IfcRelAssignsToProduct relationship, by which other subtypes of IfcObject can be related to the product.	IfcRelAssigns-ToProduct
IfcCostSchedule	PredefinedType	Predefined generic type for a cost schedule that is specified in an enumeration. There may be a property set given specifically for the predefined types.	IfcActorSelect
	Status	The current status of a cost schedule. Examples of status values that might be used for a cost schedule status include: • PLANNED • APPROVED • AGREED • ISSUED • STARTED	IfcLabel
	SubmittedOn	The date and time on which the cost schedule was submitted.	IfcDateTime
IfcCostItem	PredefinedType	Predefined generic type for a cost item that is specified in an enumeration. There may be a property set given specifically for the predefined types.	IfcCostItemTypeEnum
	CostValues	Component costs for which the total cost for the cost item is calculated, and then multiplied by the total CostQuantities if provided. If CostQuantities is provided then values indicate unit costs, otherwise values indicate total costs.	IfcCostValue
	CostQuantities	Component quantities of the same type for which the total quantity for the cost item is calculated as the sum.	IfcPhysicalQuantity

The information data model for cost estimation using IFC standard is created as shown in figure 29. IfcCostItem depends upon numerous entities which are interlinked in multiple layers of objects. When there are multiple IfcCostItem stacked up on each other, IfcRelNests will control the related objects to be nested accordingly On the other-hand, IfcRelAssignsToControl will assign the IfcCostItem with the IfcProduct and IfcCostSchedule and in-turn have a main role in controlling the value of IfcCostItem. IfcProduct is governed by the IfcRelDefinesByProperties which also have control over IfcCostItem, so we can say that IfcProduct is once of the primary entity that controls the IfcCostItem. Although IfcRelDefinesByProperties is influenced by IfcPropertySetDefinition, the latter also influences on the main character i.e IfcQuantitySet and IfcPropertySet.

Even though it is clear that IfcRelAssociatesAppliedValue have a significance over the IfcCostItem, its cascading effect on IfcConstructionResource and IfcAppliedValue should not be overlooked as it has an included description of IfcCostValue.IfcConstructionResource is then again overseen by IfcRelAssignsToControl which in fact plays a major role across the board in controlling most of the entities related to IfcCostItem.

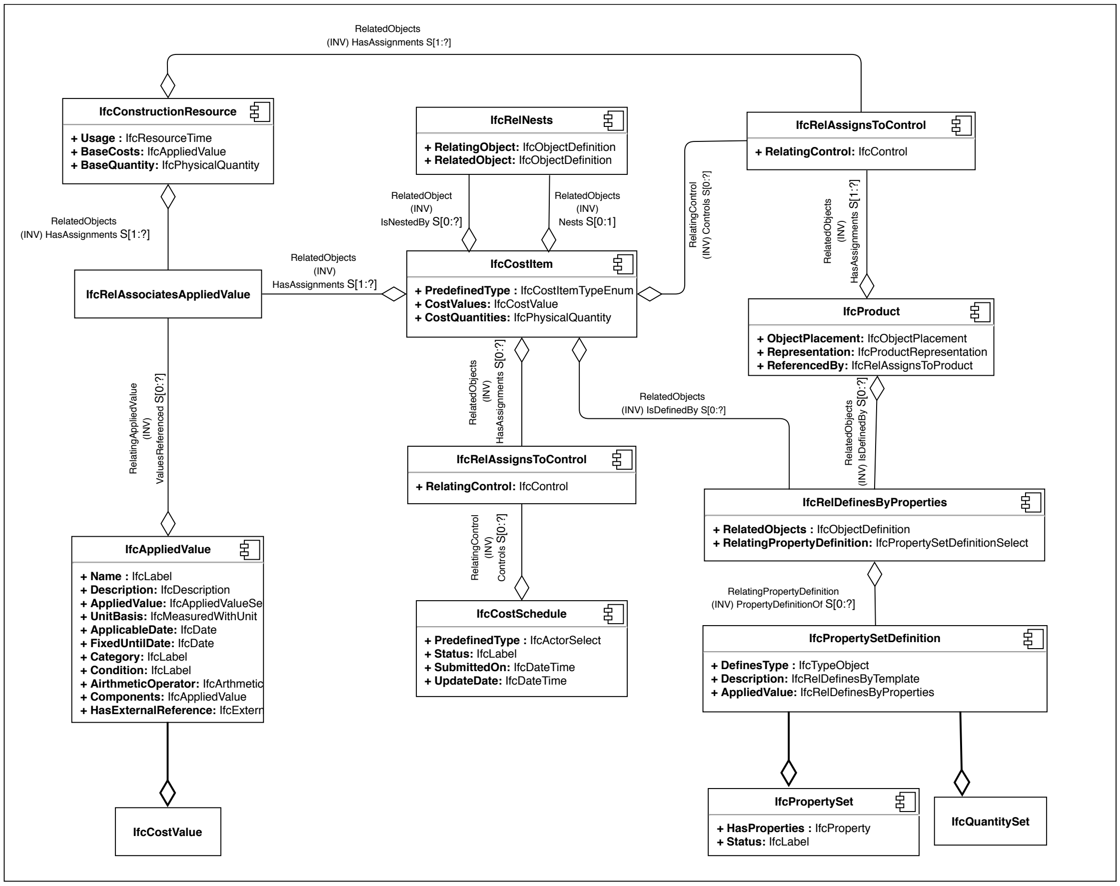


Figure 29: Logical meta data model for cost estimation

3.3 Conclusion

As a construction management domain interest, logical meta data model is developed for cost information and time scheduling information. When the modeler want to generate the models, they will use this meta models in the model construction tools and also it will be used as a reference to validate the ".ifc" files.

4 Research methodology and application

4.1 Research Methodology

The research methodology was carried out to add time and cost scheduling parameters to the object based model. To achieve this two research methodologies were proposed. One is for time schedule information i.e. a 4D model development and second one is for cost schedule information i.e. a 5D model development.

4.1.1 Research methodology for development of 4D model

This methodology attempts to add Time Schedule Information data to the object based model. This is also known as 4-Dimensional model.

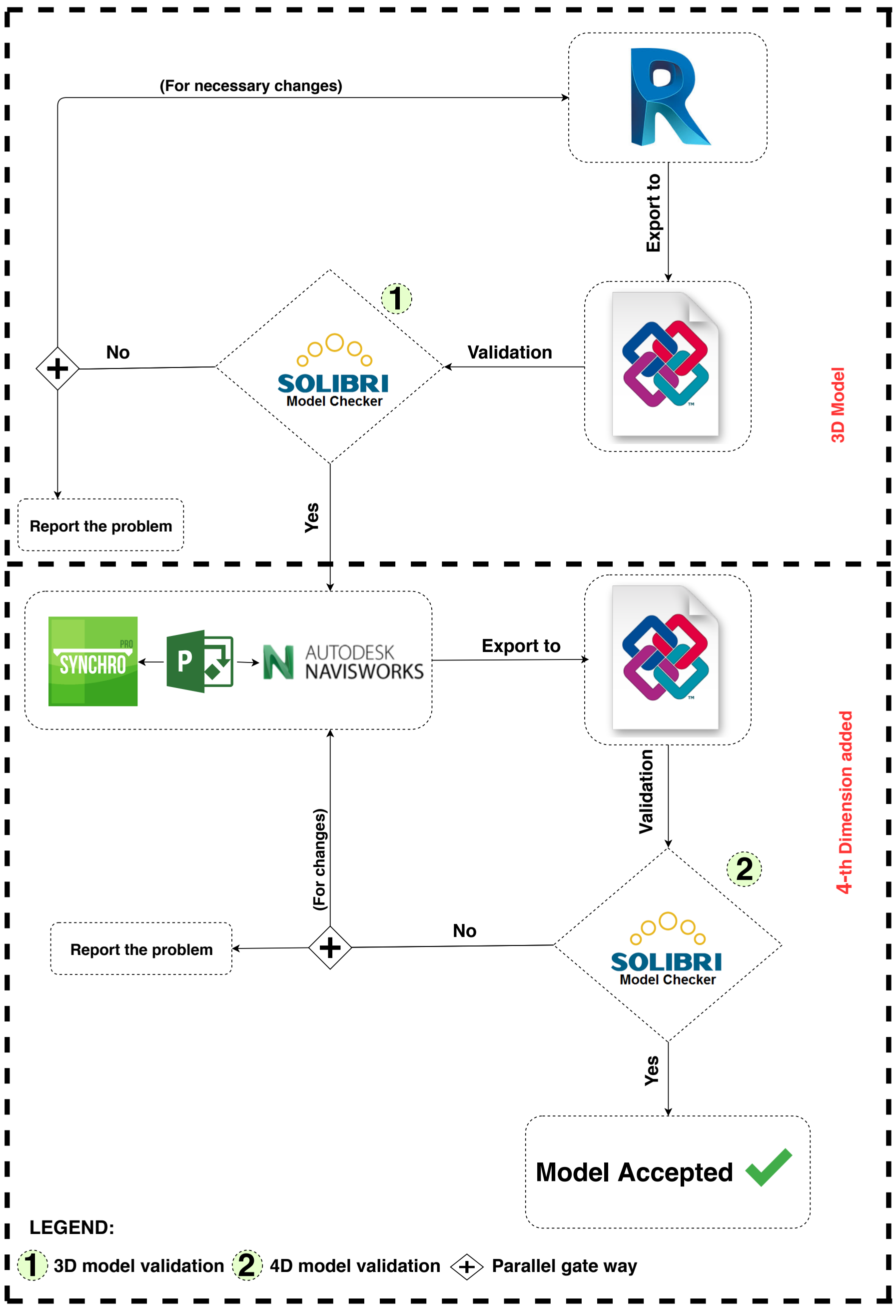


Figure 30: Research methodology for 4D model development and validation

The process flow adopted is explained as follows :

- As the first and intial step, the object based model is generated using the Revit application. The generated model is exported to a neutral format (IFC) which can be used across software's of other disciplines .However, before the model is exported to other software systems, the model is checked by model checkers like e.g. SOLIBRI.
- In the model checker, in case of any error or any incoherence of the quality of the data, the findings are simultaneously reported and sent back to the native software for further modifications.
- In case of no error or quality findings, the object based model is imported on to a 4D modeling application. Here there are two distinct ways to add time schedule information to the object based model. One way is to create tasks through software systems like SYNCHRO and AUTODESK NAVISWORKS. The other way is to import it through MS PROJECT. In this methodology the latter is chosen.
- After the import of the data, the object based model is clubbed with the Time Schedule Information data and exported to a Neutral Format file.
- In the Neutral File Format file validation is carried out by the model checker e.g. SOLIBRI to find errors or discrepancies in the quality of the data. In case of errors, the findings are reported and sent to the 4D modeling application and also the native software application to resolve the errors.
- Alternatively, if the model checker validates the data in the Neutral File Format to be error free then the model is accepted which can be used across the different BIM applications.

4.1.2 Research methodology for development of 5D model

The existing BIM tools are lack to add time schedule information and cost schedule information in one platform or to add cost schedule information to 4D model. This constraint lead to exclude the 4D data in the 5D modeling in present methodology. Thus, the methodology tries to add cost parameter to the object based model without time schedule information. The whole methodology is conceived into 2 parts where one part focuses on 3D model development and the other deals with the modeling and validation of the 5D model. The methodology is described below :

- To start with the process , the 3D BIM model is generated in Revit using the Visual programming tool Dynamo. The generated model is then exported to a neutral format file which is capable of being shared by softwares of multiple disciplines. Also, before the model is exported to other softwares, the model is checked by model checkers (i.e. SOLIBRI).
- In the model checker, an error or any discrepancy in the data is detected, reported and directed back to the native software for further modifications.
- In case of a valid and error free data model, the object based model is exported to a 5D or 5 Dimensional modeling platform which uses REVIT or IFC PRIMUS . Here the object based model is combined with the cost parameters and parametric variation is enabled to the Revit generated object based model using EXCEL and DYNAMO. Later on exported to a Neutral Format file.
- The hybrid data is sent to the SOLIBRI application for validation . The validator checks for errors and then sends back the data to the 5D modeling platform for error adjustments or corrections .
- In case data passing through the validator is error free, then the model is accepted and made available to the other BIM applications. As part of the cross verification to this methodology, after the model is accepted, it is checked with IFC PRIMUS to check its compatibility with other software applications

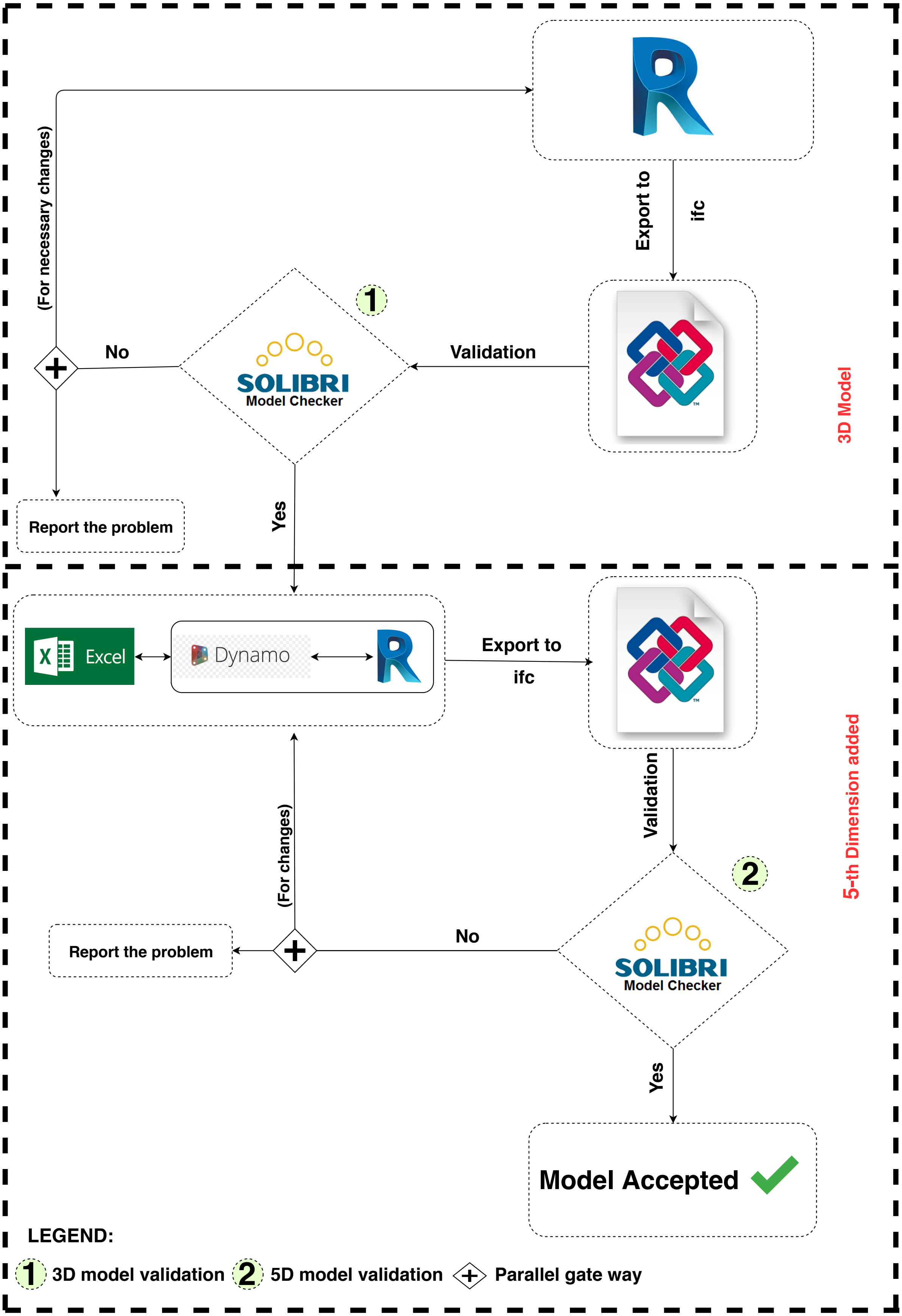


Figure 31: Methodology for 5D model development and validation

4.2 Methodology application

This section describes the application of the proposed methodologies to develop a 4D model and a 5D model, it explains about validation of the developed models using model viewers or model checkers.

4.2.1 Development of 4D model and validation

The application of the research methodology developed for the development of cost information model (4D model) is carried out in four steps.
Creation of the object based model: A BIM model of a residential building is developed using Revit 2019 tool. The building comprises of roof, floor, windows, rooms, doors, railing elements along with external and internal walls. Fig. 32 below shows the 2D model and Fig. 33 shows the 3D model of the same. The model is converted to IFC using the export option in Revit 2019. The Model View Definition called Design Transfer View is used to transfer the information into the IFC file. With this, the base quantities and element properties contained in Revit are transferred to IFC.

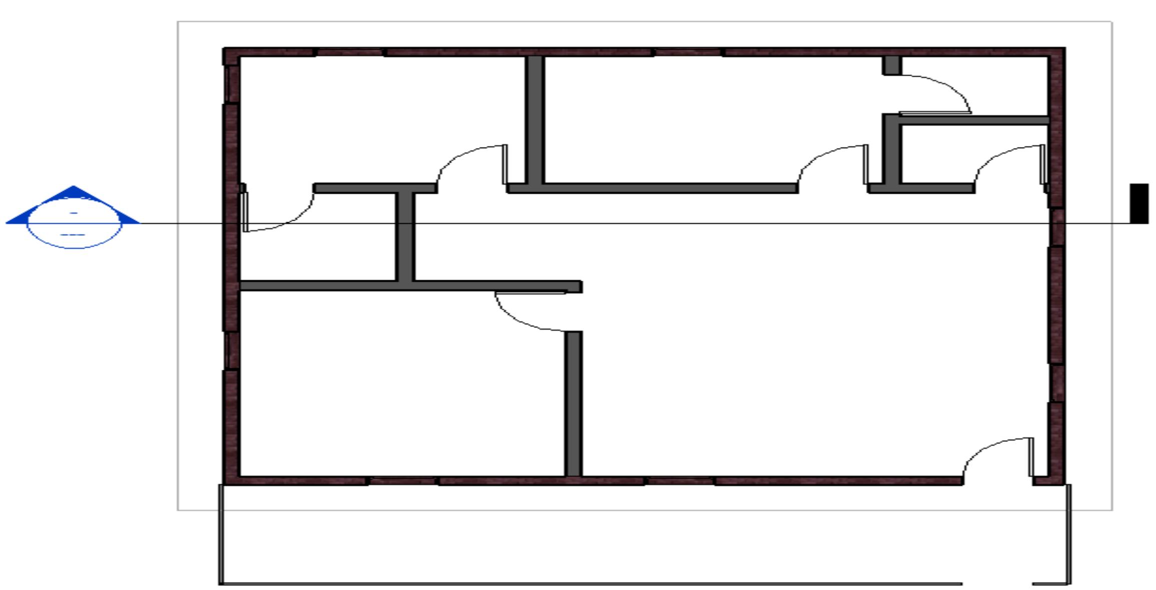


Figure 32: 2D model of residential building

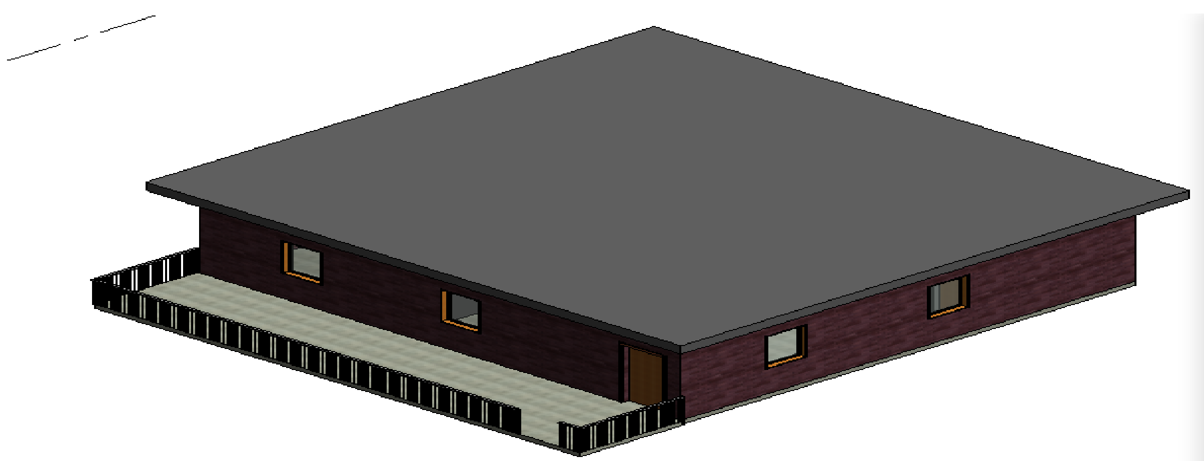


Figure 33: 3D model of residential building

Validation of object based model: The model validation is done by using the model checker Solibri. The object based data model generated using Revit is exported to the model checker in IFC format. The validation of the model data is carried out by a model checker called Solibri. The model checker essentially checks the input data which is comprised of the various elements of a structure. In Fig.34 the windows, doors, railing elements are shown. Similarly the external and inter walls, the floor and the whole structure can be viewed in Fig. 35 and Fig. 36 respectively. After validation the IFC data model is sent to the 4D modeling platform where the data is combined with time schedule information. The detailed results of this step are delineated in section 5.

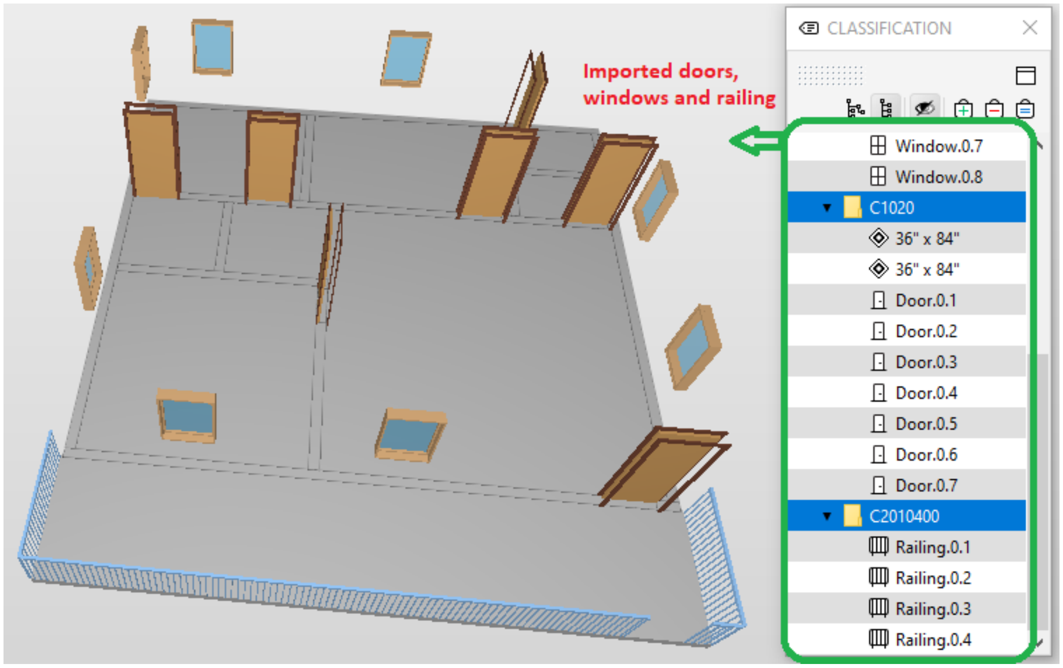


Figure 34: Residential building 3D model validation

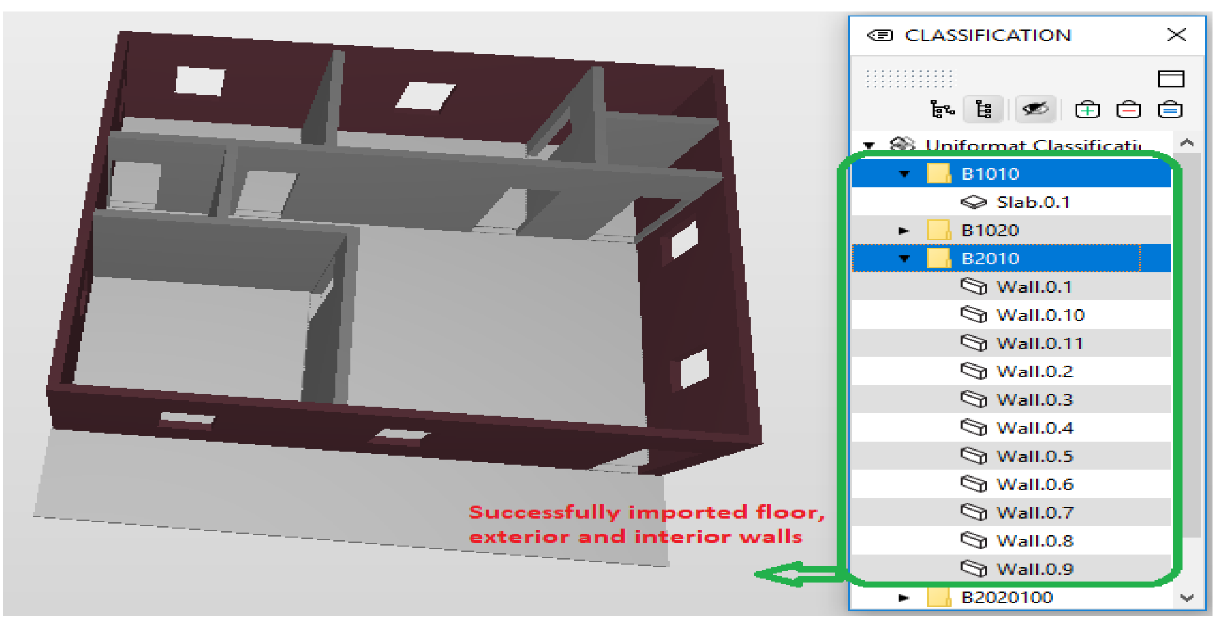


Figure 35: Residential building 3D model validation

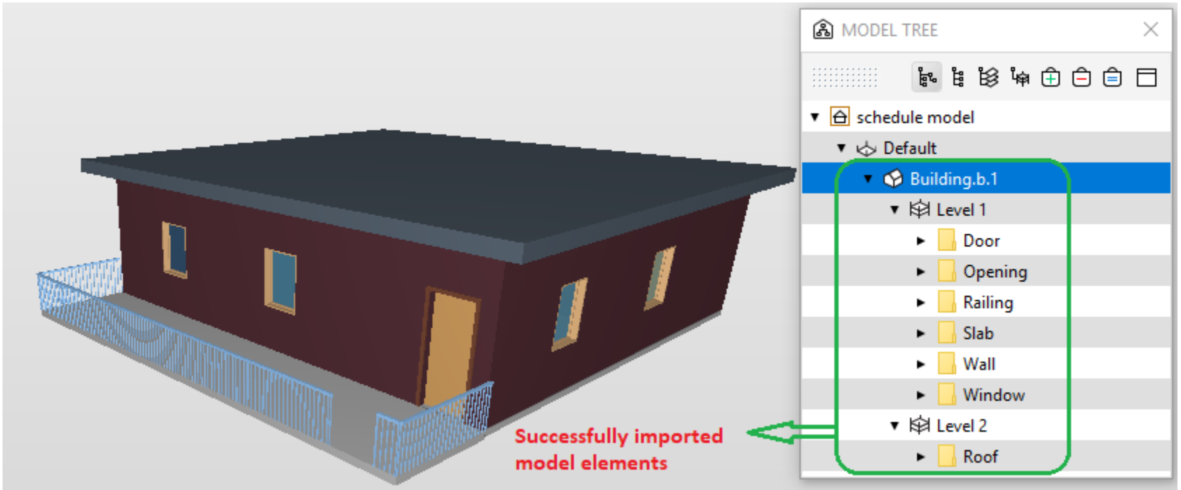


Figure 36: Residential building 3D model validation

Development of 4D model: The construction of the 4D model is done using the software tools "MS Project", "Navisworks Manage" and "Synchro". MS Project is used to develop a task planning and this data is transferred to the BIM tools Synchro and Navisworks Manage separately. The 4D model is developed in Navisworks and Synchro individually for the better results.

- **4D Model development with NAVISWORKS MANAGE**

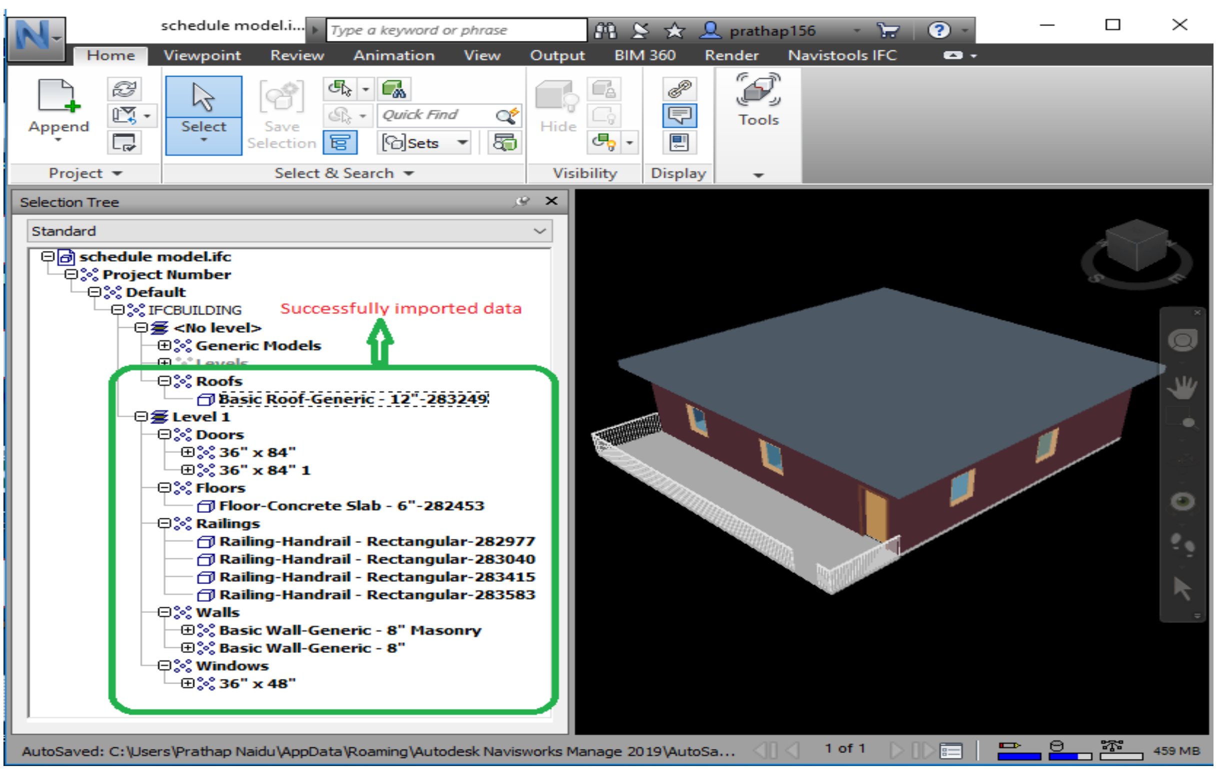


Figure 37: Imported BIM model in Navisworks Manage

The objected based data model is created using Revit and imported using Autdesk Navisworks. The below figure depicts the object based model in Navisworks. Onto the left in the selection tree, the different imported structural elements are shown and the 3D model is shown in the right.

Now that the data model is ready, it has to be combined with time schedule information. The time schedule information is imported usually from construction project management software systems such as MS Project, Primavera, etc. or it can create in the Navisworks software. In this example, the data is imported through MS Project through the data source as shown in the below Fig. 38. The imported task information can be seen Fig. 39.

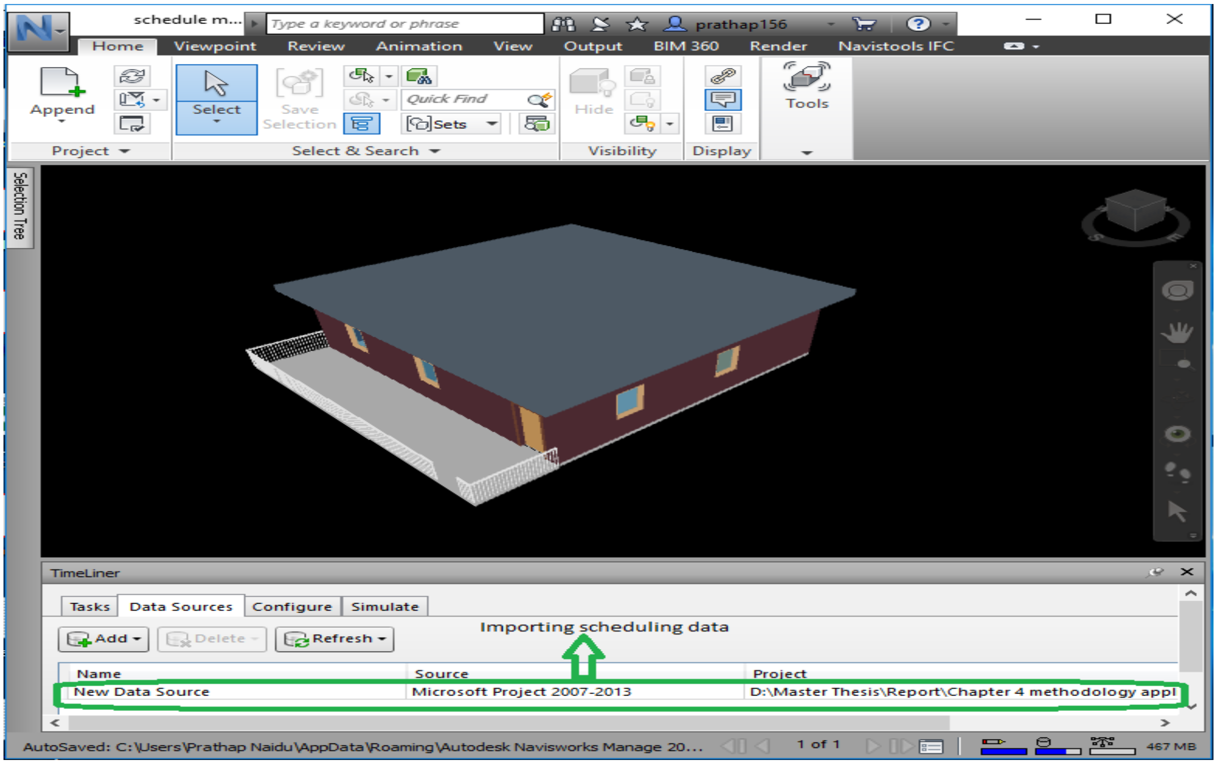


Figure 38: Importing time schedule information from MS Project

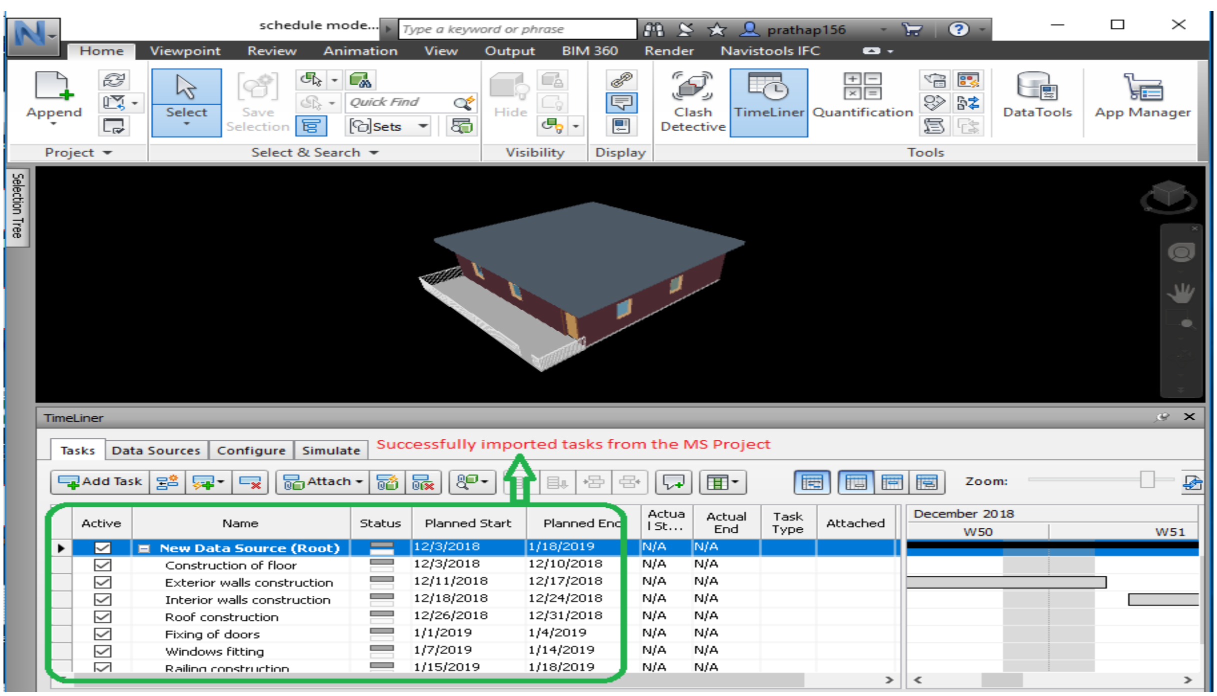


Figure 39: Imported time schedule information in Navisworks Manage

The data model consists of various structural elements which are not grouped. In order to map the time schedule information to the appropriate structural elements with the appropriate task embedded in the former, it is prudent to classify the different structural elements into sets. In the Fig. 40, it can be seen that there are sets created for floors, walls, doors, roofs, windows and railing.

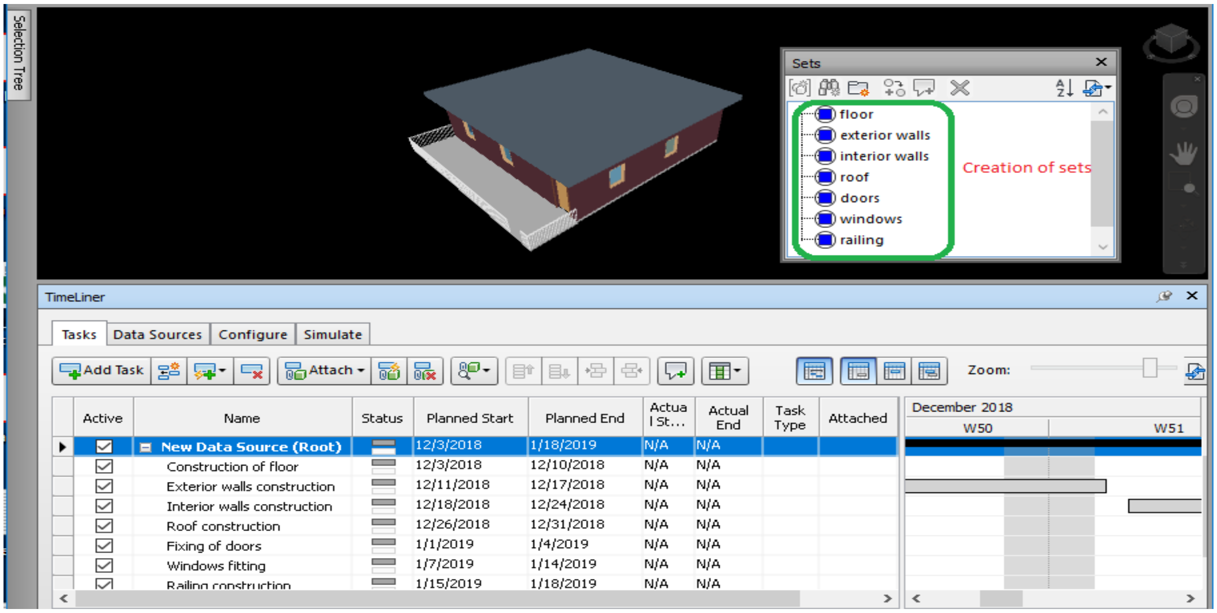


Figure 40: Creation of sets for building elements in Navisworks Manage

In the bottom of the Fig. 41, the name of the task, the type of the task and the associated structural element set is shown . By assigning the task and its type to a selected element set, the mapping is done.

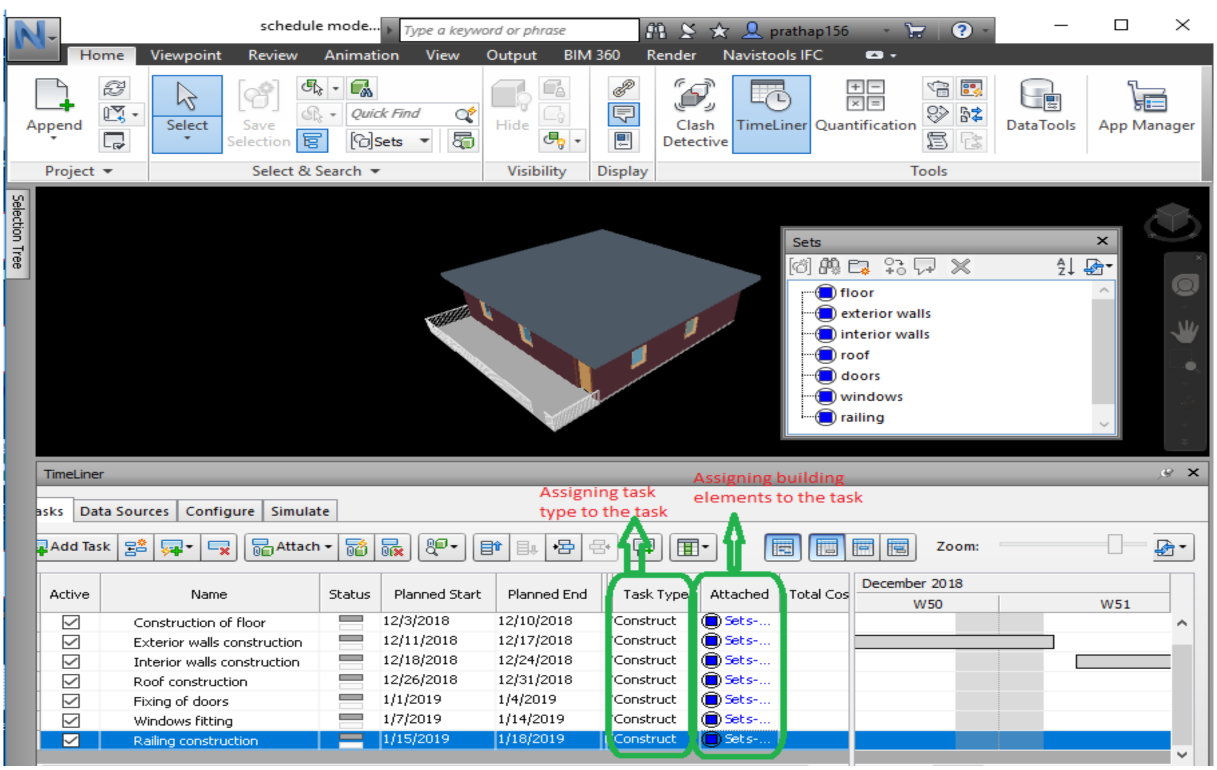


Figure 41: Assignment of sets to tasks

The assignment of tasks to a set of chosen elements is followed by the simulation process to actuate the assignment. In Fig. 42, it can be clearly seen that, the task of Interior Walls Construction applied to the interior wall set is in progress. The task together with the selected element of the data model represents the 4D model.

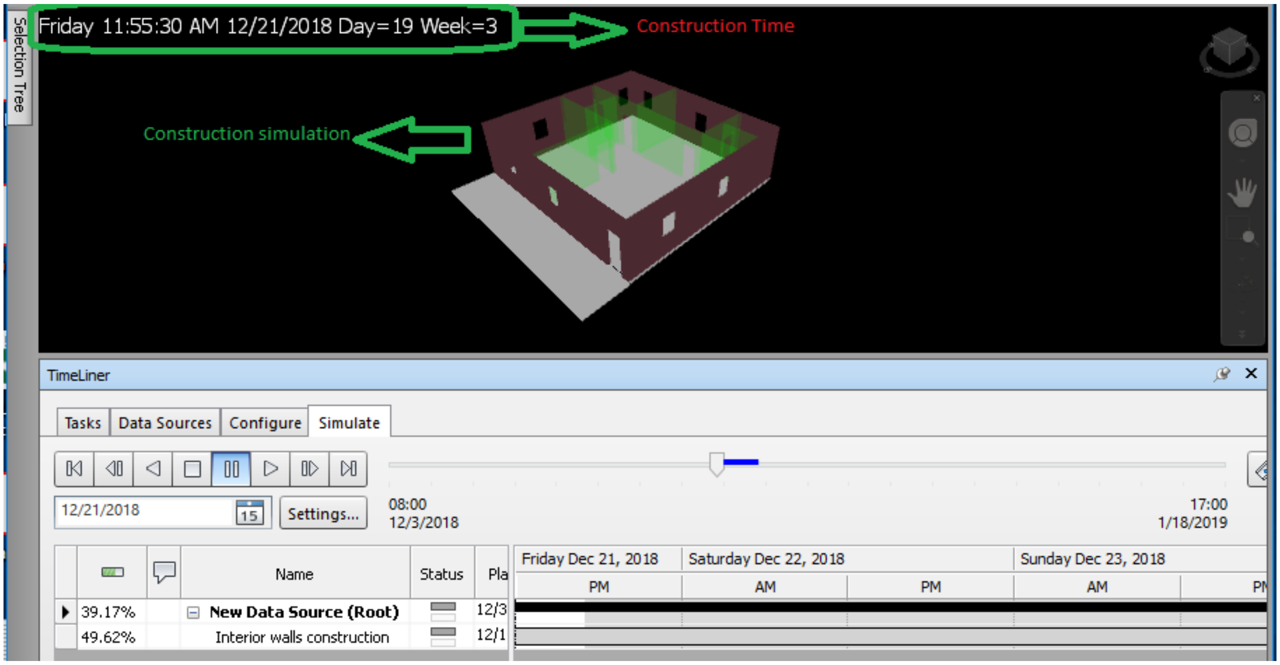


Figure 42: 4D construction simulation in Navisworks Manage

The 4D model generated using Navisworks limits itself by not allowing the 4D model to be exported in IFC format. To achieve this, Synchro is adopted and the underlying procedure to generate the 4D model is described in the proceeding section.

- **4D Model development with SYNCHRO**

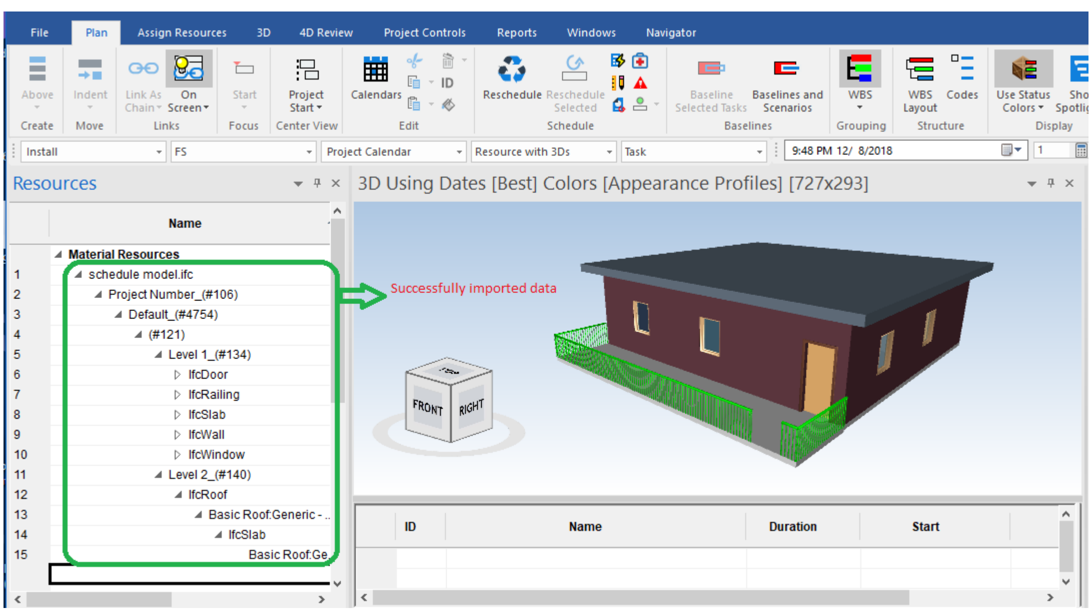


Figure 43: Imported BIM model in Synchro

The object data model developed using Revit is to be combined with the time schedule information. The generated model can be seen in Fig. 43 with the selection tree articulating the various elements of the structure and also the whole structure.
The time schedule information obtained from the MS Project application is saved in ".XML" format and Synchro has the ability of importing the information stored in ".XML" format. Unlike Navisworks the elements do not have to be grouped into sets and thus the tasks can be assigned to the selected elements. Fig. 44 illustrates the various tasks assigned to the structural elements through the respective structural ID. Also the Gnatt chart scheduling of the concerned tasks with the start time, end time and duration is shown in the figure. At the bottom right of the figure, we can see the current status of the building represented by a dotted red line.

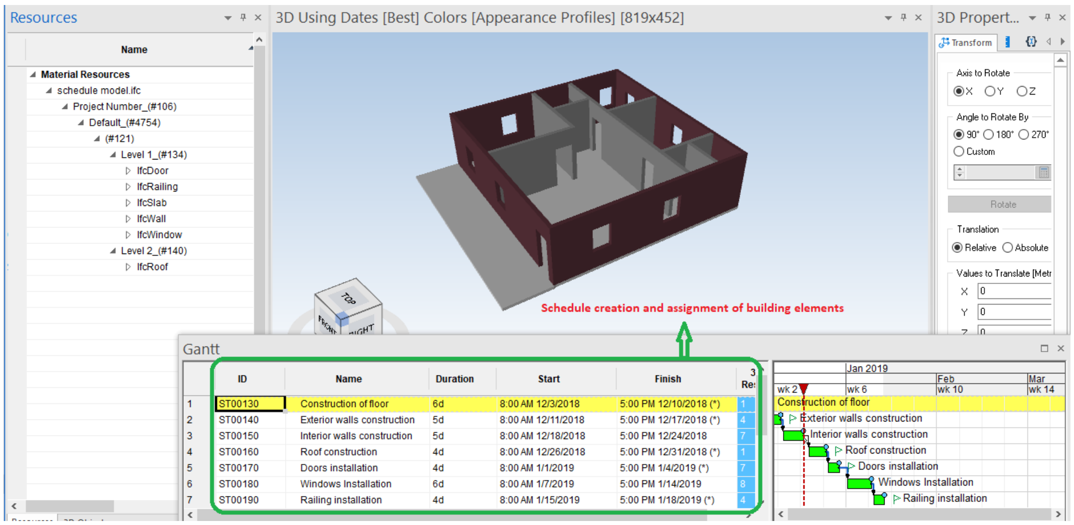


Figure 44: 4D Model in Synchro

Thus the 4D model data in Synchro can be successfully exported to IFC data for further use.
Validation of 4D model:

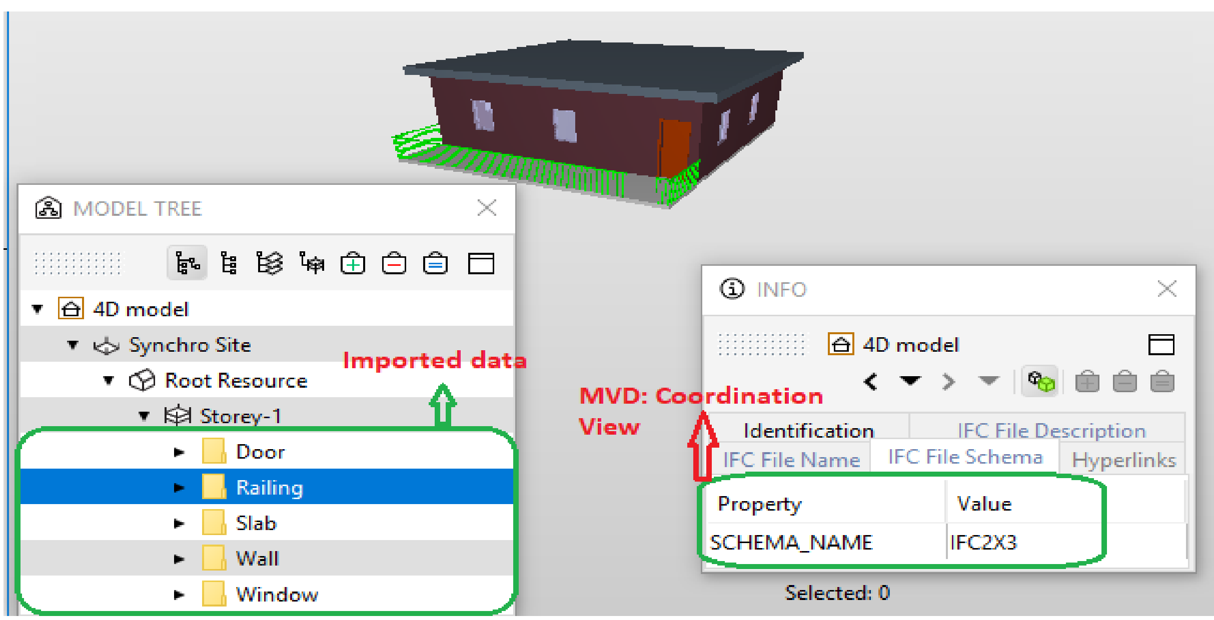


Figure 45: 4D Model validation

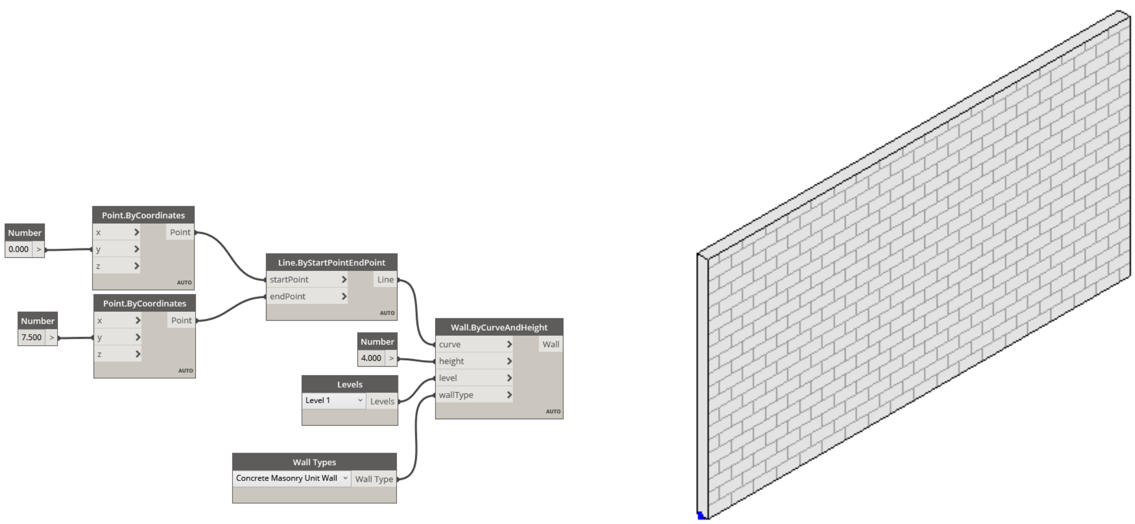
The 4D Model generated in Synchro is to be exported in IFC format which passes through a model validator/checker. The model checker used here is Solibri. Fig. 45 represents the data model imported in Solibri. Synchro uses IFC2X3 schema and Co-ordination View as the Model View Definition to export the data from

Synchro to Solibri. However Synchro is capable of exporting only the architectural information or model of the building without the time schedule information to the model checker. This renders the data to be invalid and thus the exported model cannot be accepted as per Solibri model checker.

4.2.2 Development of 5D model and validation

The steps involved in the development of 5D BIM model is categorized into four. These are explained in the following paragraphs.
Creation of 3D BIM model: As shown in Fig. 46 the wall element is developed in Revit. The physical specifications of the wall element are adopted as shown in the Fig. 47. The wall element seen in the Fig. 46 is created using an algorithm based on the application called Dynamo. In the application, the attributes of the wall are specified using nodes and wires.

The parameters of the wall are obtained through the major node called as "Wall.ByCurveAndHeight" which contains information of the curve, height, level and wallType which are necessary to develop the wall in Revit. The data for the parameters are obtained through other nodes and wires as illustrated in the below figure.



(a) Algorithm to develop wall element in Revit using Dynamo

(b) Wall element in Revit

Figure 46: Development of wall element using Dynamo

After the definition of the respective data for the wall parameters through the algorithm, the same can be seen as instance and type parameters of Revit in Fig. 47. This figure shows details about the material used for the wall element, wall dimensions and other analytical properties.

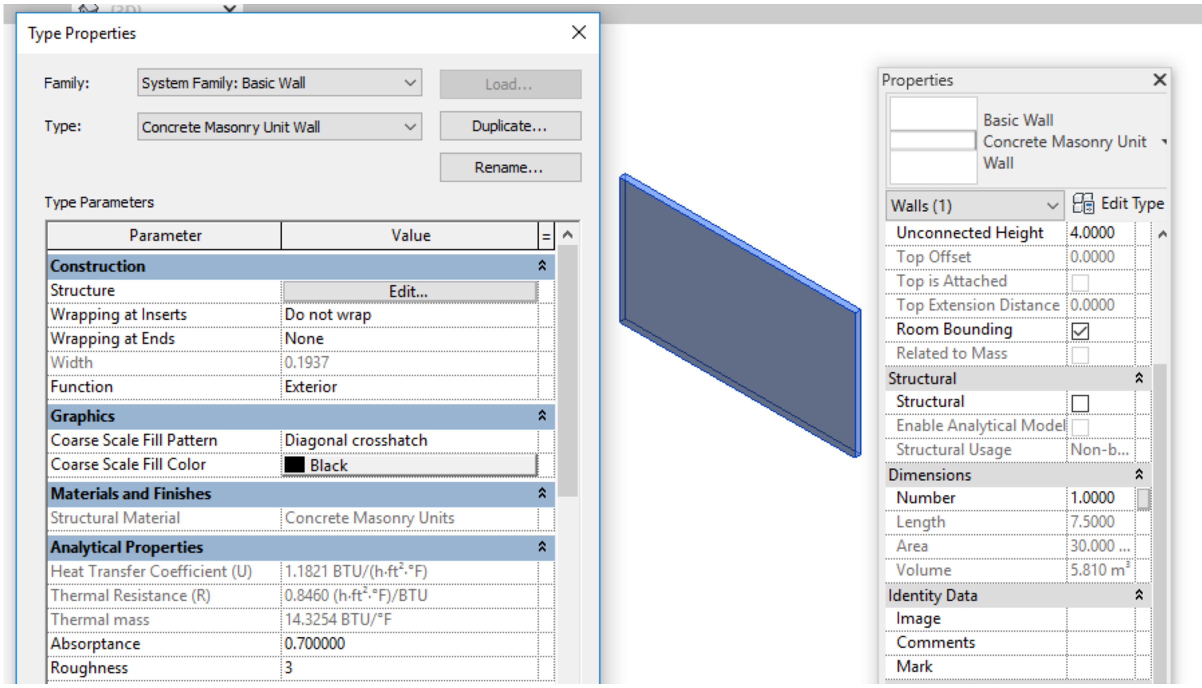


Figure 47: Instance and type parameters of wall element

The generated model is then exported to the 5D modeling software supported by IFC. In order to export the generated data model from Revit to IFC, IFC Design Transfer View is adopted as the Model View Definition.

Before exporting the data model, the IFC common property set and base quantities are exported as separate entities which can be seen in Fig. 48, After this, the model is ready for export to the IFC application and this can be seen in Fig. 49.

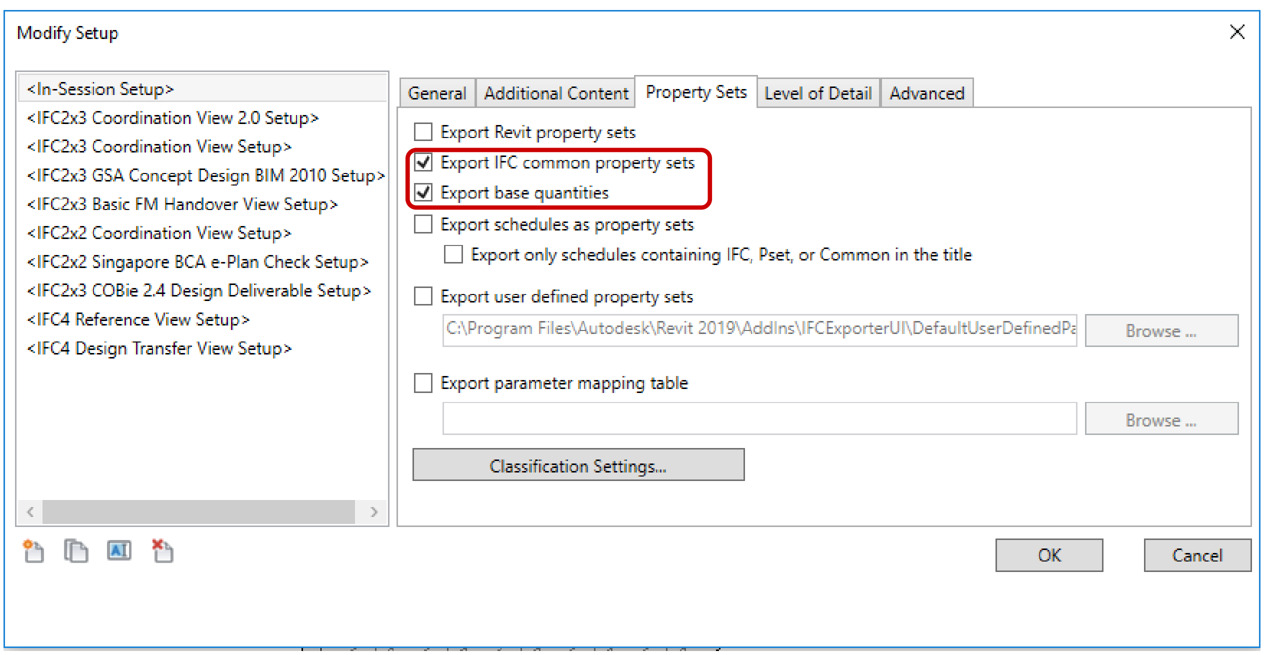


Figure 48: Exporting property sets and base quantities to IFC

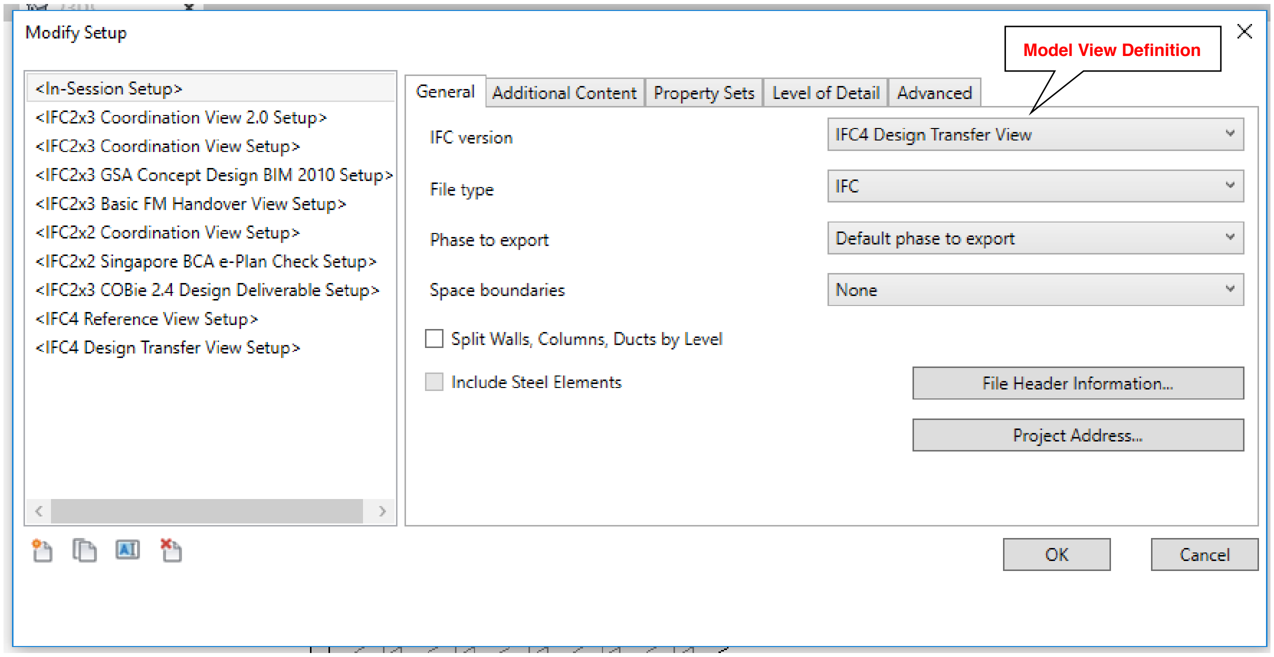


Figure 49: Exporting Revit model into IFC using design transfer view definition

Validation of 3D BIM model: Fig. 50 shows the object based model created in Revit. On to the right of the figure, the model tree is represented where the wall is shown to have a hierarchical relationship in the tree. Onto the left of the figure, the location tab of the wall is highlighted with details of the levels. These levels essentially describe the absolute and the relative location of the selected wall.

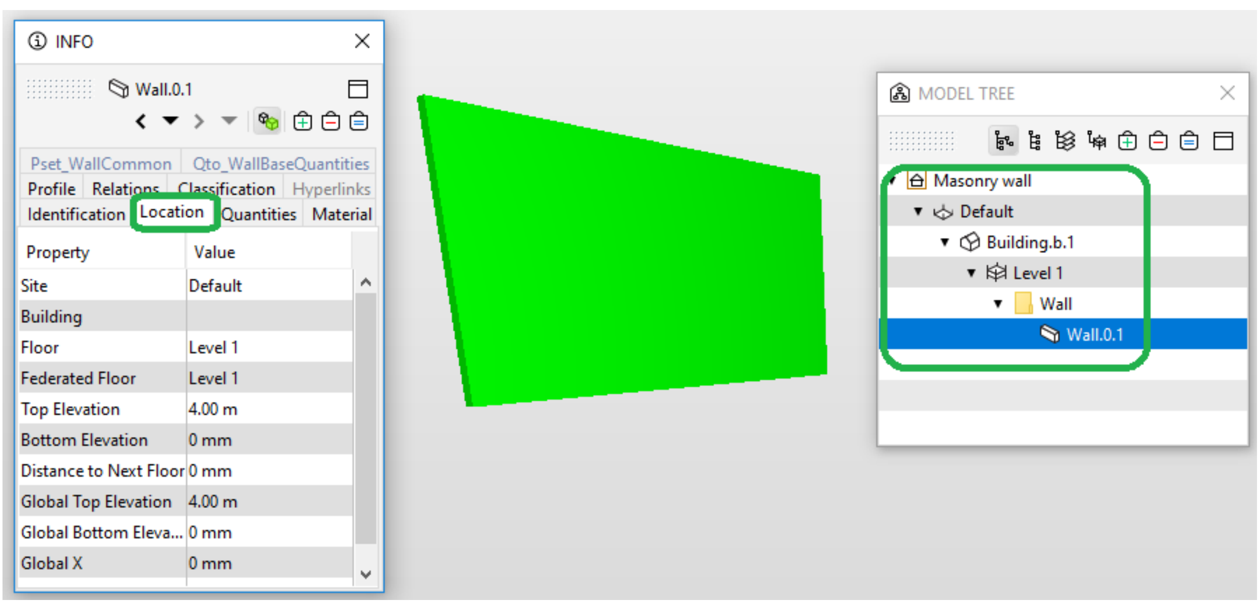


Figure 50: Validation of 3D BIM Model

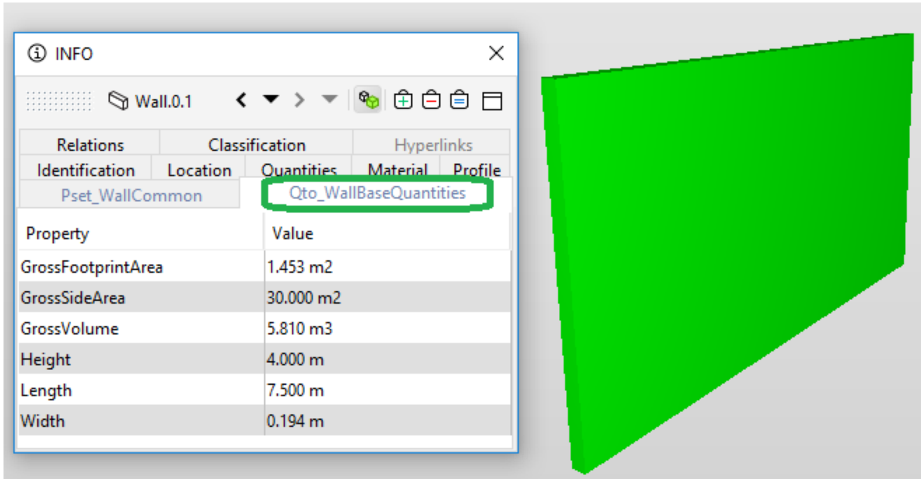


Figure 51: Validation of 3D BIM Model

In Fig. 51, the wall parameters that are essential in exporting the data to 5D BIM model tool. These parameters are available under the WallBaseQuantities tab which contain the footprint area, side area, height, length, width and volume of the wall. From the figure, it can be confirmed that all the necessary details to be exported in the IFC format are made available again to Revit to perform the cost estimation analysis. The architectural data of the model combined with the cost estimation data results in the 5D model.

Development of 5D BIM model: The wall element modeled in Revit along with the cost information is shown in Fig. 52. The main parameters considered here are element ID, wall Family and Type along with the information on physical dimensions and cost information. The cost schedule information model is developed using the schedule tab in the Revit tool. The developed cost schedule is quantity based. Now, The developed 5D model is ready for export into the IFC format to use across the other applications. Before proceeding to this step the model is enabled with parametric modeling and this process is explained in delineated paragraphs.

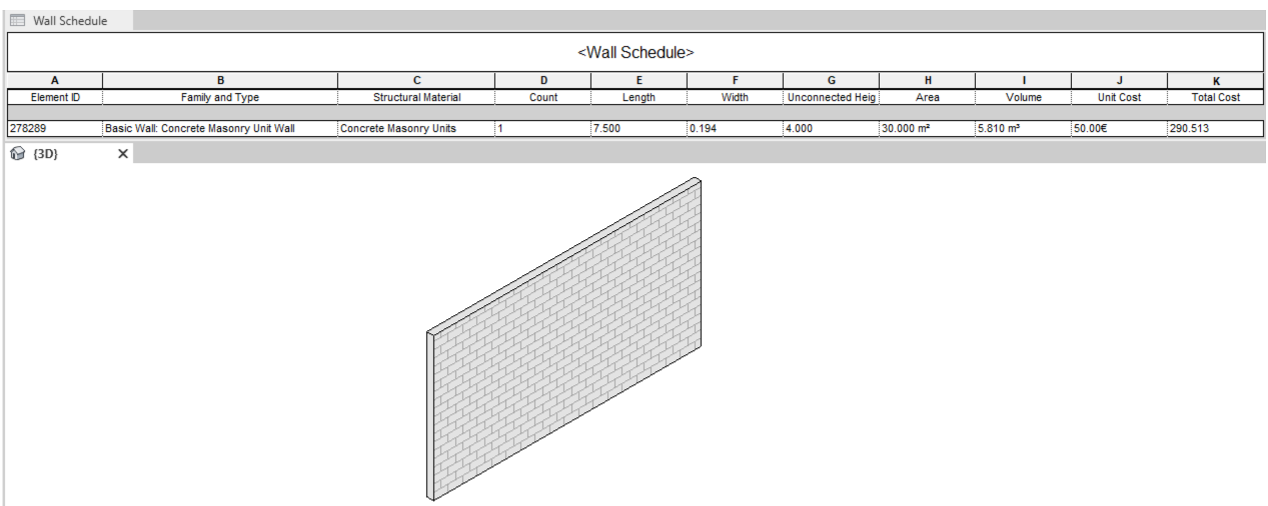


Figure 52: BIM model with cost information

As a first step in enabling parametric modeling in Revit, the algorithm through Dynamo extracts just the wall element out of the other structural elements that make up a building. This is executed by the nodes and their corresponding wires illustrated in Fig. 53. Once the wall element is extracted, the required data of the parameters of the specific wall is extracted through the major nodes which are connected to other nodes via wires and this can be seen in the Fig. 54.

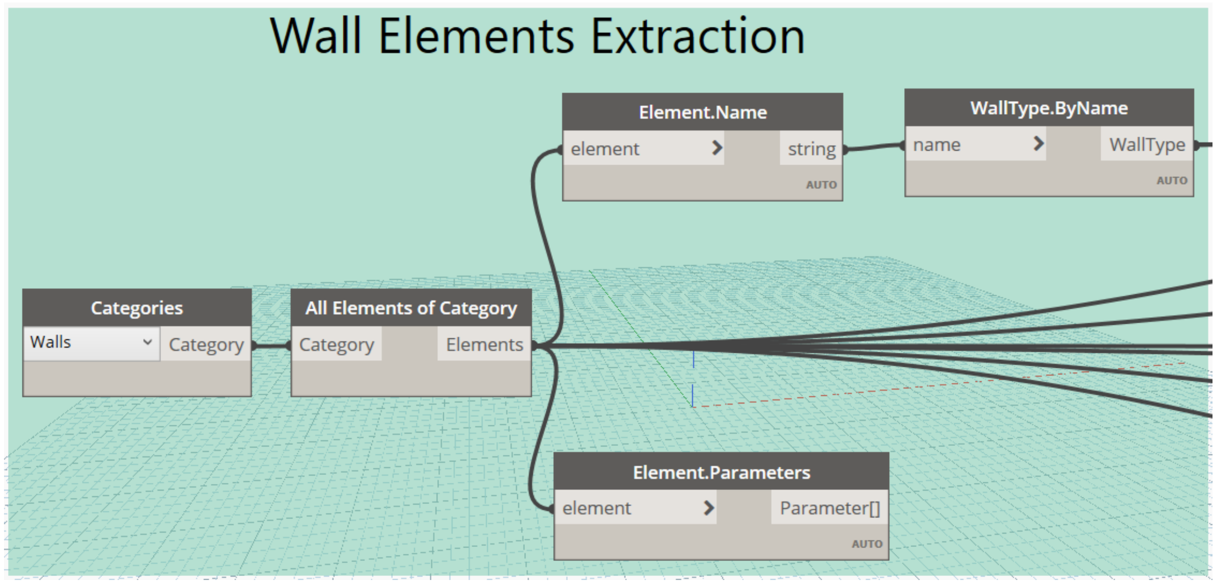


Figure 53: Extraction of wall elements from Revit to Dynamo

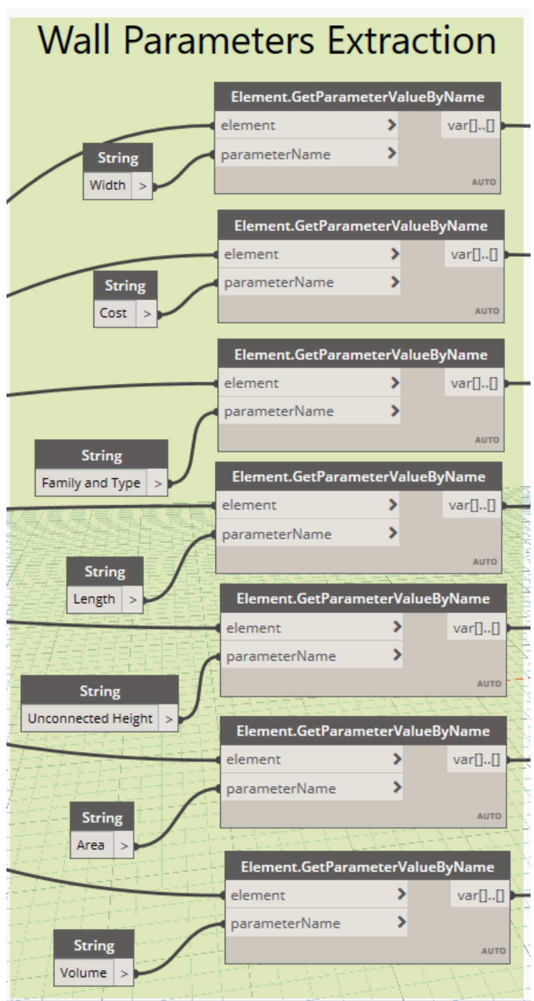


Figure 54: Extraction of wall parameters from Revit to Dynamo

The data which is retrieved through the algorithm in Dynamo is not in list. In order to make the data readable and accessible in Excel, the data of the wall parameters are stacked into lists for each parameter as shown in Fig. 55. Since our aim is to model the wall element parametrically, it is recommended to match the data with its respective name in Excel for easy recognition by the user. To achieve this, a menu bar for the wall parameters is created in the algorithm using the "List.AddItemToFront" node in Dynamo in Fig. 56 which would be reflected in Fig . 58.

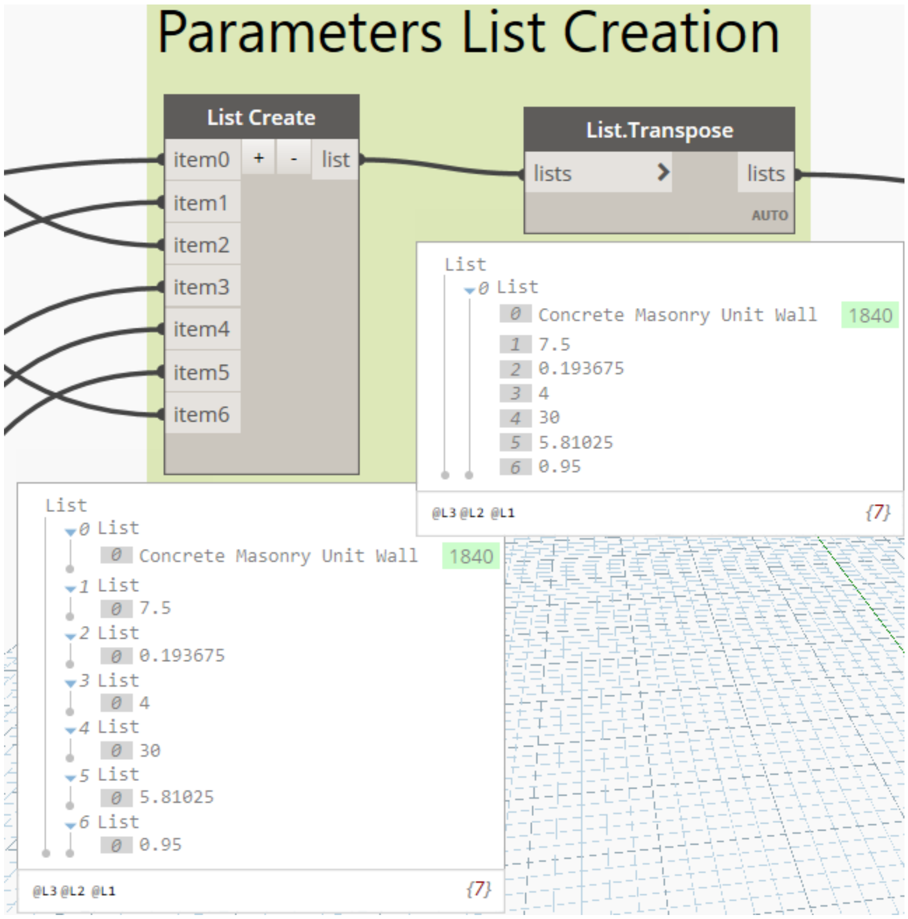


Figure 55: Creation of wall parameters list in Dynamo

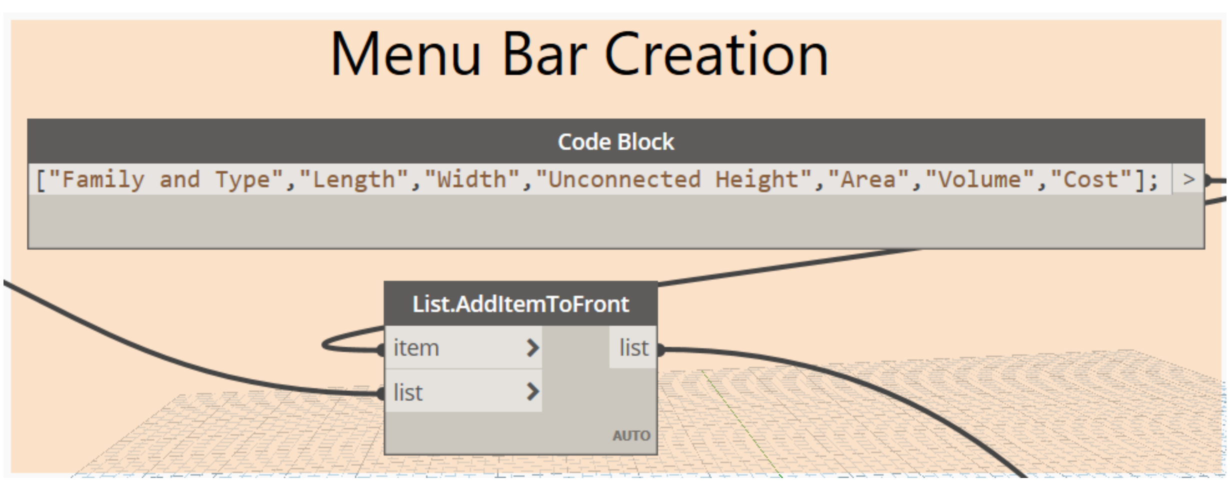


Figure 56: Title bar creation for wall parameters in Excel using Dynamo

After the data retrieval and ordering of the same, the next step is to write or transfer the data to Excel to enable a bi-directional exchange between Revit and Excel. This is achieved using the algorithm which makes use of the node “Data.ExportExcel” is shown in Fig. 57 which carries information about which data needs to be written in which cell by retrieving the information stored in the Lists. This step enables the data of the modeled wall in Revit to be accessed and varied according to the user’s discretion. Finally, as the data is required to be read and varied by Excel and Revit, it is necessary that the data or the parameters varied to be accessed and viewed by Revit . Dynamo again acts as the channel to achieve this. However , the data obtained from Excel contains the menu bar which renders the data to be invalid in Revit in its original form. Thus, the menu bar created in Excel is deleted in the algorithm using “List.RemoveItemAtIndex” as depicted in Fig. 59. After this, the data can be seamlessly viewed and changed in Revit or Excel as required by the user. Through this process, the model and its corresponding information can be changed in Excel and viewed in Revit or vice-versa.

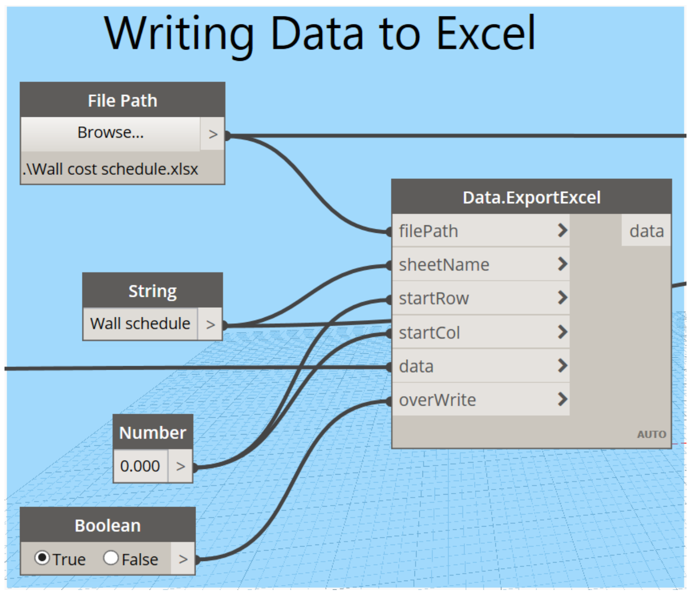


Figure 57: Data writing to Excel from Revit using Dynamo

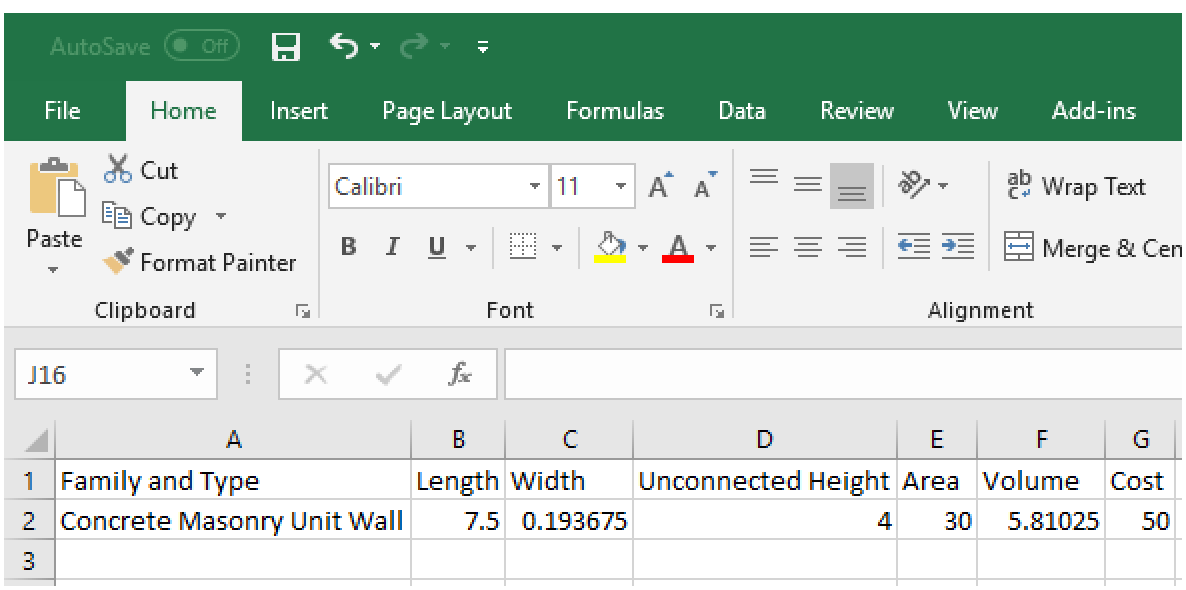


Figure 58: Exported wall parameters in Excel from Revit

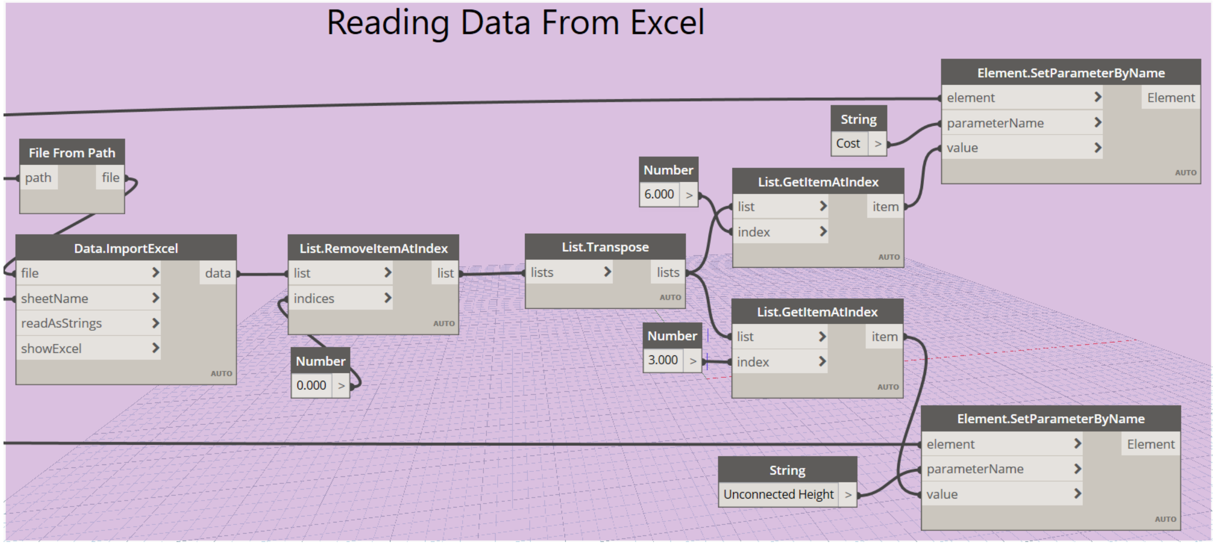


Figure 59: Data reading from Excel to Revit using Dynamo

Fig. 52 illustrates the wall schedule data of the model which essentially contains the cost estimation data of the wall added to the architectural data of the wall. The Wall Schedule tab in Revit represents the cost estimation performed on the wall. The cost data can be found next to the tab called 'Unit Cost'. Other architectural data imported from the previous step can be seen under the respective tabs within the same Wall Schedule tab. The entire data after combining with cost estimation is termed as 5D model and the model is enabled with parametric modeling. This data is thus made ready to be exported to the model checker ' Solibri' in the IFC format for further validation.

Validation of 5D models: The 5D model validation is done using the model checker Solibri. Fig. 60 illustrates the 5D model created in Revit. The cost schedule data can be found in the tab called wall schedule, which is encircled with red line. Other architectural data imported from the 5D tool can be seen under the respective tabs location and Qto_WallBaseQuantities. The unit for cost value i.e Euro is missing in the schedule details and also the total cost value.

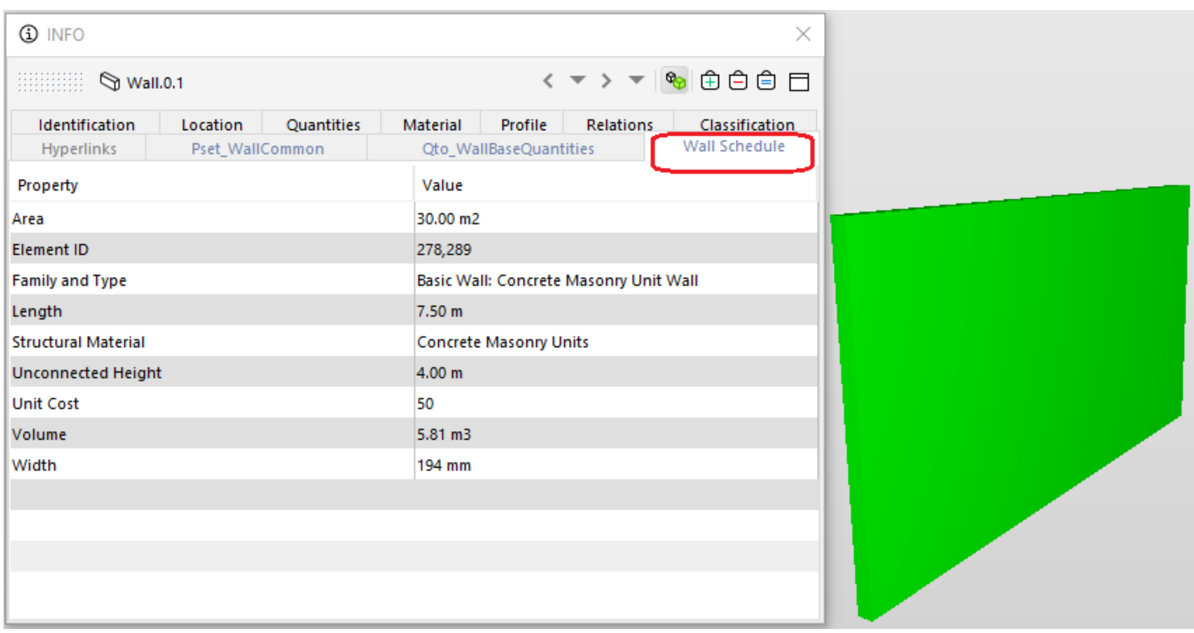


Figure 60: 5D Model validation in Solibri

4.3 Conclusion

The proposed methodologies were successful in developing 3D,4D and 5D open BIM models. 5D model validation also proved successful with limitations. whereas there were limitations in validating the 4D model and as a result , the validation of 4D model in the first methodology was not successful. On examination for the reason it was found that the 4D model does not contain any time schedule information when checked with Solibri. The detailed description of the underlying reasons for the finding can be seen in the upcoming chapter.

5 Result analysis and Discussion

The results analysis is carried out to explain the data quality and validation of 3D, 4D and 5D models, also explains the interoperability problems between the BIM tools.

5.1 Analysis and discussion of 4D BIM model results

In 4D model development, the results analysis is carried in two critical stages. These are: (1) data sharing stage between the 3D and 4D BIM tools and (2) the 4D model validation stage. In the first stage, 3D BIM model data quality is checked using the model checker and then interoperability problems were addressed during the 3D model export to the 4D BIM tool. In the later stage developed 4D model data quality checking results are listed.

- **Data quality of 3D BIM model used for 4D model development**

In the 3D BIM model considered throughout, the structure is composed of windows, rooms, doors, railing elements, exterior and interior walls, floor and roof. In order to compare the quality of the data, a single element from each of the structural components mentioned above is taken. As seen from tables 6 and 7 two exterior walls with the IDs 279950, 278390 which belongs to the exterior wall set is considered for the comparison of quality of data. Here the comparison is made against the data obtained from the native software i.e Revit with that of IFC file, Solibri, Navisworks and Synchro.

The data compared consists of length, width, height, area and volume of the wall. It can be seen that when length is compared across the different software tool, it is observed that the deviations or the error percentage in IFC file, Solibri and Synchro and Navisworks are the same. It can be observed that the length values are different in Revit and IFC file but the area and volume values are same. The reason behind this is Revit measuring the length values from center to center and the area is calculated using the face of the wall. The length values exported to the IFC are end to end. Thus, It is always good to use length values in IFC file to calculate the area or to verify the area values. There is absolutely no error in the measured data across the different softwares when measured with width, height, area, volume parameter.

Table 6: Comparision of wall element parameters in different BIM tools and with IFC

Element Property	Exterior Wall - 279950								
	Revit	IFC	Error(%)	Solibri	Error (%)	Navisworks	Error (%)	Synchro	Error (%)
Length	10.668	10.862	1.786	10.862	1.786	10.862	1.786	10.862	1.786
Width	0.194	0.194	0	0.194	0	0.194	0	0.194	0
Height	3.048	3.048	0	3.048	0	3.048	0	3.048	0
Area	28.926	28.926	0	28.926	0	28.926	0	28.926	0
Volume	5.602	5.602	0	5.602	0	5.602	0	5.602	0

Table 7: Comparision of wall element parameters in different BIM tools and with IFC

Element Property	Exterior Wall - 278390								
	Revit	IFC	Error(%)	Solibri	Error (%)	Navisworks	Error (%)	Synchro	Error (%)
Length	10.058	9.865	1.919	9.865	1.919	9.865	1.919	9.865	1.919
Width	0.194	0.194	0	0.194	0	0.194	0	0.194	0
Height	3.048	3.048	0	3.048	0	3.048	0	3.048	0
Area	27.838	27.838	0	27.838	0	27.838	0	27.838	0
Volume	5.392	5.392	0	5.392	0	5.392	0	5.392	0

Further on, the next element considered is of the floor set. Table 8 depicts the error percentage or the deviation of the floor properties only in Solibri when compared with Revit. The object model data from Revit is exported to Synchro and Navisworks in the IFC format. From the previous analysis with the wall element, it was found that IFC file, Navisworks and Synchro have almost the same error approximations since the underlying data for both of them is provided in the same IFC format. Thus, comparison with Navisworks and Synchro have not been carried out in this step.

The element properties considered for comparison are the floor perimeter, floor thickness, floor area and floor volume. On comparison, it is found that the floor thickness, perimeter, area and floor volume had no deviation in Solibri when compared with Revit.

Table 8: Comparision of floor parameters obtained from the Revit with model checker results

Element Property	Floor		
	Revit	Solibri	Error(%)
Perimeter	47.028	47.028	0
Thickness	0.152	0.152	0
Area	136.979	136.979	0
Volume	20.876	20.876	0

The next element to be compared is door. Here Door is considered out of the 7 doors in the structure. The properties of the door element under consideration are height, thickness, width, area and volume which can be seen in the table 9. On comparison with height, thickness, width, area and volume, Solibri resulted in a same value when compared with Revit resulting in zero error percentage. Thus, it is evident that Revit successfully exported the Door quantities into the IFC format.

Table 9: Comparision of door parameters obtained from the Revit with model checker results

Element Property	Door		
	Revit	Solibri	Error(%)
Height	2.134	2.134	0
Thickness	0.051	0.051	0
Width	0.914	0.914	0
Area	3.194	3.194	0
Volume	0.120	0.120	0

For a window element, the element properties considered are height, width, area and volume. On comparison with height, Solibri showed equal value against Revit. Revit showed zero difference when compared with Solibri against width. There was zero percentage error in Solibri's area, volume when compared with that of Revit. The same can be seen the table 10.

Table 10: Comparision of window parameters obtained from the Revit with model checker results

Element Property	Window		
	Revit	Solibri	Error(%)
Height	1.219	1.219	0
Width	0.914	0.914	0
Area	2.250	2.250	0
Volume	0.041	0.041	0

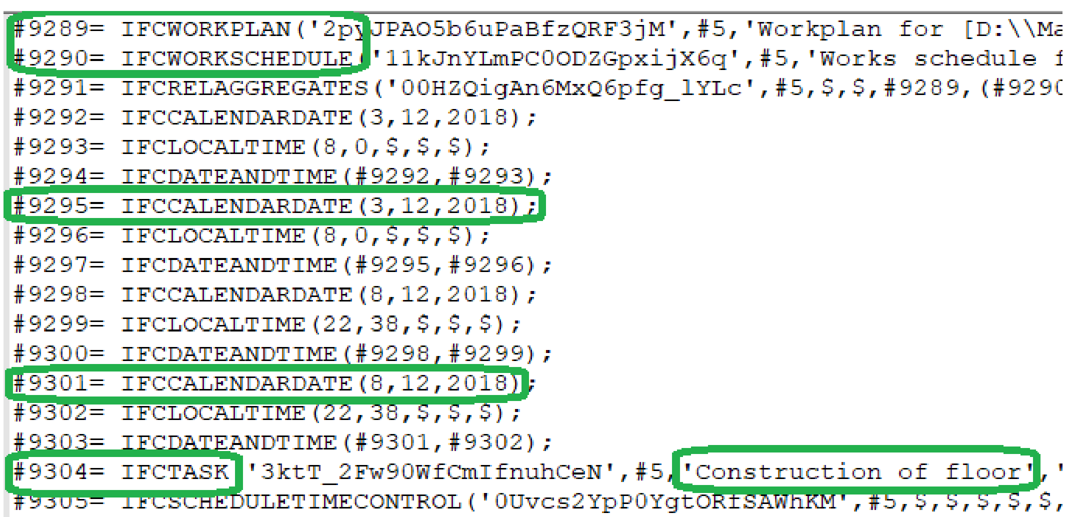
In the next stage of comparison railing element is considered. The parameters of consideration are railing length and railing height. On comparison with Revit, Solibri has absolutely zero difference in length. Similarly same value was found in the height parameter resulting in zero error percentage. The explained results can be seen in table 11.

Table 11: Comparision of railing parameters obtained from the Revit with model checker results

Element Property	Railing		
	Revit	Solibri	Error(%)
Length	9.622	9.622	0
Height	0.914	0.914	0

Data quality of 4D BIM model: As explained in the previous chapter, Navisworks can import the 3D data model and model the 4D data but not export the 4D model in IFC format. As an alternative, exporting the model using Synchro was attempted. Through the export of the 4D model, the model is passed through the model checker, Solibri for further validation of the data. However, it was found that Solibri invalidated the 4D data model because of the absence of time schedule information in the model imported in Solibri.

To ascertain whether Solibri invalidated the data because of the absence of time schedule information in the IFC file itself or Solibri invalidated despite importing the time schedule information in the 4D model, the step file generated during the export of the IFC file was checked. On examining the step file, the time schedule information was found in it. These information can be seen in the Fig. 61.



```
#9289= IFCWORKPLAN('2pyJPAO5b6uPaBfzQRF3jM',#5,'Workplan for [D:\\Ma
#9290= IFCWORKSCHEDULE('11kJnYLmPC0ODZGpxijX6q',#5,'Works schedule f
#9291= IFCRELAGGREGATES('00HZQigAn6MxQ6pfg_lYLc',#5,$,$,#9289,(#929(
#9292= IFCCALENDARDATE(3,12,2018);
#9293= IFCLOCALTIME(8,0,$,$,$);
#9294= IFCDATEANDTIME(#9292,#9293);
#9295= IFCCALENDARDATE(3,12,2018);
#9296= IFCLOCALTIME(8,0,$,$,$);
#9297= IFCDATEANDTIME(#9295,#9296);
#9298= IFCCALENDARDATE(8,12,2018);
#9299= IFCLOCALTIME(22,38,$,$,$);
#9300= IFCDATEANDTIME(#9298,#9299);
#9301= IFCCALENDARDATE(8,12,2018);
#9302= IFCLOCALTIME(22,38,$,$,$);
#9303= IFCDATEANDTIME(#9301,#9302);
#9304= IFCTASK('3ktT_2Fw90WfCmIfnuhCeN',#5,'Construction of floor','
#9305= IFCSCHEDULETIMECONTROL('0Uvcs2YpP0YgtORfSAWhKM',#5,$,$,$,$,$,
```

Figure 61: Time schedule information in in IFC step file

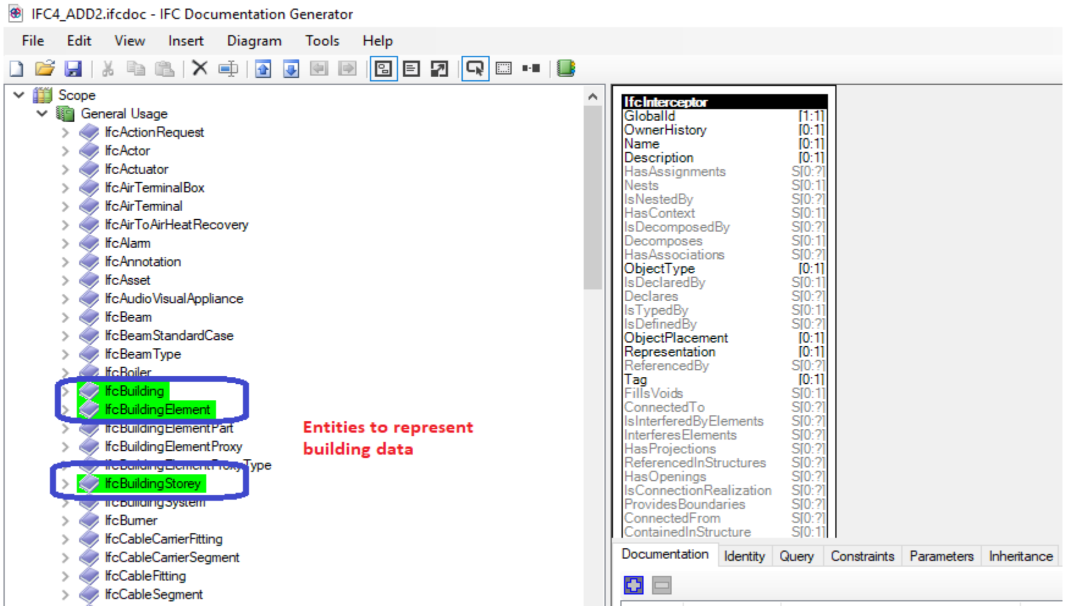


Figure 62: 4D model validation results using the IFC subschema

To check if the data contained in the step file was adherent to the standards prescribed by the IFC schema, the step file data was checked against the View Definition called General Usage in IFCDOC tool. It was found that the entities and attributes of time schedule information found in the step file matched those with the prescribed View Definition called General Usage of the IFC schema. As it can be seen in Figures 62, 63, 64 and 65 the highlighted green entities required to generate the IFC file for the validator matched with that of the General Usage defined by the IFC schema. From this, we are certain that the 4D model exported from Synchro to Solibri contains all the relevant data pertaining to time schedule information and no data mismatch has occurred.

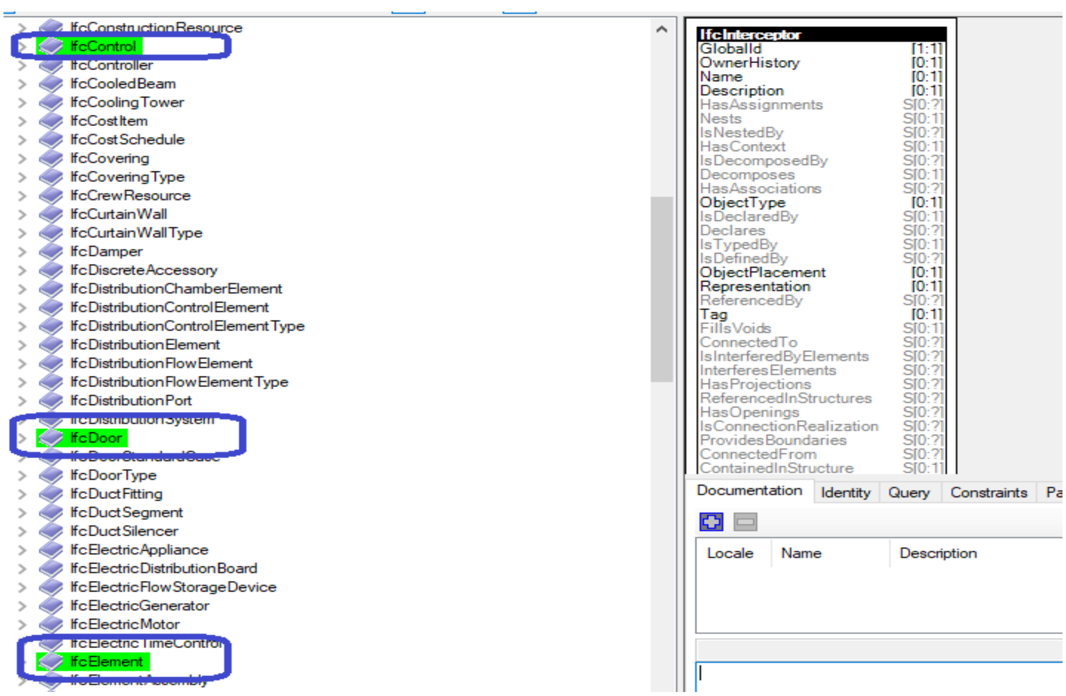


Figure 63: 4D model validation results using the IFC subschema

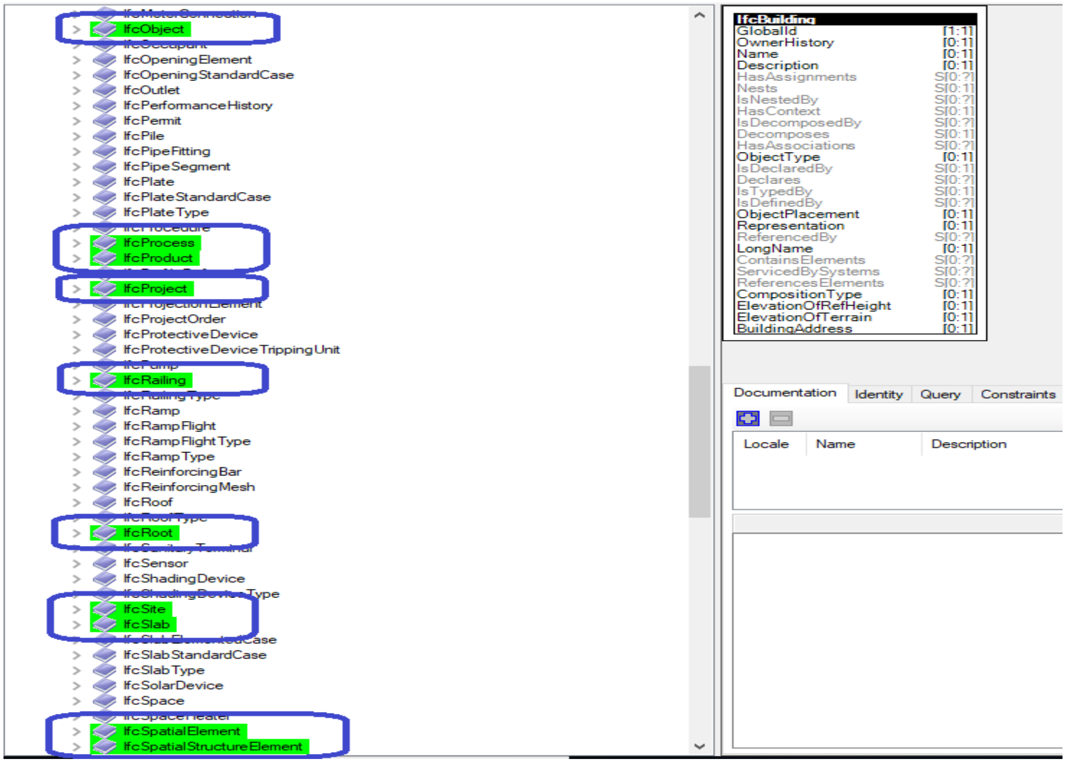


Figure 64: 4D model validation results using the IFC subschema

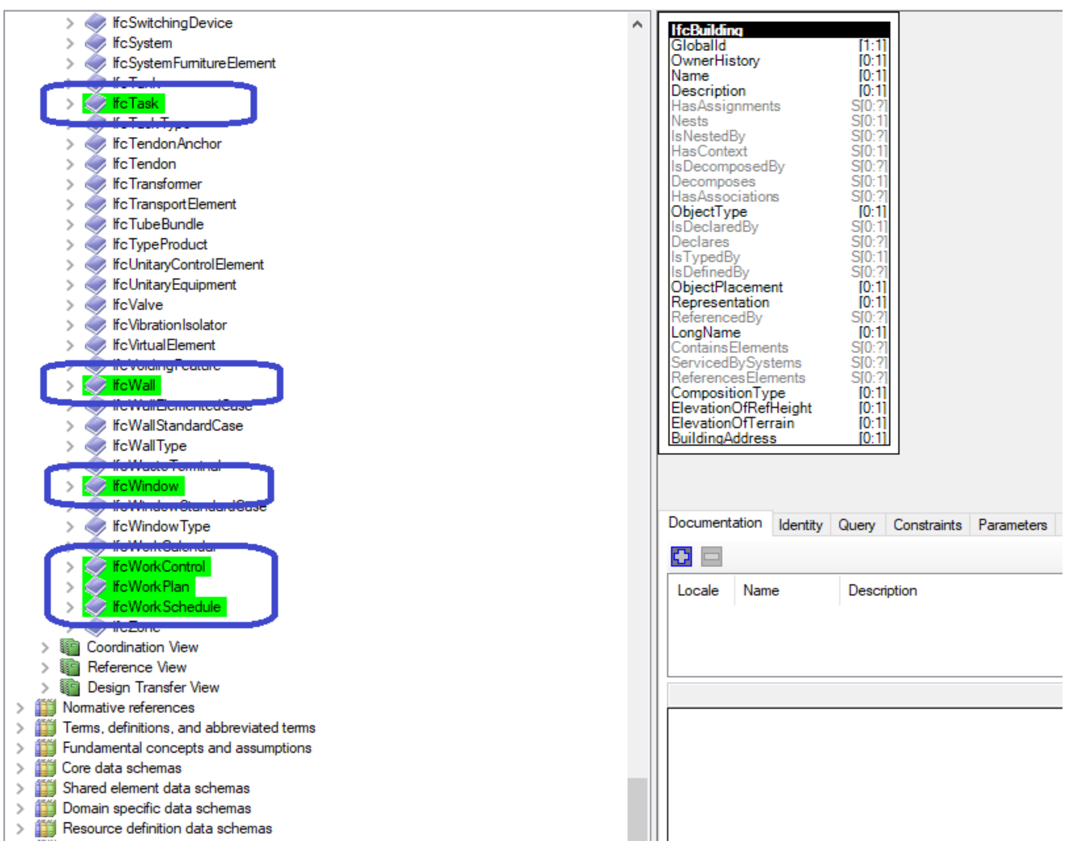


Figure 65: 4D model validation results using the IFC subschema

Nevertheless, Solibri rendered the 4D model as invalid. To identify the underlying cause, a thorough examination of the import and export methodology of the softwares was carried out and found that these applications use Model View Definitions to filter the incoming and outgoing data. Time schedule information is excluded from the data when applications make use of Model View Definition. The main reason behind this is the current three MVDs (co-ordination view, reference view and design transfer view) does not contain the information related to the time schedule information. The same can be found in the `http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-reference-view/comparison-rv-dtv`. Thus it can be concluded that Model View Definition play a crucial role in importing and exporting the data.

5.2 Analysis and discussion of 5D BIM model results

In the previous section comparison was carried out against the 4D model properties of the different structural elements in the building. This section attempts to describe about the cost estimation model and 3D wall element parameters when compared with Revit against IFC file and Solibri.

Data quality of a BIM model used for 5D model development: The element parameters length, height, width, area and volume of the wall element when compared with Revit and IFC, Revit and Solibri showed absolutely no difference resulting in a 'zero error' percentage. Thus, the 3D data model is accepted for 5D model development.

Table 12: Comparison of wall parameters obtained from the Revit with model checker results

Element Property	Wall				
	Revit	Ifc	Error(%)	Solibri	Error(%)
Length	7.500	7.500	0	7.500	0
Height	4.00	4.000	0	4.000	0
Width	0.194	0.194	0	0.194	0
Area	30.000	30.000	0	30.000	0
Volume	5.810	5.810	0	5.810	0

Data quality of 5D BIM model: The 5D model generated by Revit is exported in the IFC format and successfully validated by the model checker. However, when the data model was imported in IFC Primus to cross verify, it was found that the Wall Schedule Information to appear under the Properties section instead of cost schedule information. This is shown by the Fig. 66. This will be rendered invalid as per the norms of the IFC schema. It was also found that Revit exports the Wall Schedule Information data under the properties label as shown in the Fig. 66.

On investigation, in the step file, it was found that Revit exported the information as propertysinglevalue and not as wall schedule information because of its limitation. The wall cost schedule information in the STEP file can be seen in Fig. 67.

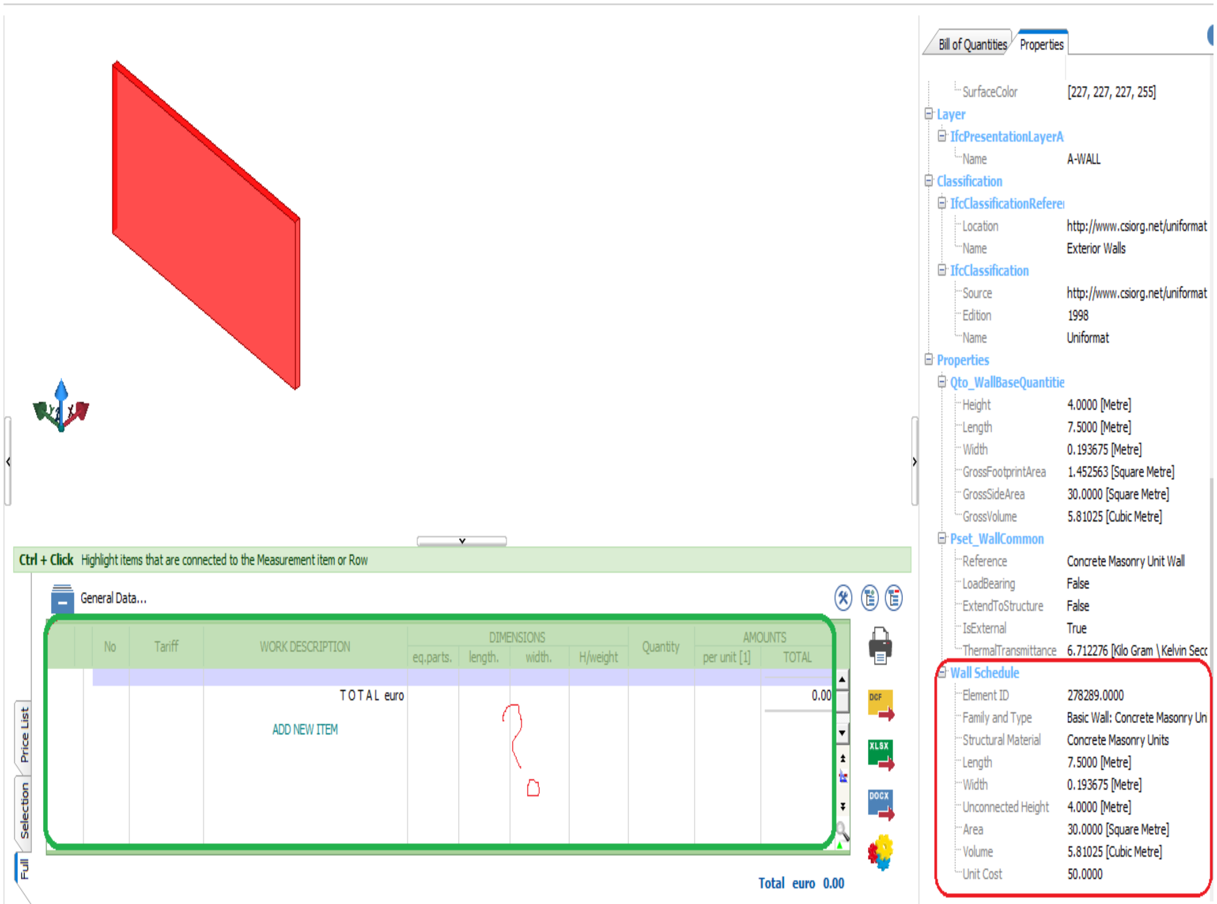


Figure 66: Cost schedule information in IFC Primus

```
#294= IFCPROPERTYSINGLEVALUE('Element ID',$,IFCREAL(278289.),$);
#295= IFCPROPERTYSINGLEVALUE('Family and Type',$,IFCLABEL('Basic Wall: Concrete Masonry Unit Wall'),$);
#296= IFCPROPERTYSINGLEVALUE('Structural Material',$,IFCLABEL('Concrete Masonry Units'),$);
#297= IFCPROPERTYSINGLEVALUE('Length',$,IFCLENGTHMEASURE(7.5),$);
#298= IFCPROPERTYSINGLEVALUE('Width',$,IFCLENGTHMEASURE(0.193675),$);
#299= IFCPROPERTYSINGLEVALUE('Unconnected Height',$,IFCLENGTHMEASURE(4.),$);
#300= IFCPROPERTYSINGLEVALUE('Area',$,IFCAREAMEASURE(30.),$);
#301= IFCPROPERTYSINGLEVALUE('Volume',$,IFCVOLUMEMEASURE(5.81025),$);
#302= IFCPROPERTYSINGLEVALUE('Unit Cost',$,IFCMONETARYMEASURE(50.),$);
#303= IFCPROPERTYSET('2X02F2ppj0c9JeL7zFeqs7',#42,'Wall Schedule',$,(#294,#295,#296,#297,#298,#299,#300,#301,#302));
#314= IFCRELDEFINESBYPROPERTIES('2Qye_sBEH5Xxn1Gz08Ddaa',#42,$,$,(#213),#287);
#317= IFCRELDEFINESBYPROPERTIES('1GJIxIbVvEnwecx42SvpY1',#42,$,$,(#213),#303);
```

Figure 67: Cost schedule information in IFC-STEP file

It is not certain whether the IFC file exported does not have the wall schedule information or Revit does not have the capacity to export the wall schedule information in IFC format. On further investigation, it was found that the wall schedule information is missing in Coordinate View, Reference View and Design Transfer View, the 3 MVDs used to export the model data in IFC format. Perhaps, this could be the reason why Revit does not map the wall schedule information under IFC Cost Schedule Information as explained in chapter 3 meta model but instead stores as a single property value.
IfcMonetaryUnit is the attribute in the IFC schema to support the units for currency. But, in the current results unit for currency (i.e. euro) is missing. Thus, Revit is not able to map its currency units with IFC.

5.3 Conclusion

It has been observed that the data quality of the architectural model is acceptable in both methodologies. Lack of development in the MVDs which contain the cost and time schedule information carrying entities leads to constraints for the software applications to export and import 4D and 5D models.

6 Conclusion and scope for research

6.1 Conclusion

One of the objective of this thesis work is to develop logical meta models to support the construction project management data using open data schema. The other being, to develop methodologies to integrate construction project management parameters into the 3D BIM models. Construction project management is broadly divided into 10 knowledge areas. However, the present study undertaken in this Master thesis work attempts to concentrate on Cost Management and Time Management aspects and their role in the BIM models. This study focuses on the Cost Schedule Information and Time Schedule Information which contain the essential information of Cost Management and Time management respectively.

In order to have a better and clear understanding of the vast available data in IFC, the information related to Time Schedule Information were gathered and categorized under 7 different labels based on the type and their purpose in Time Schedule Information. Similarly, the Cost Schedule Information was also divided into 6 different categories. As a next step towards better categorization of the data, a meta model was devised in the form of a flow chart representing the various participating entities of Cost and Time Schedule Information and their inter-relations with the aid of relational entities. With this fundamental organization of the available information, 2 methodologies were proposed to integrate the Cost and Time Schedule Information embedded in the meta models with the 3D BIM models.

The first methodology aimed at developing the 4D BIM model which is a combination of 3D BIM model and Time Schedule Information. The workflow in the methodology is comprised of 4D model development and 4D model validation . The first stage dealing with the 4D model development resulted in a success with acceptable deviations. However, next stage dealing with the exporting of the 4D model in IFC format and the validation of the same posed challenges. Navisworks was first used to export the 4D model in the IFC format .But due to its inherent inability to export the model in IFC format, Synchro was adopted. Using Synchro there was a successful export of the 4D model in the IFC format.Yet, when the model was imported by the model checker, Solibri, the model was rendered invalid.

To investigate the cause, the step file of the 4D model was checked against the existing comprehensive IFC sub-schema and it was found that the contents of Time Schedule Information in the IFC file matched with that of the IFC sub-schema. On further investigation, it was found that the Model View Definition used by the software applications for import and export of the data, was primarily responsible for filtering out the data through them and the current MVDs invariably discard the Time Schedule Information. This makes the data not only invalid when it is passed on to a model checker but also when there is a necessity to use this data in other applications.

The second methodology is aimed at the development of 5D BIM model, a combination of 3D BIM model and Cost Schedule Information.This methodology like the first one, is carried out first by the development of the 5D model and then with the validation of the same. Unlike the first case, parametric modeling was enabled in the 5D model generation with the help of Excel and Dynamo. However, there was a limitation with respect to the editing of the parameters contained in Revit. The reason being, Dynamo could edit only some of the parameters which are not 'read-only'. With this parametric edition enabled, it is possible to edit data in Excel or Revit and simultaneously update the data in the other. The next limitation was posed during the export of the 5D model.

On examination of the imported 5D model in the model checker, it was found that the Cost Schedule Information was categorized as a IFC property parameter rather than IFC Cost Schedule parameter. On further investigation, it was found that Revit inherently categorizes the Cost Schedule Information as property parameter. The causing factor for this discrepancy comes from the filtering of data from the existing MVDs used in the software applications.

The observation made in the research work has been concluded in tabular form and showed in the table 13.

Table 13: Data modeling and management capabilities of BIM tools

Item	Revit	Navisworks	Synchro	IFC Primus	Solibri	IFCDOC
3D Modeling	Y	N.A	N.A	N.A	N.A	N.A
Time scheduling	N.A	Y	Y	N.A	N.A	N.A
Cost Scheduling	Y	N.A	N.A	Y	N.A	N.A
IFC import (3D)	Y	Y	Y	Y	Y	N.A
IFC export (3D)	Y	Y	Y	Y	Y	N.A
IFC import (3D + Time schedule information)	N.A	N.A	Y	N.A	N.A	N.A
IFC export (3D + Time schedule information)	N.A	N.A	Y	N.A	N.A	N.A
IFC import (3D + Cost schedule information)	N.A	N.A	N.A	N.A	N.A	N.A
IFC export (3D + Cost schedule information)	Y	N.A	N.A	N.A	N.A	N.A
IFC import (3D + Time schedule information + Cost schedule information)	N.A	N.A	N.A	N.A	N.A	N.A
IFC export (3D + Time schedule information + Cost schedule information)	N.A	N.A	N.A	N.A	N.A	N.A
Model checking	Y	Y	Y	Y	Y	N.A
IFC file validation	N.A	N.A	N.A	N.A	N.A	Y

N.A - Not Available; Y - Yes; Y - Yes with limitation

6.2 Scope for research

From the two methodologies, it is obvious that MVDs are the deciding factors in filtering of the data from the software applications. We know that MVDs were designed according to the IFC schema. Based on the results obtained, it can be derived that existing MVDs of the IFC schema have to be updated so that the information regarding Cost Schedule and Time Schedule can be mapped accurately with the IFC schema through each software. One suggestive line of research, would be to update the existing MVDs with each software's native MVD and make it as open source. Making it open source would help in garnering various thoughts of approaching the problem and solving them, ultimately benefiting the various participants.

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Appendix

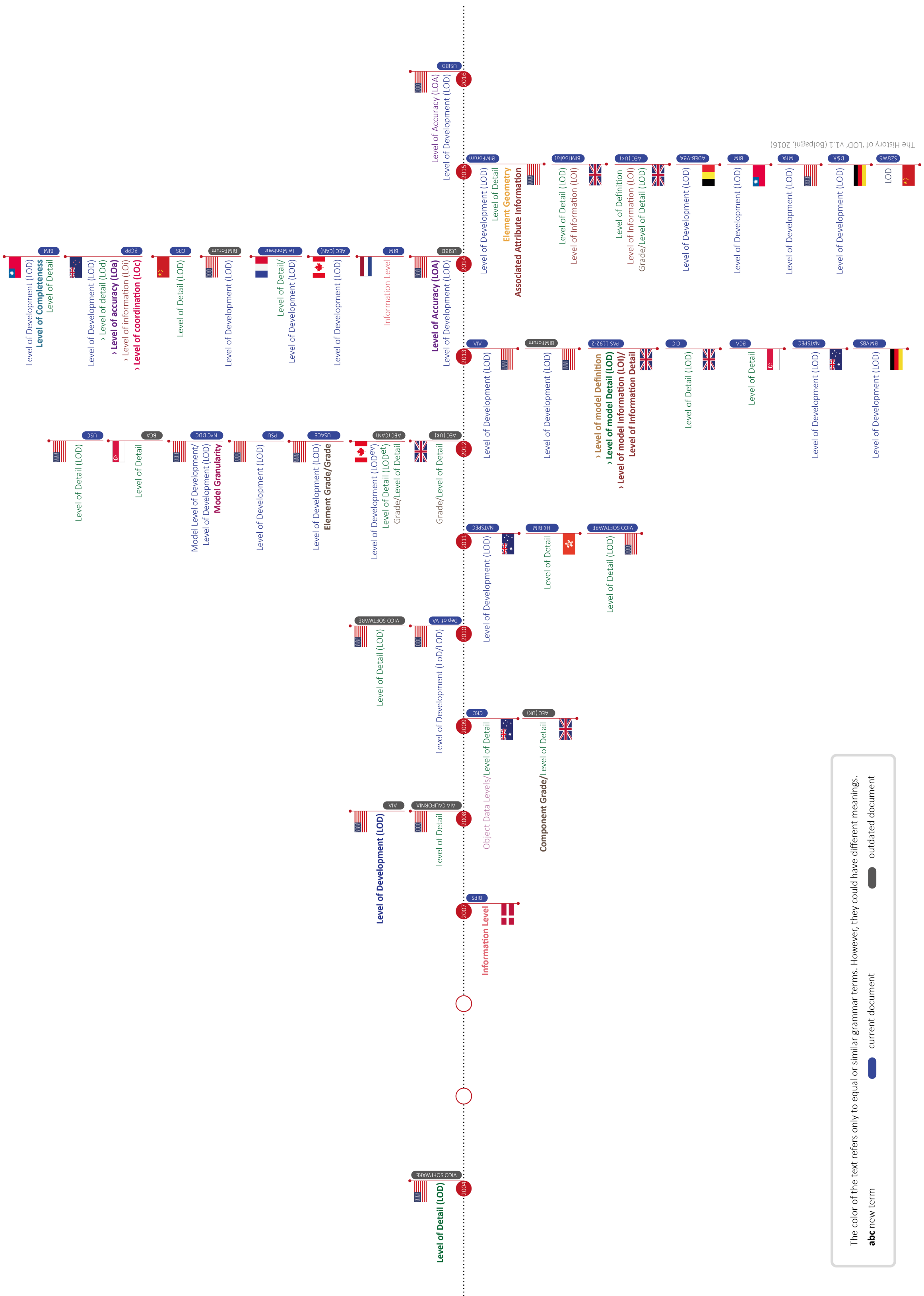

Figure 68: The History of Level of Development [3]

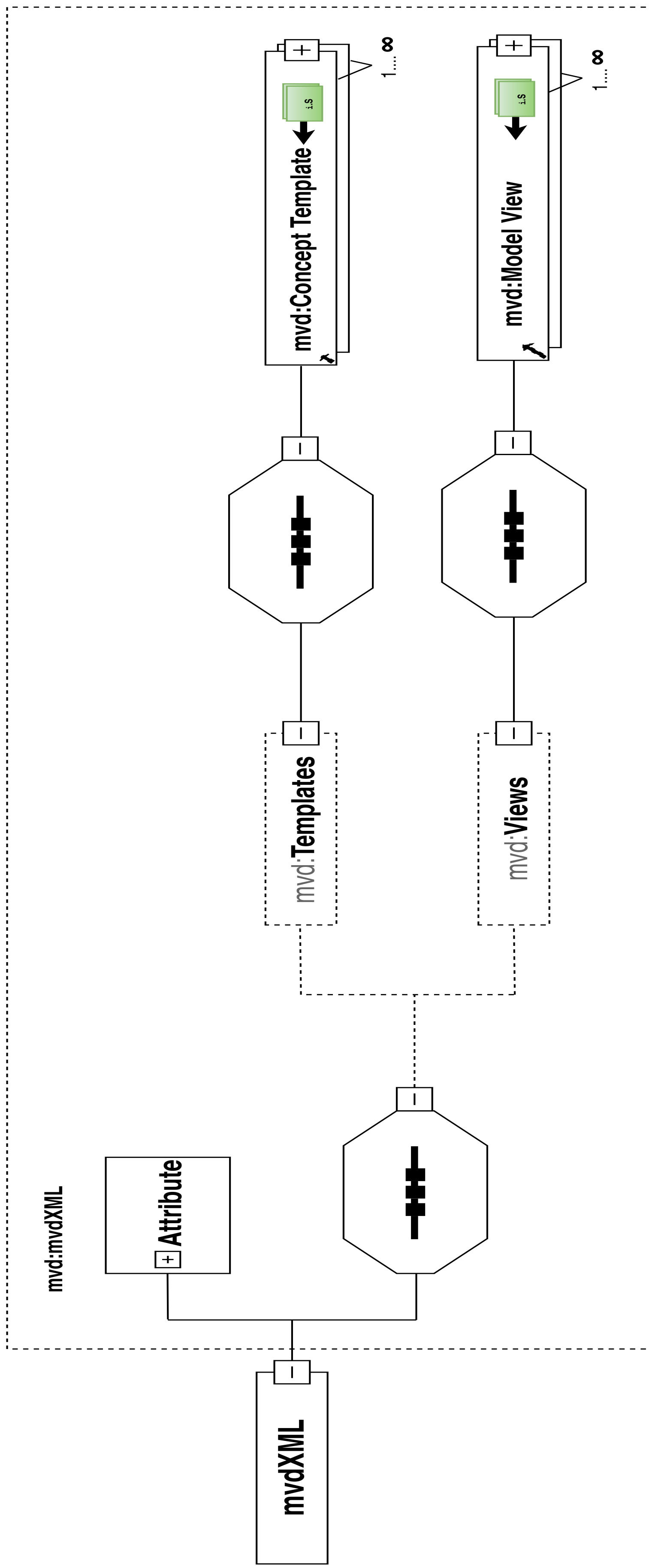

Figure 69: Basic structure of mvdXML schema[4]

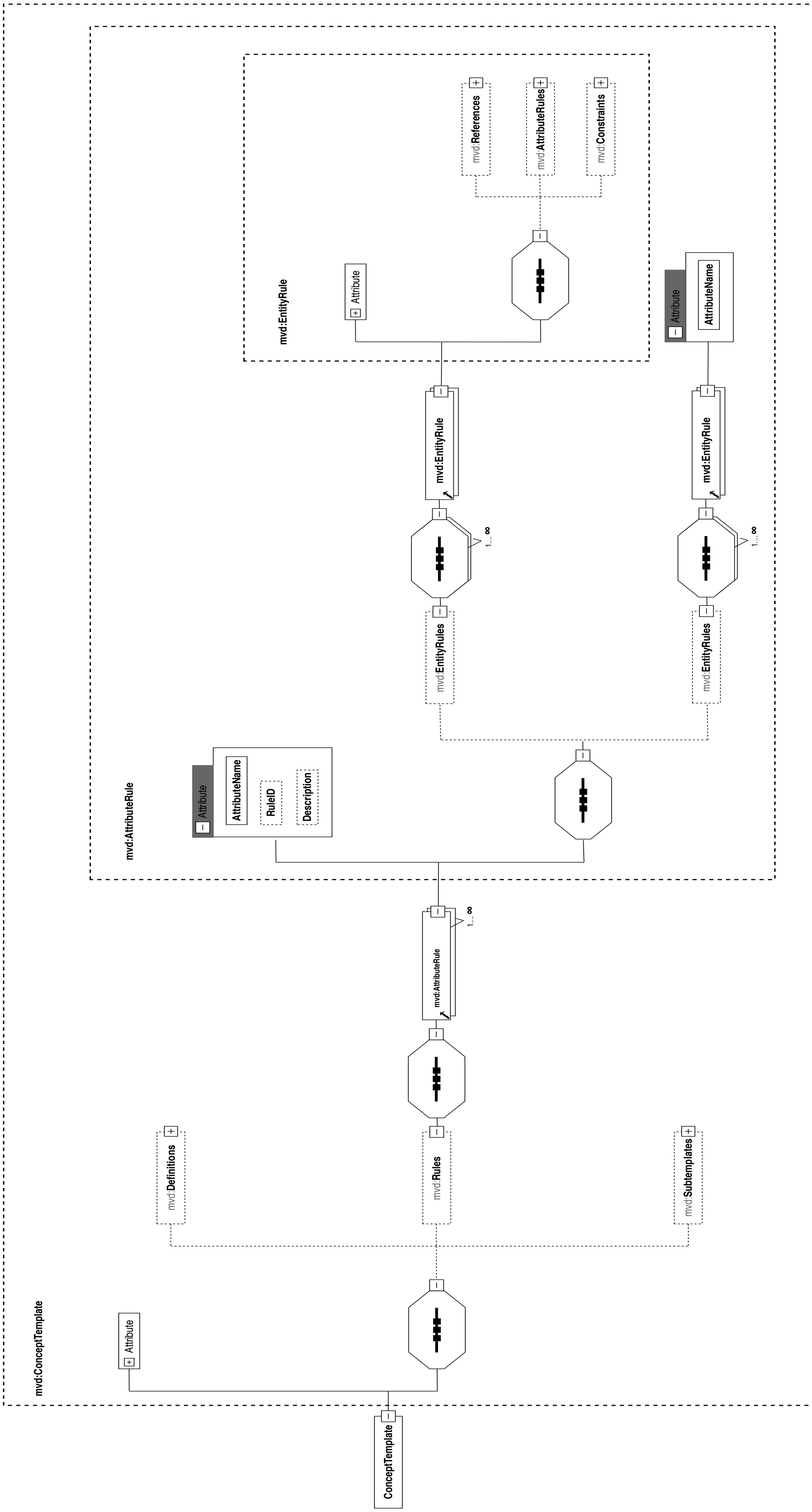

Figure 70: main mvdXML elements for ConceptTemplate[4]

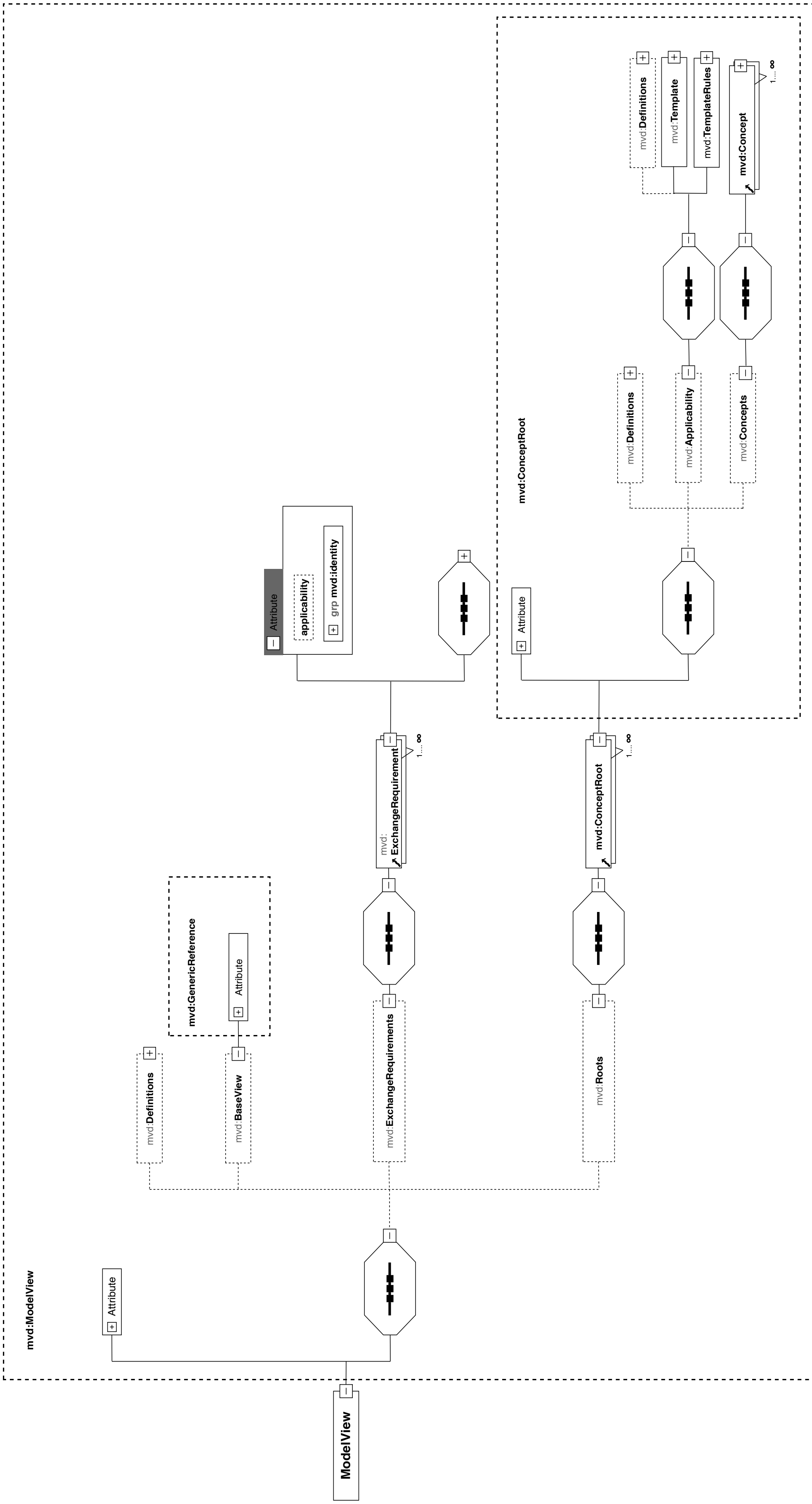

Figure 71: main mvdXML elements for ModelView[4]