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BIM-based optimization of the data acquiring process for construction and operational cost calculation

Master's Thesis

for the Master of Science Degree in Civil Engineering

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Abstract

In the world of Building Information Modeling (BIM), model-based cost estimation is considered the fifth dimension, but the cost estimation process of a building or infrastructure involves two major sections: construction and operational costs. Model-based construction cost estimation is often done in the early phases of a project, but operational planning is usually not treated as a prominent aspect in the early phases because of difficulties in obtaining relevant information. This master thesis targets optimizing both construction and operational costs, hence establishing a workflow starting from model checking and optimizing the methods for construction costs. This optimization will target a smooth shift from the existing cost estimation methods to model-based cost estimation methods, focusing more on the data exchange problem. The work is based on the perspective of BMW Group as project owners, and tests are conducted on BMW office and factory buildings to analyze the possibilities of model-based computation of operational costs and their reliability. The tests helped to analyze the minimum requirements of a model for computing operational costs and help determine the level of accuracy of the process. It has also ensured smooth interoperability with recently developed methods for data transfer. The workflow also focuses on the concept of developing a database of model-based construction and operational costs, considering sustainability aspects as well upon the availability of data. Finally, the idea of data optimization possibility with a digital twin is also discussed.

Content

List of Abbreviations

AEC	Architecture, Engineering, and Construction
AIA	Auftraggegeberinformationsanforderungen
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AVA	Ausschreibung - Vergabe - Abrechnung
BAK	Bundes Architekten Kammer
BEP	BIM Execution Planning
BEM	Building Energy Model
BIM	Building Information Modelling
BOQ	Bill Of Quantities
CAD	Computer Aided Design
CAFM	Computer Aided Facility Management
CDE	Common Data Environment
COBie	Construction-Operations Building Information Exchange
DBD	Dynamische Bau Daten- Dynamic Construction Data
EIR	Employer’s Information Requirements
FM	Facility Management
gbXML	Green building XML
GBS	Green Building Studio
GAEB	Gemeinsame Ausschuss Elektronik im Bauwesen
GUID	Globally Unique Identifier
GWP	Global Warming Potential
HOAI	Honorarordnung für Architekten und Ingenieure -

	Ordinance on Architects' and Engineers' Fees
HVAC	Heat Ventilation and Air Conditioning
IFS	Infrastructure Facility Services
LOD	Level Of Details
LOG	Level Of Geometry
LOI	Level Of Information
LCA	Life Cycle Analysis
IFC	Industry Foundation classes
LP	Leistungsphasen - Construction Phases
LV	Leistungsverzeichnis-Bill of Quantities
ISO 19650	International Organization for Standardization-BIM Norm
MDIP	Master Information Delivery plan
MR	Maintenance Rooms
MEP	Mechanical Electrical and Plumbing
NBIMS-US	National BIM Standard-United States
ODBC	Open Database Connectivity
PIR	Polyurethane Hard Foam
PV	Photovoltaics
QTO	Quantity Take-Off
TFS	Technical Facility Services
XPS	Extruded Polystyrene
WBCSD	World Council for Business Sustainability

1 Introduction

The process of digitalization in construction through Building Information Modeling (BIM) is trending in the construction industry today. Model-based construction cost estimation is one of the most critical processes in BIM, which is now possible with the help of 5D BIM software dedicated to quantity and cost analysis. Model-based cost estimation means that the quantities for calculating costs can be obtained from a 3D model. Even with the availability of sophisticated software tools, it’s hard for the industry to adopt the model-based cost calculation process to its full potential, as the costs of a building include both construction and operational costs (Gołaszewska & Salamak, 2017).

Software solutions for calculating the construction costs from the building model are well known to the construction industry. Calculating the operating expenses from a model is not a simple process as operational costs involve several additional parameters. The additional parameters for operations of the building are analyzed theoretically, and they may or may not be included within the building model. Therefore, a good transition plan for shifting the conventional methods to the latest solutions is a top priority. Hence, a proper workflow of using the model to calculate both construction and operational costs needs to be obtained. This workflow can improve data transparency and include cost estimations connected with the 3D model. The data processed with the workflow mentioned above will be stored as benchmarks which will be highly beneficial for upcoming projects as reference data.

1.1 Research objectives

This thesis targets the optimization of both construction and operational costs and, hence, establishes a workflow starting from optimizing the methods for construction costs. This optimization will target a smooth shift from the existing cost estimation methods to model-based cost estimation methods. Tests will be conducted to analyze the possibilities of model-based computation of operational costs. The tests will help to analyze the minimum requirements of a model for calculating operational costs and help determine the level of accuracy of the process.

In the course of the thesis, new concepts, comparison of standards, data exchange, and challenges encountered will be discussed. Unclear definition of BIM model requirements for operational planning in early construction phases makes it necessary to '**establish a workflow which goes from construction to operational costs and hence make a database of construction and operational costs with the best possible data transfer standards**.'

This thesis is written based on the perspective of BMW Group as a project owner, meaning that the discussions are on the data acquired from planners and designers for quality improvements. Also, the discussion will focus primarily on the early phases of construction but going throughout the process till the handover of the completed building.

1.2 Motivation

The European construction industry is worth about 12,000 billion euros (FIEC 2014), and the impeccable contribution of the construction industry to the European economy. The World Council for Business Sustainability (WBCSD) reported in 2009 that 80% of the total costs of buildings are consumed during their life cycle while the remaining 20% is consumed during their construction and demolition (WBCSD, 2009). This points out that there are multiple factors affecting costs, and, according to the impact on prices, these factors should be carefully studied for cost optimization in the planning phase of a project. The percentages mentioned could be rough but highlight the importance of operational costs while estimating the costs of a building. Operating costs are meticulously linked with construction; hence optimization should start from construction and then go on to operations. This strategy also indirectly helps achieve sustainability in buildings because the goal includes optimizing energy consumption (Borrmann et al., 2018).

One of the critical challenges among the many stakeholders involved in a construction project's lifecycle is the flow of information between the individual phases. The different stakeholders often establish their information standards and systems, but this disrupts knowledge transfer between the design, planning, building, and production/operation phases (Borrmann et al., 2018). Also, the (BIMForum, 2018) specifies that the Level Of Details (LOD) is not yet connected to construction phases. A transparent workflow is required to find the cost estimation requirements and organize them to the corresponding phase of a construction project.

1.3 Approach

The approach starts with the analysis of the existing methods for calculating construction costs on completed project models to ensure quality. This step will help to check the model's requirements that need to be fulfilled for the computation of construction and operational costs. After the check, multiple methods of cost estimations for both construction and operating costs will be suggested with or without the BIM process. The optimum solution for existing and future projects will be finalized.

The primary focus, as discussed above, will be on operational costs as they are mostly estimated theoretically or based on assumptions and comparisons in the early phases. The model is relatively coarse in early phases and may only be limited. It is intended to incorporate energy simulations to find the requirements of the model, what comes out of the model for simulations, to compare simulated operational costs with theoretical excel-based operational costs and merge it to the model using BIM software. Throughout the project, essential optimization factors such as data exchange file quality for cost estimation, standard codes, specification catalog analysis for international and German projects, standard for cost data exchange, software-based Life Cycle Analysis (LCA) of buildings, software analysis for operational costs, etc. will be considered. Finally, it is expected to provide the best solution for calculating the model-based construction and operating costs for completed, ongoing, and future projects and use the solutions as a reference database.

1.4 Structure

The structure of this thesis is as follows:

Chapter 2 - State of the art: This section explains all the technical terms, scientific background, standards, practices in the construction industry, etc., which will be used in the scope of this work.

Chapter 3 - Model-based construction and operational costs methodology: This section explains the methodology for testing model-based cost estimation as mentioned in the approach. Also, this section introduces the new workflow for model-based construction and operational costs

Chapter 4 - Evaluation for model-based construction and operational costs: This section explains the tests conducted in this work, results, and challenges

Chapter 5 - Conclusion: This section briefly discusses the phase adequate requirements for model-based construction and operational costs, changes in early phases that affect operational costs, significant challenges in the suggested process, and its important benefits.

Chapter 6 - Summary and Outlook: This section summarizes the information gathered with the help of various tests. Also, it explains what can be expected in the future so that the model-based cost estimation, which is not adequately explored now on a holistic perspective with construction and operational costs, can be transparent and harmonized.

2 State of the art

2.1 Building Information Modelling (BIM)

The world of construction has changed a lot in the past 30-40 years, starting from hand-drawn sketches, slowly developing CAD programs to do the same in the computer, then adding layers to the CAD file to improve the level of details, adding depth to the drawing created the idea of developing 3D planning in the construction industry. It got revolutionary changes to itself and the construction industry since the invention or development of the concept of CAD. The three-dimensional CAD programs were further developed. Later, individual objects such as walls, doors, and windows were already included in the programs, including all possible types of family. In his book "BIM Handbook - A GUIDE TO BUILDING INFORMATION MODELING", Eastman describes the change that has taken place, away from original 2D drawings and 3D images to the actual information in today's CAD files (Eastman et al. 2011). The recent developments were of "Building Information Modeling", which stimulated the industry to a new era of digitalization.

Building information modeling, shortly known by its abbreviation "BIM", is a design process that describes the development, management, and analysis of four-dimensional, real-time dynamic, computer-generated models (Eastman et al., 2011), (Borrmann et al., 2018). To make it simple, BIM describes the process of creating a digital building model, the Building Information Model (Eastman 1999). Elaboratively, the BIM process is intended to describe the entire life cycle, from planning through construction and operation to dismantling. One definition that the National Building Information Modeling Standard (NBIMS) committee has formulated as its vision is as follows, "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 useable throughout its lifecycle." (NIBS 2007). National BIM standard, United States, introduced new BIM definition as "A BIM is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward."

The building information model serves as a consistent digital building model that integrates the descriptive information and geometric information to one source, nowadays called the “single source of truth.” The BIM software has different interfaces, differences, and parametric working methods depending on the manufacturers. Talking about BIM software doesn’t only mean drawing or modeling in 3D. It also involves structural analysis, collaboration, model checking, quantity estimation, scheduling, sustainability, and facility management (Patel, 2020).

There is the availability of software for all these processes, and it’s more explained with the “dimensions of BIM” as in Figure 2.1. For each dimension which are separate interconnected processes, there are manufactures working on providing software solutions that may or may not be vendor-neutral (Nachrichtenredaktion, 2021). There are different explanations and definitions for the dimension of BIM after 4D, which means that there is no standard definition of dimensions after 4D. In the scope of this thesis, the dimensions of BIM can be understood, as shown in Figure 2.1. Also, this thesis focus on 5D,6D, and 7D BIM and the optimization of data acquired within these dimensions.

Figure 2.1: Dimension of BIM (Nachrichtenredaktion, 2021)

BIM is being implemented at levels by firms across the AEC industry worldwide. BIM improves the coordination and communication of the involved stakeholders. The traditional method is compared with BIM in Figure 2.2, from which the transparency that BIM introduces into a project can be clearly understood. Also, it enhances the productivity and quality control of the project (Patel, 2020).

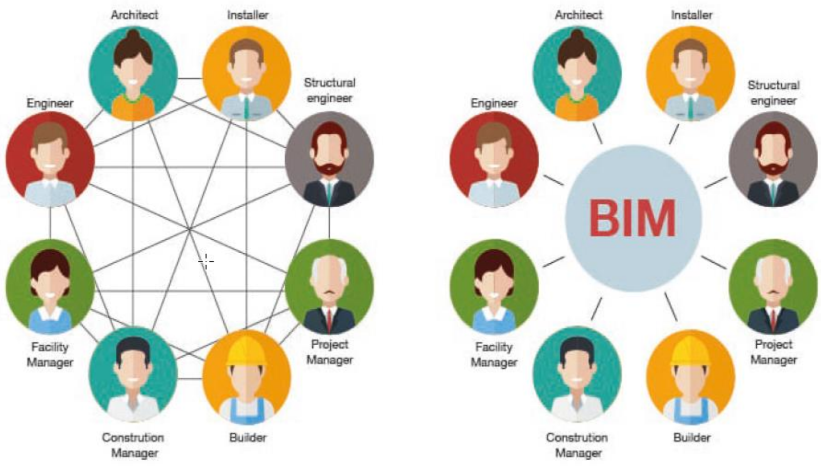


Figure 2.2: Traditional method vs. BIM (Patel, 2020)

2.1.1 BIM documents

Considering the goals of this thesis, it's imperative to discuss the different BIM documents as they specify the requirements and standards of the BIM process so that a project is appropriately planned. Model-based construction and operational costs need particular standards and conditions, and discussion about this will be available after the testing section of this thesis. Still, first and foremost, a short discussion is needed about the relevant documents of BIM with spectacles of cost estimation.

As per the British standards institution, the primary BIM documents are defined in Figure 2.3. It can be understood that BIM Execution Plan BEP, Employer's Information Requirements EIR, and the Master Information Delivery plan MIDP are the most important documents (designingbuildings.co.uk, 2021). Depending upon the regions, most clients have their BIM standards based on PAS 1192/ ISO19650/ NBIMS-US. The BIM standards specify the project owner's requirements according to construction phases such as model delivery requirements, parameter lists, use cases, etc. Planners also have their BIM standards, but generally, they tend to adapt their BIM Standards according to the clients (EFCA, 2012).

As per data from (designingbuildings.co.uk, 2021) based on PAS-1192:

- The pre-contract **BIM Execution Plan (BEP)** may include a Project Implementation Plan (PIP) with potential suppliers bidding for a project, quality documentation, collaboration, information modeling goals, project milestones, and deliverable strategy.

- **Employer's Information Requirements (EIR)** (depending on the employer) may include: standard methods and procedures defining the way information is created, named, and exchanged, information-related roles and responsibilities, an information delivery plan or release schedule identifying, delivered by whom and when, a Construction-Operations Building Information Exchange (COBie) demand matrix identifying which structured data about the facility, floors, spaces, zones, and building components should be delivered and when.
- "The **Master Information Delivery Plan - MIDP** is the primary plan for preparing the project information required by the Employer's Information Requirements" (designingbuildings.co.uk, PAS_1192-2, 2021). It lists deliverable information and makes use of it when the project information is to be prepared, by whom, and using what protocols and procedures for each project stage, setting out the responsibility for each specific information deliverable. The project delivery manager should develop the master information delivery plan, working collaboratively with the task team managers. The project delivery manager then uses it to manage information delivery during the project.

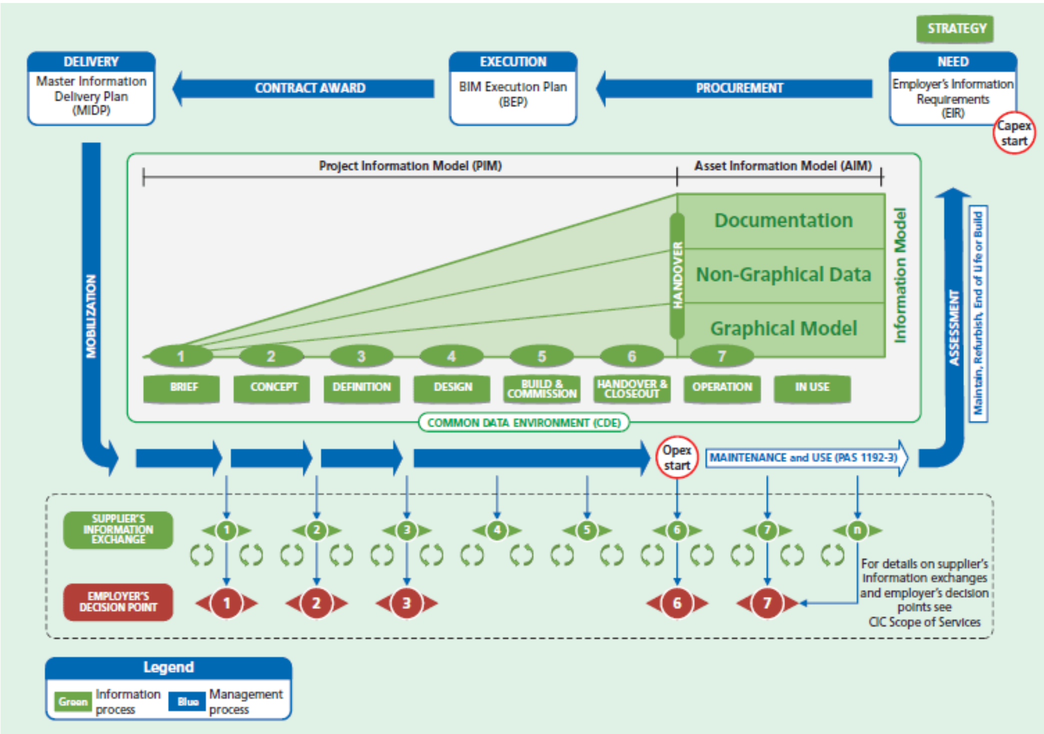


Figure 2.3: The information delivery cycle, as seen in PAS 1192-2: 2013.

2.1.2 Relevance of the BIM documents for Costs

The BIM standard documents should be specified to obtain the required information for model-based construction and operational cost estimation. It should be especially noted that the delivery of information differs according to the phases of a project. The project's cost estimation is mostly relevant just before starting the project or before the project execution phase. The information needed for construction and operations costs estimation is limited in such early stages. More details of these requirements for the model to be ready for model-based cost estimation will be discussed in chapter 4 with tests, requirements, data transfer standards, challenges, and suggestions for solutions.

2.1.3 Open and closed BIM

The most simple form of differentiation of BIM in practice is explained in Figure 2.4. Little BIM means applying specific software by an individual stakeholder to realize a disciple-specific task. The data is not transferred to the other stakeholders. On the other hand, big BIM is with a collaborative approach. There is model-based communication between all the stakeholders across the life cycle of a project. If software from one vendor is used in a project, then the project is said to have a closed BIM process, but if it's vendor-neutral with open data exchange standards, then its open BIM process (Borrmann et al., 2018). Various practices and challenges regarding the common practices/ standards will be discussed further in chapter 4 and 5.

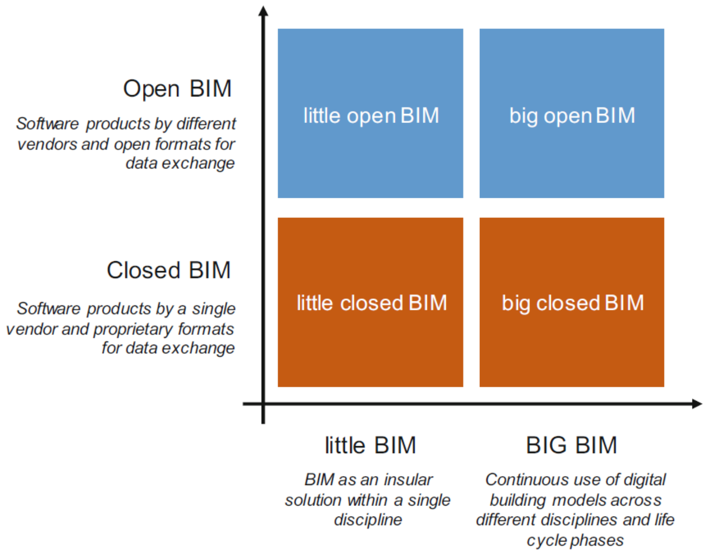


Figure 2.4: Open and closed BIM (Borrmann et al., 2015)

In common practices in the construction industry, planners often prefer to do big closed BIM and sometimes little closed BIM in a project. When it comes to data exchange with the project owners, open data formats such as Industry Foundation Class (IFC) files are often exchanged, or sometimes the native files are exchanged upon demand. When the planner uses one software vendor, and only an IFC file is exchanged to the project owner, the project, on the whole, could be understood as little open BIM, but internally it could be understood as little closed BIM. For better transparency of information, big open BIM should be preferred, but it requires tremendous changes in the industry, and the challenges involved will be discussed further in this thesis.

2.2 Quantity Take-Off (QTO)

Quantity take-off is one of the critical tasks in the construction process for many reasons. Shortly, the building elements are measured, and these quantities are then used to estimate their cost and the relevant workload. Quantity take-off is the same as quantity estimation or simply estimation, just it's known by different names in different parts of the world (Monteiro & Poças Martins, 2013).

2.2.1 Conventional methods for construction cost estimation

As per the 'Estimation and costing in civil Engineering' book by B.N Duta (Dutta, 2021), "estimating is the technique of calculating or computing the various quantities and the expected expenditure to be incurred on a particular work or project." The specifications of materials and the project's budget depend on the regional standards and market rates, and the following requirements are necessary for preparing an estimate (Dutta, 2021):

- Drawings like plan, elevation, and sections of the building.
- Detailed specifications about quality, workmanship & properties of materials, etc.
- Standard schedule of rates as per market.

The conventional process of cost estimations is to read the measurements from the 2D drawing (paper/digital) of the building, make a list of the different building elements and then write the summated quantities with the respective unit of measurements. The building elements are matched with its specifications based on the standard codes of that particular region where the project will be executed. The calculated quantities are then rated according to the rate analysis done by the planner or the market standards, and then the total costs for construction are estimated (Dutta, 2021).

The planners followed this process for a very long time. It started with pen and paper, and then later it was changed to CAD for drawings and excel sheets for quantity take-off and cost estimation, which was proven very useful for the planners. The change to excel-based cost estimation saved a lot of time for the planners using its calculation tools. Many planners still use excel to do the cost calculation.

The cost estimation for each design phase can be defined as follows: conceptual analysis in the planning phase, schematic estimate in the schematic design phases, and detailed estimate in the design development phase, respectively. The purpose of schematic estimation is the feasibility study and rough cost estimation (Choi & Kim, 2014)

2.2.2 Conventional methods for operational planning and costs

The idea of estimating operational costs from a model is relatively new. Earlier, what could have been practiced might be to compare the planned building to a reference building that is already completed and in the operational/use phase (Azhar, Nadeem, Mok, & Leung, 2008). There is not much literature to prove this fact as it’s an internal process followed by the project clients, and it’s not linked with energy consultants or planners, it’s also possible that earlier, the planners also would have practiced this method. It was considered safe to estimate the operational costs of a new building with a safety factor multiplication considering significant inflations and miscellaneous or unforeseen changes (Azhar, Khalfan , & Maqsood, 2012).

Using Microsoft excel, the building areas can be noted parallel to the room types. The characteristic value of energy consumption referred from similar projects can be used corresponding to each room type to calculate the operational costs. For this process, all the relevant operational factors should be considered for individual building types. The default values for operations of room types must be assigned to it in Microsoft excel concerning characteristic values from facility management of another project with similar room types. The area is multiplied by the energy consumption for every room depending on its type to get the net usage per square meter. The energy usage values are converted to the respective units and multiplied by the market price for energy according to its form. This conventional process was developed and followed by the operational planning department of the BMW group. An adapted version of this method is attached to the Appendix.

2.2.3 BIM-based methods for cost estimation

One of the most valuable tasks in the construction process that can be automated through BIM use is quantity take-off which is explained above with its conventional methods. A BIM model is an assembly of objects defined with specific properties, some of which are the geometric attributes of elements. Most BIM tools contain inbuilt settings to perform calculations using the geometric properties of elements and provide quantities like area and volume in text form. BIM-based QTO is known to offer more straightforward and yet more detailed and accurate cost estimates of the project, reducing time and expenses, though it is also a tricky feature and it tends to be used only by experts (Monteiro & Martins, 2013).

Although capable of providing QTO tables as material/room schedules, popular BIM tools cannot manipulate that data. This is usually done with another type of software that is mainly used for QTO. Information is generally exchanged between the BIM and cost estimation software in one of two ways:

- both systems use the same proprietary/exchange format for product data definition, and the exchange is done smoothly without data loss.
- the systems use different proprietary formats, and the exchange is done by converting the data to a third, standard format, usually the Industry Foundation Classes (IFC). IFC is an ad-hoc standard data structure for the definition, classification, and organization of AEC data that, despite providing a wide range of applications, fails to offer a lossless vehicle for the exchange of data" (Monteiro & Martins, 2013). The following chapters will provide more information on IFC standards and exchange requirements.

The tendering processes are called AVA in German for **A**usschreibung, **V**ergabe und **A**brechnung. This term 'AVA' will be mentioned often on the contest of quantity take-off and tendering process and the software used for the latter. Some of Germany's popular quantity take-off software are shown in Table 2-1 along with their brief function's specialties. Other than the software mentioned in the table, there are many different software like Bexel Manager, California.pro, Vico-Office, etc., which could be used for cost estimation.

Table 2-1: Comparison of some of the QTO/AVA programs (Cosuno, 2021)

Software	ORCA AVA	NOVA AVA	AVANTI	RIB iTWO	Sidoun Globe
Common Functions	• Tendering - Awarding - Billing • Quantity takeoff, measurement and room book, • Order, supplement, budget, project, cost management				
Cloud	No	yes	No	No	No
Specialties	• Complete program • No division of modules	• Cloud Based • SaaS AVA Software • Access to all modules to assigned members	• Easy to learn • GRAFA for graphic Quantity Measurement	• 5D model oriented BOQ Editing	• Connecting plugins for MS Word and Excel

On the other hand, there is no availability of a complete tool for operational costs, whereas some tools can partially contribute to calculating the operating costs. The energy simulation methods are one of the best possible ways to calculate energy consumption. Using BIM tools during energy performance analysis may prove financially beneficial due to improved communication and reduced time consumption (Patel, 2020). More discussions on energy simulations, software tools for simulations, and building tests will be available in chapter 2.4.

2.3 Phases in construction and their relevance in cost estimation

Most of the construction projects are divided into phases starting from the pre-planning stage to the handover of the project. The phases in construction are specified as shown in Table 2-2 per ISO 19650, HOAI standards. It varies according to regions but remains the same in principle, although it might differ in names and number of phases. In Table 2-2 ,there is the comparison of German phases with international project phases, corresponding Level of Development (LOD), Level of Geometry (LoG), and Level of Information(LoI). As per BIM forum 2020, approved by the National BIM Standards (NBIMS) of the USA, the LODs are not defined by design phases. The LOD language could represent design phase completion or any other milestones, and the reasons are the following (BIMforum, 2020):

- "There is currently no detailed standard for the design phases" (BIMforum, 2020). Many planners have their own BIM standards, but these differ according to regions and one firm to the other, and even within a single firm, the requirements are sometimes adjusted to the needs of a project. These different standards are also influenced due to the different specifications provided by the project owners to the planners.

- “Building systems progress from concept to the precise definition at different rates, so at any given time, different elements will be at different points along with this progression. After the schematic design phase, for example, the model will include many elements at LOD 200, but will also include many at LOD 100, as well as some at LOD 300, and possibly even LOD 400” (BIMforum, 2020).

Sometimes LOD is understood differently according to regions, and it can be very confusing as LOD is known as Level of Detail and Level of Development. The (BIMForum, 2018) explicitly points out the difference between the level of detail and level of development and differentiates between both terms: The level of detail stands for the number of geometric details in a modeled object. The level of development describes the degree to which the geometry and the semantic information are well thought out and to what extent the project participants can rely on the information when using the model. The BIMForum (2018) describes the level of detail as input into the model element and the level of development as a reliable output.

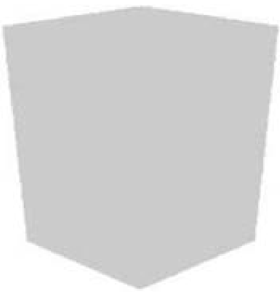
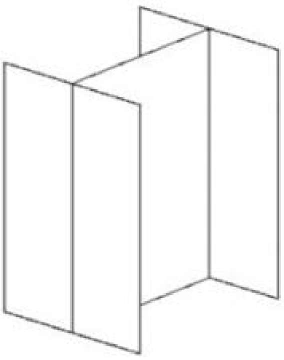
The level of detail is subsequently replaced by the term level of geometry and abbreviated with LOG to avoid confusion. The input to semantic Information is given in the literature with the Level of Information and the abbreviation LOI (Hausknecht & Liebich, 2016; Van Treeck, 2016). The proximity to the term level of development suggests that the level of information has the same level structure. However, the majority of authors agree that the level of information cannot be structured into several levels (see Hausknecht & Liebich (2016); Kaden et al. (2017)). In the level of development is adequately explained with an example of a steel column. In Table 2-4, the LOI and LOG are illustrated with a sample pile wall.

It’s vital to discuss the terms mentioned above to understand what details should come with the model as per the standards in respective project phases. Also, a project must cross-check these detail requirements with the model to ensure transparency. After the tests on a building model, more details on the model’s needs for construction and operational cost estimation could be analyzed.

Table 2-2: Comparison of project phases in different standards with LOD, LoG, and LoI adapted from (Nguyen, 2019)

Phases in Construction-ISO (EFCA, 2012)	**LP-HOAI**	**LOD**	**LOG**	**LOI**
1.Concept phase	1.Basic investigation	LOD 100	LOG 100	LOI 100
2. Design phase	2. Pre-planning	LOD 200	LOG 200	LOI 200
3.Pre-construction phase	3.Design	LOD 300	LOG 300	LOI 300
4.Procurement phase	4.Approval planning			
5.Construction phase	5.Execution planning	LOD 400	LOG 400	LOI 400
6.Delivery phase	6.Perparing for the contract award			
7.Operational phase	7.Participation in the awarding of contract			
	8.Object monitoring			
	9.Property care	LOD 500	LOG 500	LOI 500

Table 2-3: LOD definition with steel column example adapted based on the data from BIM Forum 2020 (BIMforum, 2020)

LOD 100		"The model element may be graphically represented in the model with a symbol. Information related to the model element (i.e., cost per square foot, the tonnage of HVAC, etc.) can be derived from other model elements".
LOD 200		"The model element is graphically represented as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the model element". E.g., model elements to be added: - Floor with approximate dimensions - supporting frame elements roughly dimensioned - grid precisely defined

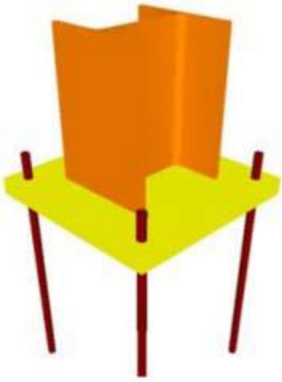
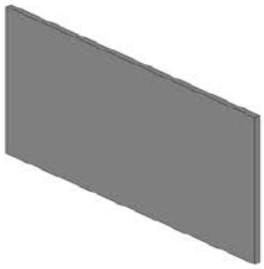
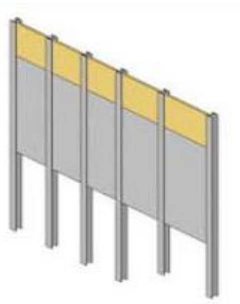
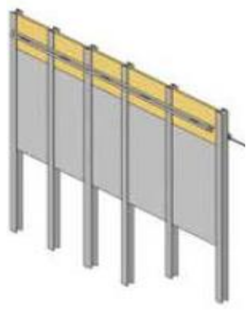
LOD 300		“The model element is graphically represented as a specific system, object, or assembly in quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the model element”. E.g., To be included in element modeling: - the specific size of the mainframe elements model with a defined grid and correct position and orientation
LOD 350		“The model element is graphically represented as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the model element”. E.g., To be included in element modeling: - actual height and location of connections - main elements of distinct compounds, all-steel connections such as head plates, knot plates, anchor rods, etc. - all other steel elements with correct position, shape, orientation, and material. - further reinforcements of the steel structure such as stiffeners, etc.
LOD 400		“The model element is graphically represented as a specific system, object, or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the model element”. E.g., to be included in element modeling: - welds - connection type - screw covers - washers, nuts, etc. - All assembly element
LOD 500	[Not Used]	“The model element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the model elements”.

Table 2-4: Example of LOG and LOI with a pile wall (FreieundHansestadtHamburg, 2017)

LoG 100	LoG 200	LoG 300	LoG 400
			
Linear representation	Wall-like representation with the thickness of the pile wall	Carrier/piles, planks as wall elements	Girder pile wall with stiffeners
LoI 100	**LoI 200**	**LoI 300**	**LoI 400**
Length	Length, Height	Material, Steel profile	Position, length of the girder, number, profile,

The data mentioned above, except Table 2-2: Comparison of project phases in different standards with LOD, LoG, and LoI adapted from Table 2-2, are based on different research works, but in actual practice as per (VBI, 2016) & (BIM4INFRA, 2020), the LOD and the German project phases are compared as in Table 2-5.

Table 2-5: Comparison of LP and LOD, adapted as per data from (Nguyen, 2019), (VBI, 2016)& (BIM4INFRA, 2020)

LP-HOAI	LOD
1.Basic investigation	LOD 100
2.Pre-planning	
3.Design	LOD 200
4.Approval planning	
5.Execution planning	LOD 300
6.Perparing for the contract award	
7.Participation in the awarding of contract	
8.Object monitoring	LOD 400 &500
9.Property care	

2.3.1 Early design phases

The astounding complexity and specialization across all areas of planning and construction make it essential for project stakeholders from discrete disciplines to be brought together at project start. The early stages in the design process have a significant influence on the overall appearance of a building, costs associated, the performance over the total life cycle of the building, and the ability of the building to meet changing needs in the future. In these early stages, the opportunity for influencing the design is still high, and the costs associated with these changes are still low. As shown in Figure 2.5, the earlier a change is suggested, the higher the opportunity for influence and the lower the proposed changes cost. Once the design becomes finalized and the construction phase begins, the cost of making changes increases drastically, and the possibilities become far more restricted (Drewes, 2020).

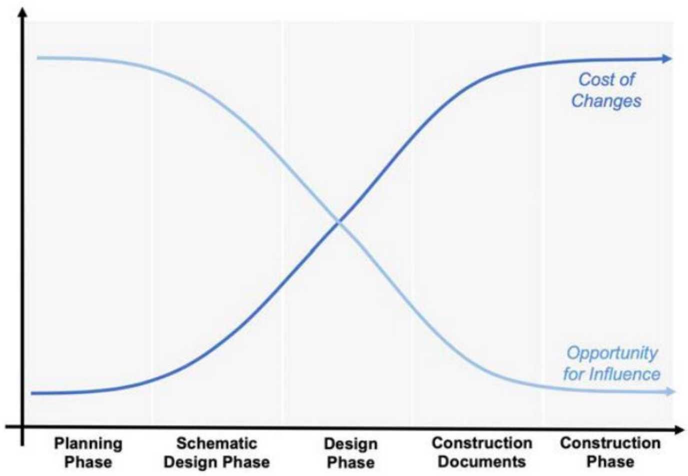


Figure 2.5: Influence and cost of design changes per planning phase (WBCSD, 2009)

There is no general definition that could be easily found of what precisely the early design stages must entail. Braganca et al. define the early design stage as including only the conceptual phase and ending at the design phase. The conceptual phase encompasses the definition of project goals, objectives, and schedules as well as general information regarding materials, the type of architecture, and functional aspects of spaces. This phase is presented in the form of early schematic drawings and layouts (Bragança et al., 2014).

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the early design stage is broader and includes the schematic design phase as well (ASHRAE, 2006). The plans, sections, and elevations are created in this phase, and the design decisions proposed in the conceptual phase are developed to find the preferred design solutions. The German HOAI (Ordinance on Architects' and Engineers' Fees) defines the early stages as spanning from service phases 1 to 3, covering basic project evaluation, preliminary design, and design. For this thesis, the early phases could be understood as highlighted with blue color in Figure 2.6, considering the international project phases.

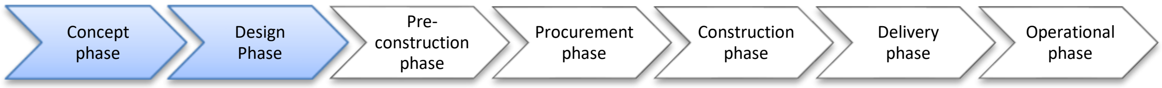


Figure 2.6: Understanding early phases (highlighted in blue color)

2.3.2 BIM standards in early phases

Now it is essential to discuss BIM standard requirements and, as an example, compare those standards with the German phases of construction or the “Leistungsphasen (LP).” The Bundes Architekten Kammer(BAK), an association for Architects, has some specifications of phase adequate requirements according to the LP. Only the early phases will be under consideration in a simplified form adapted from the BAK brochure (BAK, 2021), and it is as follows:

LP1

- Provision of a digital collaboration platform (CDE)
- BIM management
- Digital recording of existing buildings or property information
- Clarification of the requirements for data exchange with authorities

LP2

- Set up of model-based room books
- Creation of a digital model according to special requirements
- Creation of largely integrated collision-free models at intermediate points in time

LP3

- Visualization of a schedule in the digital model
- Preparation of a model-based cost calculation
- Unique forms of presentation and preparation of the digital models for communication and coordination

Furthermore, there will be a discussion on the BIM requirements and the phases mentioned above, considering model-based construction and operational costing.

2.4 Operational energy simulations

To understand more about the operational costs, it’s crucial to discuss the energy simulations. The energy simulations are performed to have a relative idea of how much energy consumption will be at the use phase of a building. Many software tools are available now which may or may not use BIM to simulate energy consumption (Claridge & Paulus, 2019). The requirements for energy simulations (model-based) are not generally described in any BIM standards though some specifications in the BAK brochure (BAK, 2021) about the model details requirements for building operations and facility management. Although such specifications are described, it will not help that much in the decision-making process since they are not specified for early phases. As the influence of decision making and its impact are plentiful in the early phases, as discussed in the previous section, any significant changes afterward would cost high effort, time delay, and money loss.

The operational costs of a facility not only deal with the energy consumption but also other services like maintenance, cleaning, etc., need to be analyzed in detail through tests. The energy simulation results are expected to estimate many factors that influence a facility's operations, and it will be discussed in detail in chapter 4.

2.4.1 Building Energy Modeling (BEM)

The energy performance of a building is often predicted by creating a Building Energy Model (BEM) to perform energy simulation when the model-based process is followed. Many software packages are available with various capabilities that help to interrelate the design and its impact on energy performance. The BIM to BEM is a complex process undergoing tremendous research (Farzaneh, Monfet, & Forgues, 2019). The data required will be often scattered in different phases of a project, and often in early phases, generation of BEM would be leaning on lots of assumptions. The data for modeling can be gathered from similar projects, literature, from experts of the building stock (Facility Managers), or from building audits and metered data. Not only does the simulation software overdemand the users in the early stages, but also the user interface of these software is often designed for energy consultants, which is too complex for planners who lay hands on the model. Even though every complexity is solved with high efforts, BIM-BEM still faces issues and challenges because of factors like maintenance, services that cannot be modeled, interoperability, etc. (Kamel & Memari, 2019).

The BEM is mainly exchanged in the Green Building XML(gbXML), and also sometimes, IFC files are used to create BEM, but generally, the information related to energy settings is exported with gbXML. The exchange standards will be discussed in detail in chapter 2.5.

2.4.2 Types of energy simulations

Currently, several simulation software's are available for the energy performance of buildings, as mentioned above. Each software uses a specific algorithm for the calculations, has different input modes, and produces different typologies. In general, the more powerful and complete is the software, the more detailed and precise input it requires. The systems for assessing the energy performance of buildings currently available are static, semi-dynamic, and dynamic (Adhikari, Lucci , Pracchi, & Rosina , 2013). In static simulations, there are not many details, or it's based on a formula that, for example, it doesn't count the storage space in a kitchen or a toilet in the bedroom or a machine in the work area. It just categorizes the entire area as a single mode of usage. In other words, energy assessment in static simulations is in a stationary regime considering a limited number of factors. Every tiny detail is counted in dynamic simulations, including user behavior and climate changes.

The semi-dynamic software uses a dynamic simulation to consider the thermal inertia but requires a simplified input in climatic data and building description. The user interface is usually based on graphical icons related to numerical values. Finally, the dynamic simulation software analyses the contributions of the thermal inertia of walls, variability of the outside temperature, solar radiation, natural ventilation, and users' management. Detailed data must be used for describing both climatic conditions and the building properties (Adhikari, Lucci , Pracchi, & Rosina , 2013).

Static simulations are often the preferred choice at an early phase of a project as dynamic simulations require a lot of information. Nevertheless, tests should be performed to check the requirements and the software's capabilities and limitations, discussed in chapter 4.

2.4.3 Performance gap

After having an overview of simulations, the next goal is to find the reliability of the information inferred from simulations. To validate the findings from simulations, the best choice will be to compare the simulated values with the actual consumption or the metered data. The metered energy consumption may come close, but not necessarily it would be similar or in close range because it depends on the user. The user behavior cannot be predicted precisely, so there is always a difference in the actual and simulated values. This difference is technically called the “Performance gap.” The factors causing the performance gap are user and climate, unexpected demand due to unplanned changes in working plan, specification uncertainty, and sometimes technical equipment failure (Dronkelaar, Dowson, Burman, Spataru, & Mumovic, 2016).

Table 2-6: Factors affecting performance gap adapted based on (Dronkelaar, Dowson, Burman, Spataru, & Mumovic, 2016)

	Underlying cause	**Impact on Energy use**
Context	Target energy performance Early design decisions impact Complexity of design	High High Medium
Model	Specification (geometry, material, equipment) Modeling (simplification) Numerical (discretization) Scenario (weather, schedule, operation) Heuristic (user) Inter-model variability	High Medium Low Medium High Medium
Construction	On-site workmanship Changes after design	Low Low
Commissioning	Poor commissioning	Medium
Operation	Poor practice in operation Occupant behavior Degradation of system and materials Measurement system limitation Energy use variability in operation	High High Low Low Medium

Based on the study from (Dronkelaar, Dowson, Burman, Spataru, & Mumovic, 2016), it was observed that from 62 case study buildings, “the average discrepancy between predicted and measured energy use is +34%, with a standard deviation of 55%. These studies include a prediction of equipment energy use (Dronkelaar, Dowson, Burman, Spataru, & Mumovic, 2016).” There is no clear description of what types of buildings were considered in the study. It cannot be generalized for industrial facilities because of complications in use cases within a building. For example, it can be a hybrid building with offices, workshops, production, and logistic areas. It’s imperative to determine the energy consumption as accurately as possible because the low performance in design may have to deal with legal, financial implications, and demands for compensation and rectification work. This thesis also aims to estimate how much this performance gap is for industrial buildings. More discussion of the performance gap will be discussed in chapter 4 and the appendix.

2.4.4 Energy simulation tools

Energy simulations can be performed with static and dynamic simulation software. BIM tools like ArchiCAD have their own internal static simulation tool. Revit has its own simulation tool called Green Building Studio (GBS) and a cloud-based simulation optimization and visualization platform called Autodesk Insight. The core of tools mentioned above is dynamic but not used directly and not to its full potential (Kamel & Memari, 2019). Besides these, CAALA is another static tool used for both energy simulations and Life Cycle Analysis (LCA) (with the help of gbXML file generated by an authoring tool) but cannot be used on industrial buildings; therefore, it remains out of consideration in this thesis.

On the other hand, dynamic simulation tools are generally not directly connected to the BIM Authoring tool like Revit, but there is ongoing research on integrating dynamic simulations to BIM authoring tools, e.g., pollination plugin for Revit. Dynamic simulations primarily work with the gbXML file, but some tools like energy plus need another tool like the Open Studio to integrate geometry design. Furthermore, Open Studio with Energy plus is the state of art energy simulation tool, and they are open source. Table 2-7 shows some of the Static and dynamic tools used in the industry.

Table 2-7: Some of the static and dynamic tools used for energy simulations

Dynamic tool	Static tools
Open Studio+ Energy Plus	ArchiCAD
IES VE	CAALA
Design Builder	Solar Computer
IDA ICE	
ESP-r	
TRNSYS	
Autodesk Revit+ Dynamo/Insight 360	
Autodesk Revit + Pollination	

2.5 Data transfer

Data transfer is a big issue in the digitalization part of the construction industry because of the availability of different software tools for authoring (Closed BIM). Every software has its own native file format, which is hard to handle if the other stakeholders do not use the same software/software workflow. The availability of the Industry Foundation Class (IFC) helps a lot in file transfer, as almost every CAD software has the option to import/export IFC files. Also, there are many free IFC viewers available in the market today, with which the inspection of the 3D models is made easy. Regarding cost estimation, the possibility of doing cost estimation based on the model is excellent, but the transfer of data with proper model quality and the consistency of the quality is a big issue. A lot of data regarding cost estimation is being transferred via excel and pdf file formats which have no real-time connection with the model. However, it might have been created using the model, hence losing the transparency of the data (Choi , KIm, & Kim , 2014).

Some options to export the details from AVA programs are Excel, PDF, GAEB XML, .x81,.x82, .mmc, etc. When it comes to model-based cost estimation, mostly software uses IFC or their own individual transfer format like cpixml from Rib iTwo. In Germany, GAEB (Gemeinsame Ausschuss Elektronik im Bauwesen-) is popular in cost estimation process. With GAEB, more than data exchange, a container form to carry out a service specification (also known as the bill of quantities). “The GAEB format was designed to meet the needs of modern tendering processes, allowing all stakeholders in the AEC industry to exchange bills of quantities and related data” (DBD-BIM, 2021). Typically, the responsible architectural bureau will create a bill of quantities at the beginning of a project and then distribute it in the GAEB format to interested construction companies that bid on the award. After each bidder has created and offered, the data is again exported as GAEB and sent back with the software of their choice. New advancements in tendering and calculation software make it easy to manage even huge projects in this way (dangl-it, n.d.).

2.5.1 Multi-model container

Multi-model combines BIM and other application models to allow for a flexible integration of distributed information from design, production, and operations. To exchange multi-models, the Multi-Model Container (MMC) was defined by buildingSMART Germany (buildingSMART, 2021). DIN SPEC 91350 is a practical application of the multi-model container (.mmc) to implement the GAEB data exchange phases from tendering to invoicing. The “Linked BIM data exchange of building models and service specifications” standardized in DIN SPEC 91350 – also called BIM-LV Container (LV-Leistungsverzeichnis is the German term for BOQ- Bill Of Quantities)- enables a linked, open-source data exchange under common application of the existing standards IFC (DIN EN ISO 16739) and GAEB-XML. With this method, the complex relationships between components and construction services in the IFC building model on the one hand and the GAEB service specifications, on the other hand, can be explicitly transferred in a link model during data exchange without structurally interfering with the existing standards for building models and service specifications.

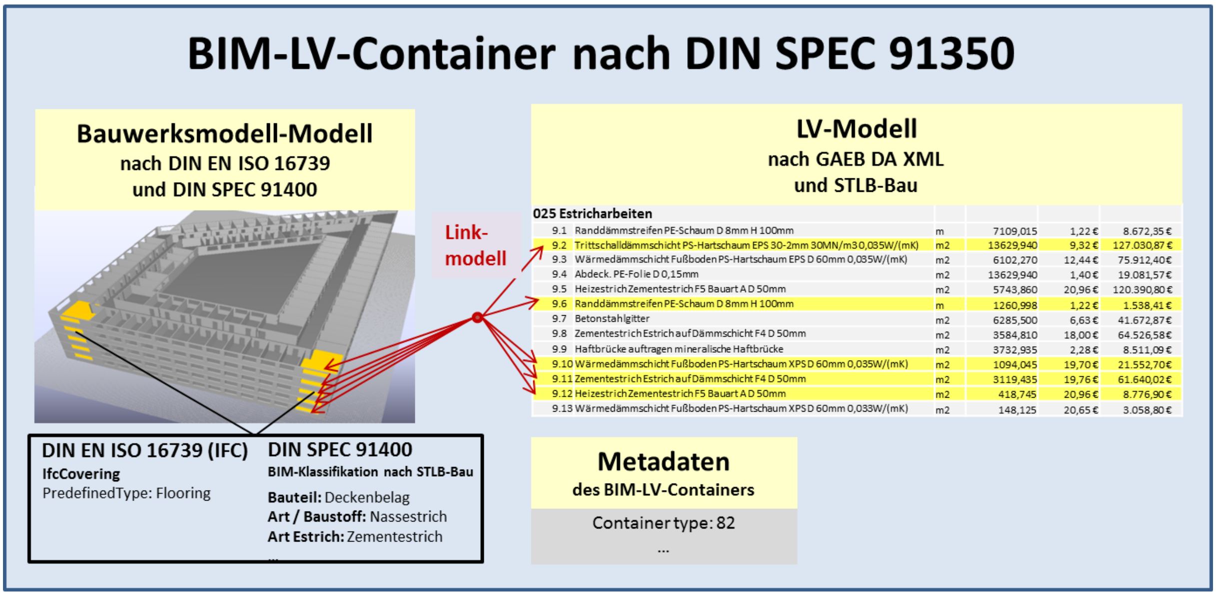


Figure 2.7: Multi-model container / BIM LV-container concept. Figure based on DIN SPEC 91350

The latest updates of AVA Software like ORCA AVA, RIB iTWO, NOVA AVA, California.pro, and many other AVA software supports the exporting of Multi-modal containers, which enables the potential of using .mmc files just like the IFC as global standards for model-based cost estimation. In this context, it’s essential to discuss DBD BIM, a software with BIM-data for components costing,services and attributes. It provides the data for components in the BIM process and can be used in various software, and enables the CAD and AVA programs to export the multi-model container. The cross-application use enables flexible use during the entire planning process. In early service phases, for example, to perform the cost estimation model-based in CAD or AVA, using Building models for BIM 5D, time estimates are available in addition to costs and services. The immense scope of data includes BIM components for building construction, technical facilities, infrastructure, and outdoor facilities. This means you can use the same platform for cost groups 300, 400, and 500 according to DIN 276. Also, DBD BIM is available as a plugin for many AVA Programs and CAD programs, along with the price data of construction elements according to the regions currently limited to Germany (DBD-BIM, 2021).It should be noted that, from the data in multi-model container, the model data cannot be manipulated but all the other information that are related to costs generated via an AVA program can be edited or manipulated.

2.6 Interoperability

According to (Eastman, 2011) “Interoperability is the ability to exchange data between applications flawlessly, to achieve a smooth workflow in which the models’ transaction is automated. This unified data exchange should avoid any possible human error and data repetition and accelerate the reproduction of the model”. The discussion in the previous section about the issues in data transfer points to the more significant Interoperability problem (Elnabawi, 2020). To understand interoperability problems, there is a need for more information on IFC and gbXML as the primary focus here is on costing and the most widely used file format for construction cost estimation is IFC (Choi , KIm, & Kim , 2014) and gbXML for energy simulations (Kamel & Memari, 2019).

Table 2-8 discusses some of the significant versions of IFC, and it’s much relevant to know as the BIM standards ask for IFC versions in the data drop at every phase of construction. Even though the model is with LOD 300 or above, it doesn’t necessarily need to be included in the IFC file.

Table 2-8: Some of the major IFC versions as per building SMART (BuildingSMART, IFC Specifications Database, 2021)

Version	Name (HTML Documentation)	ISO publication	Published (yyyy-mm)	Current Status
4.3.dev	IFC4.3.dev	Final version expected mid-2022; published by ISO in 2023	Continues updates	Under development
4.3.RC4	IFC4.3 Infra/Rail deliverable	-	2021-07	Under voting by SC
4.0.2.1	IFC4 ADD2 TC1	ISO 16739-1:2018	2017-10	Official
4.0.0.0	IFC4	ISO 16739:2013	2013-02	Retired
2.3.0.1	IFC2x3 TC1	ISO/PAS 16739:2005	2007-07	Official
2.2.0.0	IFC2x2	-	2003-05	Retired
2.1.1.0	IFC2x ADD1	-	2001-10	Retired
2.1.0.0	IFC2x	-	2000-10	Retired
2.0.0.0	IFC2.0	-	1999-10	Retired

This thesis mainly uses Autodesk Revit as the BIM authoring tool, so it’s relevant to see the contents of IFC primarily used or the official IFC version, as shown in the table above. There are different options available in Autodesk Revit to export the IFC files. Some of the default IFC export setups are IFC 2x3 and IFC 4 etc. Independent of what buildingSMART IFC specifications mention, the software has such export options. Only the in-session setup of Revit allows the user to modify the export options, such as exporting Revit property sets, IFC id, dimensions, etc., for complete model-based cost estimation. The need for such settings will be explained in detail in chapter 4 based on the challenges encountered while IFC exports. Also, a detailed export setup option based on setup in Revit is shown in appendix.

The quality of IFC depends on software export options but for example, mentioning IFC 2x3 or IFC 4 as the model view definition does not make it ready for cost estimation. It should be ensured that all the properties discussed below should be available with the model. Lack of information leads to extra work, which will make the whole model-based cost estimation process unreliable.

On the other hand, for operational costs (considering energy simulation as the essential factor for operations), both IFC and gbXML are used. It has been found that there are almost five times as many energy modeling programs that support data transferring to gbXML than those that support the IFC format (BuildingSMART, 2016). The gbXML export includes spaces, rooms, walls, slabs, windows, doors, columns, roofs, Geo-referenced site location, and all the remaining energy settings. The gbXML was developed by Autodesk; therefore, it has been widely integrated within CAD tools and other engineering programs. IFC identifies spaces like an architectural model rather than an energy model; consequently, it considers the thickness of the elements, while energy modeling only considers the thermal properties of virtual thickness as numerical figures. Additionally, when it comes to BIM-based BEM, gbXML was proven to have better performance than IFC (Elnabawi, 2020).

2.7 Life cycle analysis and its influence on costs

The energy performance depends a lot on the material used for construction, for example, the better the insulation, the lesser the heating demand. Indirectly, the better material might also be better on its emissions, contributing to sustainability. This should be analyzed in-depth with a life cycle analysis.

A “Life Cycle Assessment (LCA) is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product’s life, which is from raw material extraction through materials processing, manufacture, distribution, and use” (Muralikrishna & Manickam, 2017).

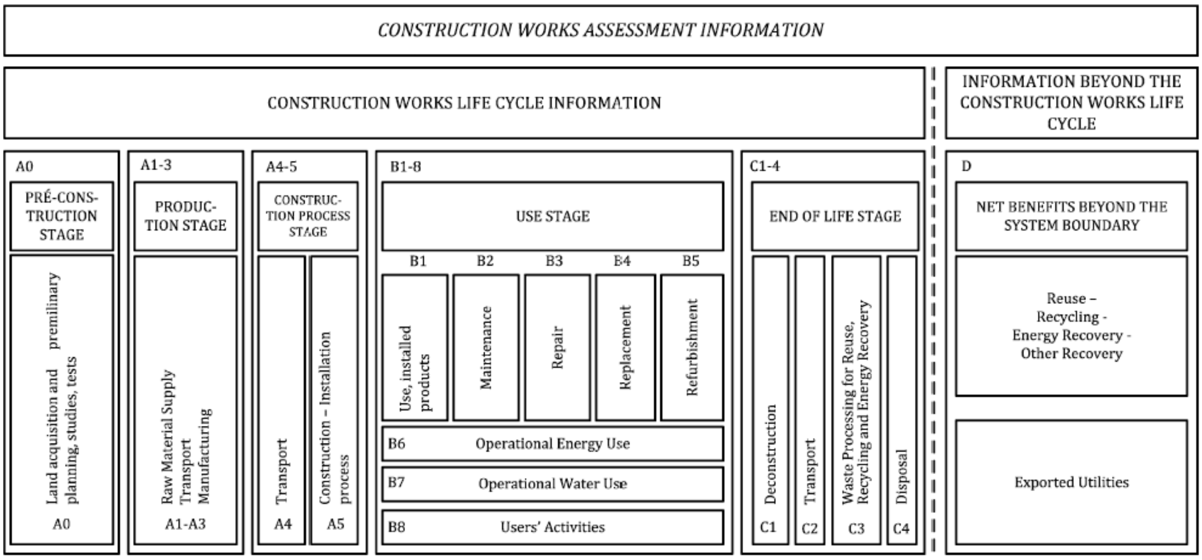


Figure 2.8: Life cycle division in AEC according to DIN EN 15643-2

Considering the different phases of LCA for a building as shown in Figure 2.8, it is distinguished between the "product phase" A1 - A3, including the environmental impacts of the raw material supply, transport, and manufacturing of the building elements. Secondly, the "construction phase" contains the ecological influences from the transport to the construction site (A4) and the assembly of the building (A5). Thirdly, the "use phase" (B1 - B7) includes environmental impacts from the use of the building itself, maintenance demands, and operational consumption of energy and water. The use phase of the construction needs very much deep analysis, which will be carried out in the test phase of this thesis, and therefore it's not considered in the LCA. Finally, the "end of life phase" (C1 - C4) that covers environmental influences from the disassembly up to the disposal is essential in carrying out an LCA. Additionally, the "phase of benefits and beyond the system boundary" (D) might be used to aim for an entirely holistic approach (Gervasio, Dimova, & European Commission, 2018), (DGNB, 2021).

Looking at the LCA as a tool for resource and energy-efficient development, the general interest of many researchers and construction and architecture companies has developed over the last fifty years. As a result, the LCA analysis in the construction sector has become standard for building in a holistic approach considering resource and energy-efficient consumption (Vigovskaya, Aleksandrova, & Bulgakov, 2017) (Weißenberger, Jensch, & Lang, 2014). As practical examples, buildings such as the "Mjostarnet" built-in Brumunddal Norway 2018 or the "Brock Commons" built-in

Canada 2017, or the skyscraper “Skeleftea Kulturhuset” established in 2020 in Sweden can be seen. The general idea of these constructions is the replacement of significant amounts of concrete and steel by the more sustainable material timber via the application of so-called “hybrid structures” - a combination of concrete, steel, and timber elements - to enhance the environmental impact of these buildings also regarding the life cycle assessment (Winter, 2020) (Kohaus, 2020).

In the scope of this thesis, the LCA is only used to find suitable materials that will reduce energy consumption and the emission related (CO_2) impacts of materials on the environment across the life cycle except for the use phase of the test subjects. The use phase is not considered because it’s being tested with energy simulations, and to have an idea of the performance of a material in its use phase, the U-value can be considered. U-value is the thermal transmittance of a material that tells how good the material is to conduct heat or simply how good the insulation is. “The lower the U-value of an element of a building's fabric, the more slowly heat can transmit through it, and so **the better it performs as an insulator**. Very broadly, the better (i.e., lower) the U-value of a building's fabric, the less energy is required to maintain comfortable conditions inside the building” (designingbuildings.co.uk, U-values, n.d.).

LCA has a vast spectrum of applications, and it gets complicated when it’s applied to industrial buildings. The study focuses on early phases, and it was not possible to try different LCA software on the industrial buildings because of problems with acquiring a license. Also, the goal particularly focuses on improving the workflow, LCA is the final parameter, but it depends on the availability of completed model data. So, this study only focuses on the capability of BIM for delivering necessary data for doing LCA, and hence the test scope is reduced to CO_2 emission, U-value and to determine the factors influencing material selection in early stages.

2.8 Digital Twin concept

“A digital twin is a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning” (Gallan et al., 2019). In other words, a digital twin can be understood as a “virtual model designed to accurately reflect a physical object” (IBM, 2021). The study object is subjected to various sensors related to crucial areas of functionality, and these sensors produce data such as physical object’s performance, energy output, temperature, weather conditions, etc. This data is embedded in a processing system and applied to the digital copy (IBM, 2021). In the scope of this work, the digital twin concept is used only to a limited extent, which will be explained in the methodology.

3 Model-based construction and operational costs methodology

3.1 Discussion of existing practices

For construction costs, excel sheets are used with quantity and cost details (based on DIN 276 in Germany).The quantities are taken partly by the designers, out of the model and added to the excel sheets. This procedure is followed because the details of the BIM are sometimes not sufficient or complete to do a purely model-based cost estimation, particularly in the early phases as the details often come with LOD 200 and there is less probability that it will be LOD 300 or more, but it is wholly left to the planners as the standards are defined mostly to deliver model with LOD 200 as explained in chapter 2.3.

The planners do the project planning and quality checks, while the project owners do quality control at each data delivery phase or simply data drops. The project controller/ estimator takes a 2D or 3D plan for quantity take-off, and it is done as per the respective region's standard specification. The prices for quantities are fixed according to the available market rates and specifications. The final cost estimate is delivered in paper, PDF, or excel format to the project owners.

Operational cost estimation is a relatively new idea as earlier it was practiced only in a later phase for facility management (Lin, Chen , Huang, & Hong , 2016). The idea behind calculating operational costs in the early phases is to use the area (as per DIN 277 in Germany) of room types and assign them characteristic energy consumption values referenced from a similar old project. The room types and corresponding details are obtained from the room book, which may or may not be generated from a model delivered on or before the end of the design phase of a project. The reference data for consumption values of a room type is obtained from the facility management data, and a rough estimation of the operational costs are made.

3.2 Problem definition

3.2.1 Challenges in adopting a fully model-based costing system

- Phase adequate model detail requirements are difficult to be defined as the LOD and project phases work differently. As mentioned in chapter 2.3, the BIM forum clearly stated that the project phases are not appropriately defined or do not have international standards, making it difficult to relate to LOD. As this situation prevails, the stakeholders involved in a project make their own standards, and due to this, there is a high probability of lack of information; hence the model-based costing system fails to deliver accurate information.
- Even though in a project, the cost calculation is done through BIM-5D, the data transfer is done with excel/pdf, as mentioned in chapter 2.5, which is not connected to the model and lacks transparency. Such data would be difficult to understand for someone who was not a part of the project when it’s taken for reference in the future.
- The model must be defined with element property sets; all the elements should be appropriately named, coding should be checked, and IFC 4 classes must be maintained for proper costing with AVA Program
- Generally, the requirements set by BIM standards for cost estimation add a massive amount of data to the model. In the early phases of the project, it is considered something that needs immense effort from the planner.
- Sometimes the export format fails, or the IFC property sets are lost.
- Lack of communication between different project stakeholders leads to project delays, even in the BIM project, its challenging to ensure collaboration of all the stakeholders, such as MEP engineers, with planners.
- Confusions with the data of projects which were not designed with the concept of BIM. When making a databank for costs, it should include all the projects, including existing, ongoing, and future projects.
- In general, BIM is a new concept for AEC, and it’s not entirely possible to discard the conventional methods and adopt a completely new concept.

3.3 Process definition and Workflow

From the problems defined above, it's clear that there is a need for a more harmonized, transparent, and reliable workflow for model-based cost estimation.

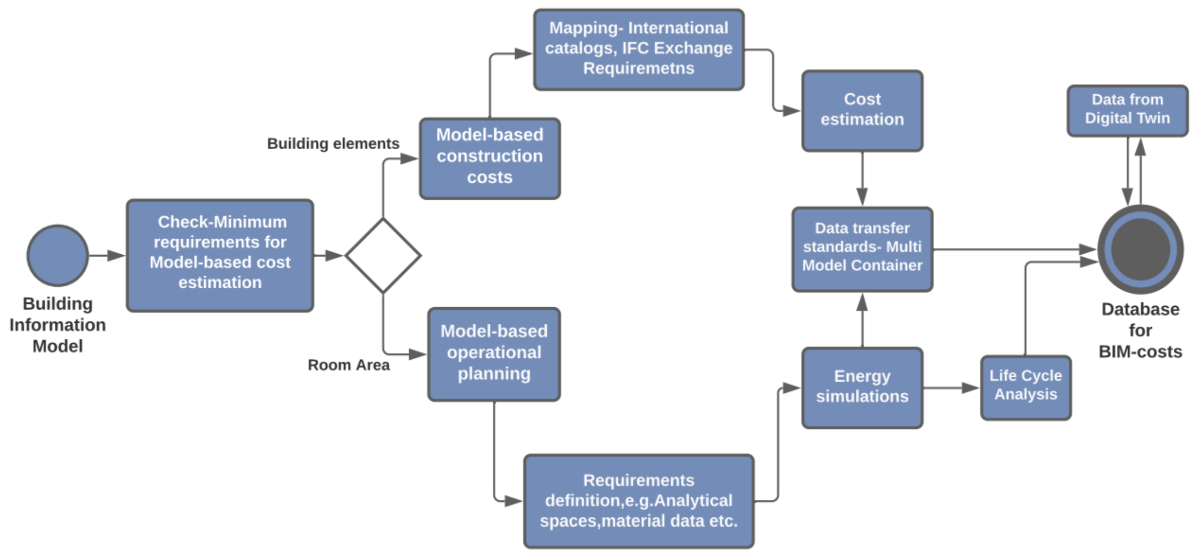


Figure 3.1: Workflow for construction and operational planning for Costs with BIM

Figure 3.1 depicts the proposed workflow for construction and operational planning with BIM. The workflow starts with analyzing the acquired data of a building information model. The model should be checked for minimum quality and the required level of details for cost estimation, which are mentioned in different sections of chapter 2. After the check, the process diverges into model-based construction costs and model-based operational planning. There is the availability of existing standards for construction costs as the 5D BIM is already well known to the construction industry. Considering only the technical aspects, the challenges are mapping international catalogs onto a database from the perspective of an international project client and IFC exchange requirements. Furthermore, there are many challenges when it comes to practicability. Still, it can be solved by following the general BIM workflow, so it's only relevant here to discuss the requirements for model-based cost estimation in the early stages of the project. The challenges mentioned in chapter 3.2.1 should be solved before finalizing the construction cost estimation.

On the other hand, model-based operational planning should be tested from scratch as there are no proper existing standards for model-based operational planning. Operational planning is specially mentioned instead of operational costs because of the lack of standards. The creation of standards should be dealt with not only from a cost’s perspective but also from a holistic perspective. The idea is to use the rooms and their functional type, just as mentioned in chapter 3.1, but here, the rooms are taken from BIM, unlike the traditional process of referring to the room book or written data. For a model which is not built for energy simulation, the room area is the most common aspect that can be used from BIM , the other factors influencing energy simulation can be described into the model. Hence the workflow shows building elements as nessential factor for construction cost estimation and room area as an essential factor for operational costs.

The requirements must be specified for model-based operational planning for early phases in construction, and then the model should be used for energy simulation. After generating the energy simulation and construction costs, the necessary data should be filtered to be taken to a database. According to the exchange standards defined as discussed in chapter 2.5, which can vary according to the planner compatibility, the data can be taken to the database.

The existing cost data can also be taken to the database along with both construction and operational costs. The term ‘database’ is used here with meaning, a cloud space to gather all data regarding costs of a project. The concept of a cost database will be discussed in detail in chapter 4.4. If the data in the databank satisfies all the requirements, it can be used as a reference for future projects. If necessary, a life cycle analysis could be performed on the available data to find the plan's reliability for the long term and for sustainability aspects. The scope of LCA is extensive, so it's not possible to test all of them on the scope of this thesis, but still, the possibilities will be discussed in chapter 4.5. The final step is to use the data stored in the database for developing and using the digital twin of the building and vice versa.

3.4 Methodology of energy simulation for operational costs

As the factors considered for operational planning were determined based on the data from projects, now it is time to find what comes from a model for model-based operational cost estimation. An energy simulation test on an example model was carried out to find those details mentioned. All the tests below were done with the help of Autodesk Revit as an authoring tool. Figure 3.2 shows the steps involved in generating an energy simulation. Also, a databank concept for operational costs is picturized towards the right of the figure.

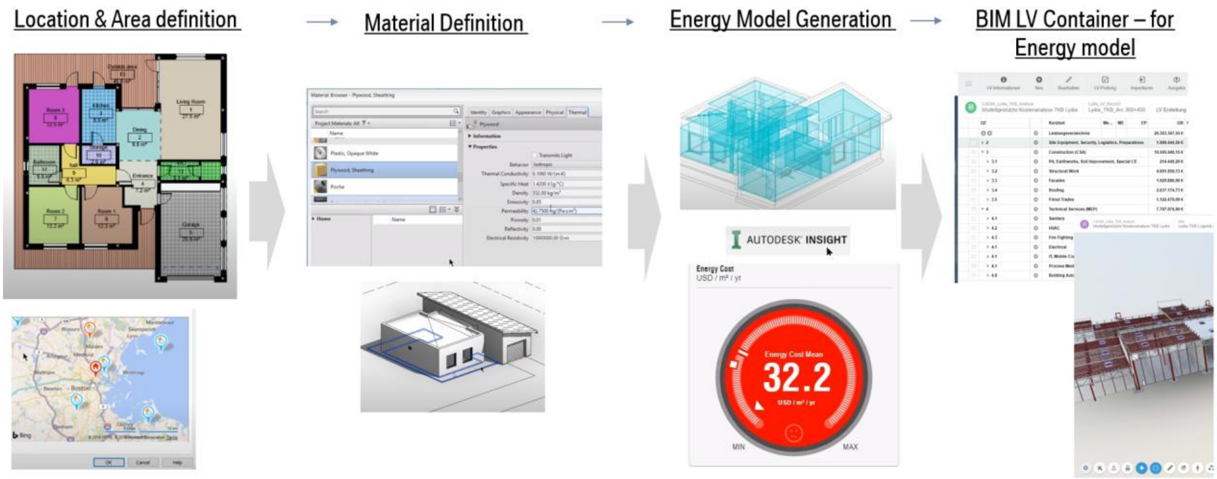


Figure 3.2: Workflow for operational cost estimation with energy simulation

The process starts with defining the project's location with an internet mapping service available in Revit. The areas should be defined appropriately after assigning the functions for each room type. The model should then be described with materials for each building element like walls, floors, roof, etc. The next step is to generate an energy analytical model (BEM) used for energy simulation. Before developing the BEM, some basic details must be specified as energy analysis settings. Figure 3.3 highlights the most critical settings required for energy analysis.

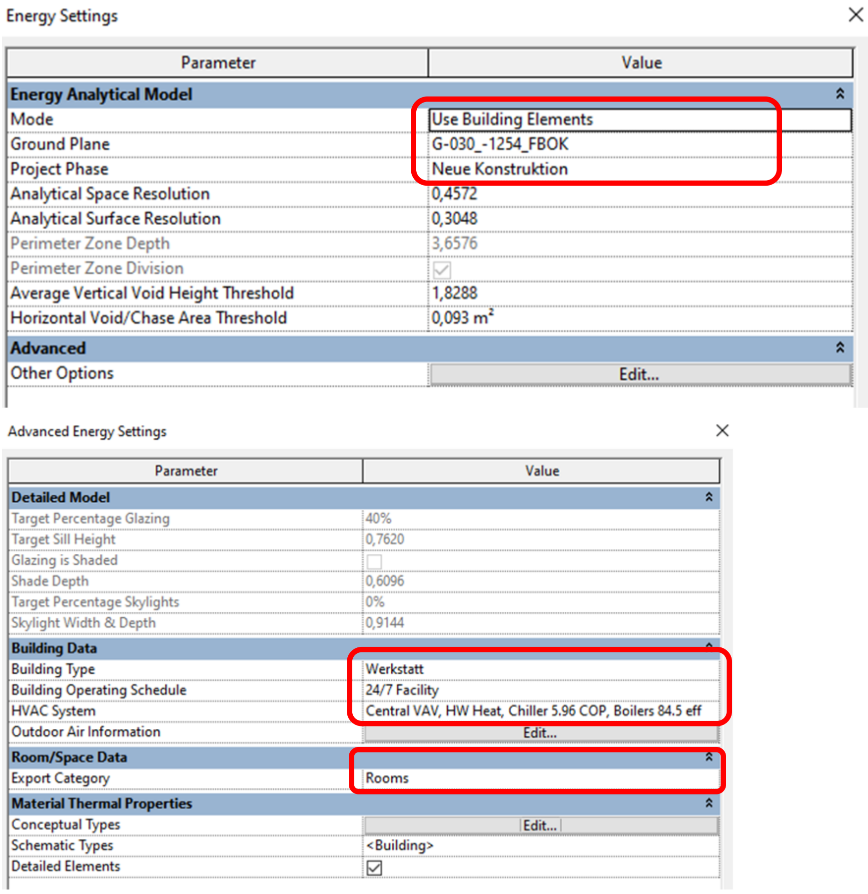


Figure 3.3: Energy analysis setting in Autodesk Revit

After specifying the energy analysis settings, the BEM can be generated as shown in Figure 3.2; BEM can be seen in light blue color in the figure. After creating the BEM, it can be used to generate energy simulation utilizing the cloud platform of Autodesk Insight. Revit generates energy simulation in Insight by clicking on the tab Analyze>Generate.

3.5 Methodology for model-based LCA

As explained in chapter 2.7, the goal is only to extract information regarding the calculation of CO_2 emission of certain building elements such as facade, roof, etc., and also the U-values. The idea is to extract the material data from BIM and to find the CO_2 emission of the extracted materials using the tool eLCA, which uses "ÖKOBAUDAT" as material database. For finding the best material which could reduce energy consumption along with optimum CO_2, the easiest solution considered was to analyze the building elements based on its Global Warming Potential-GWP measured in kilograms CO_2 Equivalent per square meter (kg-CO2 eq/m²) and thermal transmittance value (U-value) measured in watts per square meter-kelvin (W/(m²K)). The GWP in different phases can be calculated with the help of eLCA tool, and the U-value can be calculated with the details extracted from the BIM model. The material database of Revit is having by default, the thermal conductivity value, which is required to calculate U-value, and all other thermal properties of common building materials. As explained in the literature, the use phase is not considered because of many complexities, but the U-value helps find if the material is efficient in its use phase. There are many online tools like ubakus.de, which can be used to find the U-value, but here, only excel is used with the help of U-values from Revit for different materials.

3.6 Integration of digital twin concept

As explained in chapter 2.8, the digital twin is only used with a specific purpose in this work. With the defined workflow in chapter 3.3 for model-based construction and operational costs, the data can be transferred as a multimodel container. The transferred data can be stored in software such as Nova AVA, which can act as a cost database. The model is updated during every phase and the corresponding data as well. Finally, when the project is handed over to the owner, the as-built model is updated with all the extracted construction and operational cost data so that the transparency of knowing costs for each and every part of the building is achieved. This model can be used as the foundation for the digital twin. When the building is in its operational phase, the problems or inaccuracies with estimated operational costs can be crosschecked and updated. This updated data from the digital twin can be taken back to the cost database, and the estimation process or characteristic values in the estimation process can be improved. Such references with digital twin can reduce the performance gap within simulations/estimations and real values. Also, the data regarding maintenance, repair, or retrofitting can be recorded in the digital twin and then be updated to the cost database to compare and evaluate costs invested.

4 Evaluation of model-based construction and operational costs

4.1 Model-based Construction costs

Autodesk Revit 2020.2/2022 was used as the BIM authoring tool for the tests. After several tests on example models, three methods are proposed for model-based construction costs:

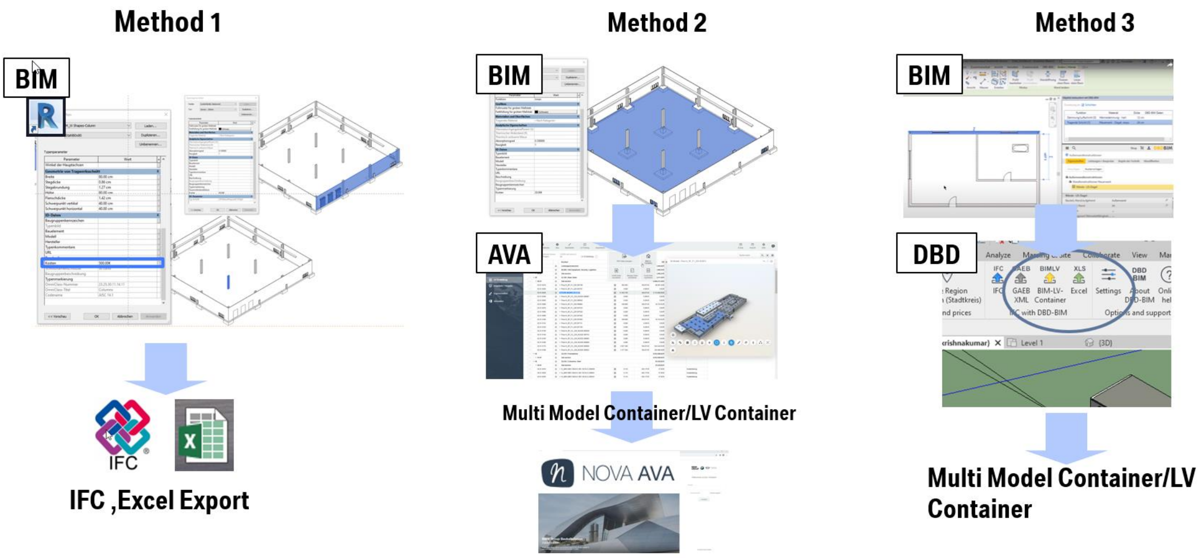


Figure 4.1: Different methods for model-based construction cost estimation.

Method 1 (Figure 4.1**):** The Revit property sets can also be exported on IFC exports, along with IFC property sets. The AVA programs can read every property set shipped with IFC, such as identity, geometry, material, energy performance, assembly code, costs, etc. Data such as assembly codes and price are not available in the software as they are significantly user/region-specific. Nevertheless, there is the provision of exporting all the properties of building elements needed for construction cost estimation. The necessary data can be exported as material take-off and copied to an excel sheet. According to the region and data from the planner, the building elements can be assigned with standard specifications and related costs according to the market rates in the excel sheet. This process is partially model-based as the quantities are exported from a model, but it cannot be stated as a complete BIM process as there is no involvement of a QTO/AVA program or a databank to store the generated data.

Method 2 (Figure 4.1**):** The IFC file is exported with all the necessary data to Nova AVA. The cost estimation is completely done in Nova AVA with region-specific standard specifications for building elements and costs. The software makes it easy to synchronize similar building elements with requirements and costs once assigned. The bill of quantities can be generated and exported as PDF, GAEB XML formats, or as a multi-model container. The data could be delivered to the project owners at the end respective phases of the project.

Method 3 (Figure 4.1**):** This method is especially only applicable in Germany. The idea is to use a plugin for the CAD authoring tool, DBD-BIM, with standard specifications for Germany and the region-specific costs. This plugin is available for most of the widely used BIM-CAD authoring tools and most AVA programs. With the help of the plugin, the data can be exported directly from the authoring tool as PDF, XML, GAEB XML formats, or as a multi-model container. If the planners prefer to use their own cost database, the plugin can be used to assign the specification codes in the AVA program.

The following Table 4-1 briefly describes the advantages and disadvantages of the different methods. One of these methods can be chosen as the standard for model-based cost estimation to improve the transparency of the process.

Table 4-1: Different methods for construction cost estimation based on test on example model

Method 1 – Cost Estimation in Revit (Material Takeoff)	Method 2 – Cost Estimation with Nova AVA /AVA Program	Method 3 – Cost Estimation with DBD BIM
Advantages: Easy process, do not need an extra AVA Program.	Advantages: Flexibility; can be maintained as a database, can work with both existing excel sheets & 3d-models and future projects, Exchange format with multi-model container can be obtained with existing and future projects, simultaneous comparison of different projects from the database	Advantages: can be installed in any BIM-CAD program as a plugin, inclusive with specifications and price database, price sorting available according to regions

Disadvantages: Not transparent, need CAD expert, only excel export possible, not possible to make a proper standard BOQ.	Disadvantages: Must optimize the database, someone must take the responsibility of quality control	Disadvantages: Not international, based only on DIN standards, no English version.
No additional expenses	Ava Program costs	AVA program/CAD program +DBD BIM costs

4.1.1 Challenges in model-based construction cost estimation

The following were the challenges observed in the model-based construction cost estimation process based on tests conducted:

- From the perspective of BMW Group as an international project owner, the major challenge in model-based construction cost estimation is mapping international standard codes when the data is taken to a databank. For example, a project from the USA will be estimated according to the American standards or international standards, which could be **Uni-class** or **Omni-class** codes. On the other hand, a project in Germany will be assessed according to DIN standards. When these different projects are taken to a common cost databank such as Nova AVA, the building elements should be organized according to any one standard. For this process, mapping is required, which could be done with CAFM connect or with Nova AVA or with the extremely time-consuming process of manual excel mapping.
- Another major challenge observed is the data transfer with IFC. It's well known that IFC files have some amount of data loss. When the project standards say that IFC 4.0 needs to be delivered, not all the required property sets must be exported. Either it must be exported with the design deliverable setup of the IFC version (according to the IFC export option in Revit), or it must be especially (user defined-in session setup) specified what all properties should be exported with the IFC. The authoring tools are not developed to automatically export all the necessary information for cost estimation with the IFC. This challenge would

probably be why Rib iTwo, state of the art AVA program, prefers their own file transfer standard, “cpi-XML,” for model-based cost estimation.

- Proxy elements: The IFC files have a common issue: they are often not set up correctly at the start. Many category element translations are set to a default value, IfcBuildingElementProxy. This default output does not contain element-type specific properties and can give an output that does not meet the project's needs for exchange (White, 2021). IfcBuildingElementProxy has a default basic property set and should be used to exchange special types of building elements. The current IFC release does not yet provide a semantic definition for proxy elements, additional parameters can be added but will not be included as part of the export without intervention on your model.

4.1.2 IFC exchange requirements

Considering the challenges mentioned above, the export of an IFC file ideally should be with the following requirements:

- Each Globally Unique Identifier (GUID) must be unique.
- Always export the "Base Quantities" (units of volume).
- The material must be assigned to all elements.
- According to DIN 276 2008-12 /2018-12 (in Germany), all elements must be classified.
- The "IFC-Type” should be mentioned for every building element.
- Prevent using the IFC entities “Building element proxy” and “Building element part," which are assigned to the building elements by default unless specified.
- Export the "renovation status" or the "construction phase" in the PropertySet of the same name.
- In Revit, use the “in-session setup” to export all required details; in other authoring tools, IFC 2x3/IFC 2x3 COBie setup can be used.

4.2 Model-based operational costs

4.2.1 Analysis of requirements for model-based operational cost estimation

To establish the process of model-based cost estimation in the operations of a building, it's imperative to find all details required or what factors are considered to do operational planning without thinking of BIM. Based on tests conducted on existing project data which are in the operational phase, the following were found as the essential factors influencing the operational costs-:

- **Net area (useful area), including gastronomy, parking, green areas**
- Electricity
- Heating
- Natural gas
- Water
- Wastewater
- Processed gas
- Security
- TFS (Technical Facility Service) / hard-Service costs
- IFS (Infrastructural Facility Service) / soft-Service costs

Contents TFS:

- General repair
- Maintenance and inspection
- Repair - construction costs
- Repair -technical facilities
- Repair - outdoor facilities

Contents IFS:

- General cleaning and maintenance
- Facade cleaning, glass, ground (deep cleaning for the floor), chimney cleaning
- Special cleaning (unexpected/accidental)
- Outdoor Facility services- exterior cleaning, gardening services, winter services

Additional requirements:

- Simultaneity factor or ratio peak load to base load for technical machines
- Connected load (plug load)
- Energy & resource efficiency
- Operating time/shift model of building use
- Number of employees (white and blue-collar/number of shifts)

4.2.2 Energy simulation test

The tests were conducted on models with Autodesk Revit as the BIM authoring tool and Autodesk Insight as the simulation tool. A sample model available with Autodesk Revit Installation files was chosen to test the energy simulation process. As per the data from the sample, it is a school building. Only a linked or merged architectural and structural model is needed for the test as the principle behind the simulation is to use the rooms. Figure 4.2 shows the Revit sample model with an analytical model generated from spaces on the right top. The analytical model generated from spaces and building elements is on the right bottom. There is also the possibility of exporting rooms, the mass of the building, but the energy data such as electric and HVAC cannot be added to such elements, such data can only be added to analytical spaces. The analytical space with building elements also considers additional elements other than spaces relevant for the energy analysis.

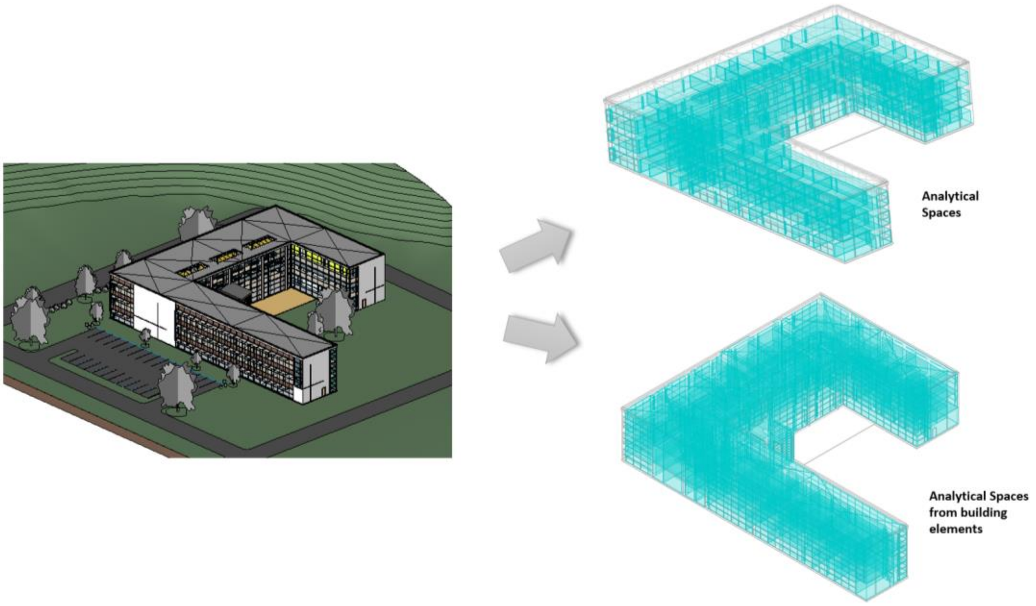


Figure 4.2: Revit test model with analytical spaces

Following the methodology mentioned in chapter 3.4, the energy simulation was generated using Green Building Studio (GBS), the simulation core for Autodesk Insight. GBS gives rough results for the building's energy consumption using DOE2, the simulation engine. GBS is more beneficial in the design phase of the building to develop an efficient design and construction methods and materials in terms of energy consumption.

Figure 4.3 shows the visualization of the energy simulation in Autodesk Insight. The simulation shows the model with the building elements in different colors as per its generated energy consumptions. Also, the mean energy consumption can be viewed on the left corner of the picture in kWh/m^2/year. There are many options to optimize the energy simulation, which will be further discussed in this chapter. The simulation with only analytical spaces results in low consumption as there are certain building elements not considered as it only takes the spaces, but on the other hand, the simulation with building elements and spaces shows the higher value, which should be considered as a reliable result.

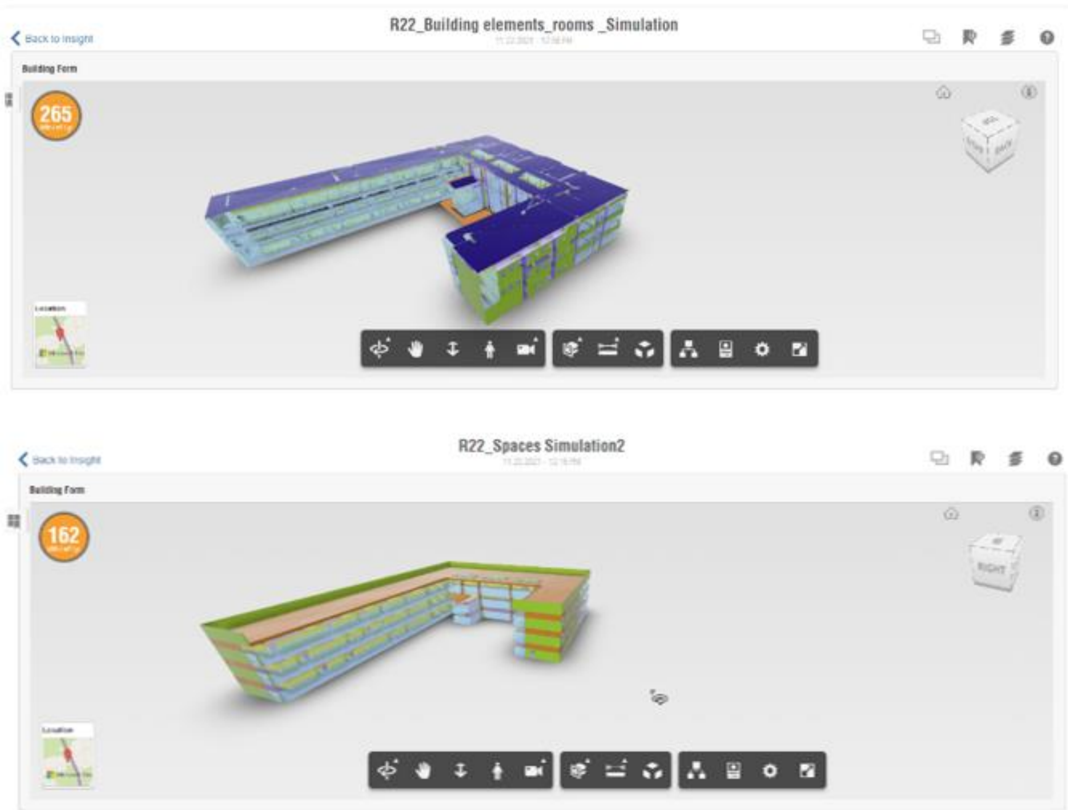


Figure 4.3: Visualization of the test subjects in Autodesk Insight

Furthermore, these two simulations are considered mainly to highlight the interoperability issue. The GBS automatically converts the Revit model to gbXML format and then to Input Data File-IDF, which is read by the simulation engine DOE2. During the conversion to gbXML, the model with only the analytical model showed intact surfaces when viewed in Aragog gbXML viewer shown in the left of Figure 4.4. In contrast, the model with analytical spaces and building elements showed ruptured surfaces in some parts of the roof, as highlighted in the right part of Figure 4.4. According to (Kamel & Memari, 2019), this problem is mainly due to the irregular geometry of the building element. The gbXML format is especially built to handle rectangular and square-shaped, moreover simply geometric shapes. The solutions to this challenge will be discussed later in this chapter.

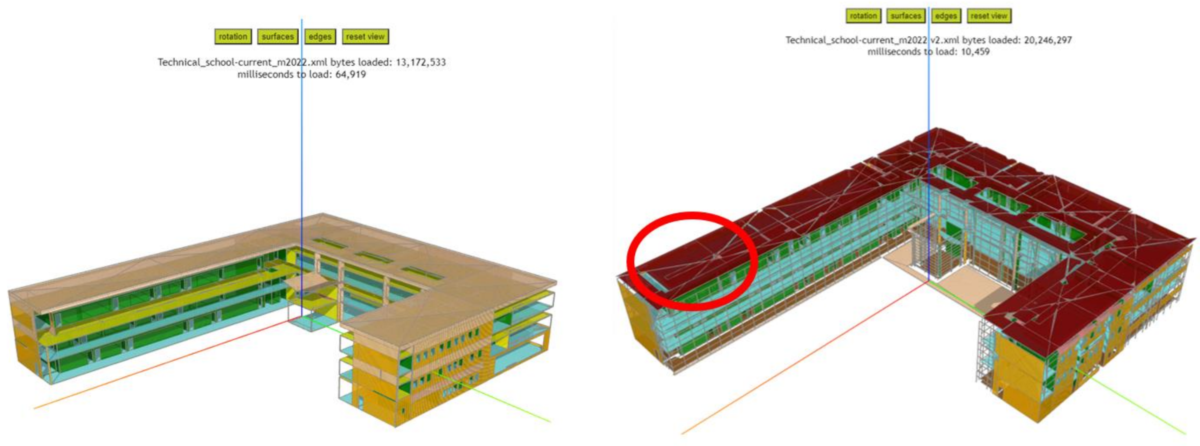


Figure 4.4: Analysis of gbXML file of Analytical models of the test subject in Aragog gbXML Viewer

According to the analysis from Autodesk Insight, the following parameters can be used for optimizing the building:

- Building orientation – for natural ventilation and PV Position.
- Infiltration Value (IN ACH) – Air leakage from conditioned areas
- **Lighting efficiency –average internal heat gain and power consumption of electric lighting per unit floor area – (e.g:20.45W/m2)**
- Daylight dimming/ saving and occupancy sensor controls- (with or without these)
- **Plug load efficiency- the power used by equipment, e.g., computers, excludes heating and cooling equipment (W/m2)**
- **HVAC- Represents the HVAC efficiency (Heating and cooling equipment)**
- **Operating schedule**
- Photovoltaics (PV)– How much solar energy is generated
- PV – Period of usable time (seasons)- got weather reports
- PV - Usable area (mainly roof)

The highlighted optimization factors were found to be having the most substantial influence on the end energy consumption. According to the availability of an energy expert, the values can be optimized to the best design.

4.2.3 Results from energy simulation on an actual project

As the methodology was successfully performed on the sample model, it was also tested on an actual project at BMW Group. The new test subject is an industrial building, and it has a complex structure and is much more prominent compared to the model mentioned in the previous test section. The model was not built to perform energy simulation and needed many modifications. The model was also designed in parts and had to be merged to have a complete model with all building parts such as facade, structural elements, etc. Based on the same methodology mentioned in chapter 3.4, the energy simulation was performed on the test subject, and it was successfully simulated and visualized in Autodesk Insight. More details on the tests will be available in the appendix.

The test results were compared with the calculated values using the traditional methodology mentioned in chapter 3.1. The values were close, but it was not reliable as the simulation was performed with default values for energy consumption such as electric loads and HVAC in the GBS based on the ASHRAE system. These default values are totally based on the US standards and cannot be compared with the German standards. On further investigation, it was found that the values came close due to the assignment of some room types as technical areas, and GBS had by default high consumption values for such areas.

Since the reliability was not dependable, the simulation process was repeated with the characteristic values used in the traditional method for room types. It resulted in a very high value compared to the initial simulation result. Such a performance gap was observed due to the presence of production areas with high consumption. The details of the production area are only available in the advanced stage of the project. These details were neither considered for the traditional method or the first simulation, which is why the values somehow came close. **The reliability of the new value can only be validated by comparing the energy consumption in the use phase of the project.** As the project is still in progress, validation is not possible. The performance gap can be assumed to exist and be a higher value as in the simulation as mentioned above.

The accuracy of the simulation can be improved with a dynamic simulation, but it needs more sophisticated data input and energy experts. The main goal was to make sure that energy simulations are also possible on buildings with complex geometry, and the reliability of the simulation can be improved with the input of characteristic reference values to the analytical spaces. Finally, the model requirements for operational planning were found, and it was recorded to the phase adequate details for construction and operational costs. The phase adequate requirements can be found in the next chapter along with the conclusion.

4.2.4 Requirements of operational costs deliverable via BIM

Figure 4.5 represents the possible data that can be extracted for operational cost estimation based on the requirements stated in chapter 4.2.1. All the additional information stated along with IFS and TFS should be added to the databank with the help of MS excel.

- **Net Area (useful area), including gastronomy, parking, green areas**
- Electricity
- Heating
- Natural Gas
- Water
- Wastewater
- Processed Gas
- Security
- TFS (Technical Facility Service) / Hard-Service costs
- IFS (Infrastructural Facility Service) / Soft-Service costs

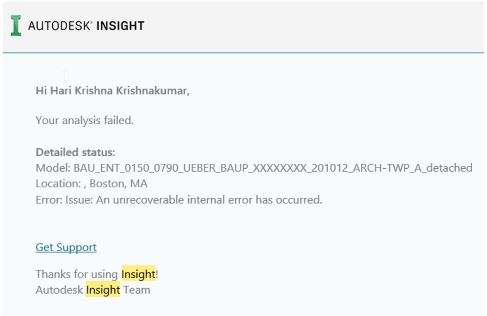
Figure 4.5: Requirements of operational costs deliverable via BIM

4.3 Specific requirements for model-based cost operational estimation based on encountered challenges in generation of energy analytical model

As the models were not built for energy simulations, there were some properties in the model that were missing and had to be manually corrected, and they are the following:

1. Origin point of the project:

Work zero point or the origin point must be specified, and it should not be away from the building as the insight searches for model only in the vicinity of the origin point. If it's too away, then the following error will be displayed while the energy analytical model is being generated:



AUTODESK INSIGHT

Hi Hari Krishna Krishnakumar,

Your analysis failed.

Detailed status:
Model: BAU_ENT_0150_0790_UEBER_BAUP_XXXXXXXX_201012_ARCH-TWP_A_detached
Location: , Boston, MA
Error: Issue: An unrecoverable internal error has occurred.

Get Support

Thanks for using Insight!
Autodesk Insight Team

Figure 4.6: Energy analysis error

To run the energy analysis successfully, the coordinates in the Revit model should be changed so that the project origin/base point is less than one mile (5280 ft. or 1.6 Km) from the survey point. Also, no geometrical dimension should exceed this limit; for example, if the height is about 2km from the origin point in the Z-axis and both X and Y axis are at zero/origin, the generation of the analytic model fails in Revit. This error was mainly observed in some of the test projects considered in this Thesis. The solution for this problem is mentioned in the appendix.

2. Normal rooms and analytical spaces/ MEP rooms:

The tests revealed that normal rooms are insufficient to give the characteristic values concerning energy consumption on its availability. It's suggested to use the MEP room/ analytical spaces for this purpose. The spaces can be understood just like rooms in a building. "There is a need to subdivide large rooms (such as an open office or an atrium) to represent the heat transfer processes accurately. This approach is called thermal zoning, chunking, or blocking" (Autodesk, Support and Learning, 2021). Also, the normal rooms do not require entering the characteristic energy consumption values such as electricity loads.

Typically in a project, an EIR never demands analytical spaces in the early phases, it is needed only for MEP planning in the construction phase. If the simulation accuracy needs to be improved, then the analytical spaces should be created manually. This is a tedious task as the test model had many rooms that needed to be mapped to spaces. The spaces can be placed automatically, but it will only assign boundaries to the space, no name, type, and properties will be set to the spaces. In the test project, each and every space was matched with the room type, and the characteristic values for energy consumption were written to it manually. Discussion regarding these characteristic values written to the analytical spaces can be found in the appendix.

3. Thermal properties of materials:

It was found in a test model that materials used in the walls and facade had inconsistent thermal conductivity values (U-values). This inconsistency leads to the failure of energy simulation. Typically, Revit material library has accurate information on the thermal conductivity of materials. In case of additional materials used in the project that are region-specific and additionally added to the project, it should be made sure that the u-value comes close to the other materials used within the building element. The example picture of this inconsistency is shown in the appendix.

4. Wall layers

When the wall has too many layers, for example, the facade of the model considered for the test had five layers, and it was consolidated as two elements, but the material was not added to it as it was in the early phase of the project. The sandwiched double-wall was consolidated into a single material layer. Because of the consolidation of layers, the material density was way off the actual and may trigger simulation failure. So, when material layers are consolidated into one or two layers, it should be ensured that the thermal properties match the description.

5. Non-merged models

Revit fails to generate an energy analytical model if the model is merged with architecture, structure, MEP. The reason for failure is that energy analytical model creation only recognizes certain building elements which are useful for the simulation process. The extra modeled elements might be relevant for many other purposes, but it should be unmerged and separated for generating an excellent analytical model for energy simulation.

4.3.1 Challenges - Autodesk Insight simulations

If various design disciplines such as facade, electric, and HVAC elements are linked, the simulation will fail as these elements are not recognized by Insight, and it’s a limitation of the software as of now. The simulation only works the building elements and the room spaces specified in the early stages. So, Insight simulations are ideally suited for rough calculations of energy in the very early stages of construction where some mass model or a review model is available with minimum details.

The origin must be inside 100m of the permitter in x, y, and z directions as the simulation core only search for the origin point and 100m vicinity. Sometimes on complicated industrial models, the core of insight which is green building studio fails to convert the gbXML file to DOE-2.2 file, the reasons could be unidentified elements, detailed elements of HVAC / electrical or architecture which Insight does not recognize, overlap between layers, incompleteness or open areas, improper boundaries of spaces, etc. A dynamic simulation tool like energy plus which requires more input from user, will be the best option for advanced calculations with HVAC elements.

4.3.2 Model specific requirements for operational planning

As chapter 4.1 explains about the various requirements of operational planning, it's also crucial to describe the model-specific requirement for operational planning. The following summarizes the model requirements for operational costs found based on the tests:

- Location
- Project zero point
- Material details
- Analytical Spaces/MEP rooms with type details
- Non-merged models
- Orientation
- Energy setting as shown in Figure 3.3

4.4 Databank for construction and operational costs

According to BIM4 INFRA (BIM4INFRA, 2020), the following requirements arise to the BIM database concept:

- The objects of the digital models must be uniform.
- Relevant properties of the model objects become defined uniformly and reusable.
- Model objects are in the form of BIM object templates available digitally and neutrally.
- Test tools are available to check whether the information to be provided is in the form of digital models.

- Models are created with the help of suitable interfaces transferred to the existing systems. Inventory systems, classification, and characteristics are needed to harmonize the database.

As stated in the workflow in chapter 3.3, when the model-based cost estimation is complete, it could be taken into a cost database such as Nova Ava in the form of a multi-modal container. There are databanks such as Open Database Connectivity (ODBC), Microsoft Access, etc., which are used for storing different kinds of data, but here these are not valid because the concept developed is about costs connected with the 3D model, so only a cloud platform such as Nova AVA or a BIM software with data storing capability of 3D model and costs are considered in the scope of this work.

If the planner is using different ava programs (other than Nova AVA) or different Workflow for model-based cost estimation, then the standard could be so defined to deliver the multi-model container, If the tools used by the planner is not compatible for the multi-model container, then this can also be done manually by the project owner with the support of an external consultant.

In the case of planner incompatibility with the multi-model container, the data obtained as IFC for models and excel sheets for cost estimation can be put together in Nova AVA. This method can also be adopted for existing and old projects for which the model-based cost estimation standards were not defined. The idea is to convert the existing cost estimations in excel to Nova AVA standards, i.e., converting the excel sheets to match the standards of Nova AVA. An excel tool was developed internally to convert the BMW cost estimation sheets to Nova AVA standards. This excel tool takes out the non-relevant information from the column list and only takes the necessary data required for the Nova AVA database. After the excel sheet is made ready for Nova AVA, it can be uploaded to the BOQ section of Nova AVA. The IFC file will be already uploaded to the project data, and excel data will be uploaded to the corresponding BOQ section of the project. The data could be synchronized to the IFC elements with standard specifications using the inbuilt tools available in Nova AVA, creating a transparent database for a completed old project. This method was tested in a project, and the excel sheets were successfully combined with the IFC model in Nova AVA. This is only possible with a proper IFC file, and the standards should be as defined in chapter 4.1.2. This process is obsolete for older projects with 2d data as it does not make the data transparent.

The same process could also be practiced for model-based operational costs that combine the energy consumption data and corresponding costs to the IFC rooms, clearly defining the costs for operating a particular room. The major challenge is that Nova AVA is a costing software (AVA Program), and its functions are not meant for operational costs. The difficulty is with adding another column for energy consumption. This possibility was discussed with the software company. It was confirmed that the interface can be adapted to make a database for operational costs, provided they are funded for the adaptation.

4.4.1 Databank concept for operational costs

The idea of taking the excel sheet of existing projects with construction costs to Nova AVA was adapted to suit the operational costs, as shown in Figure 4.7. The first column can be filled in with a subsection for yearly consumption, and several subsections can be made throughout the life of the building. The second column should be again subdivided into type of areas, for example, production, office, logistics, residential, etc. It should be filled with the project data with the factors for operational costs found in chapter 4.2. The third column should be used to fill in the usage, as per the simulation results or as per characteristic values as stated in the traditional method mentioned in chapter 3.

Usage Years	Description	Quantity-Energy Use	Unit	Factor	Unit Price	Total Costs for Energy	Code
Verwendungsjahr	Gebaudetyp	Verbrauch	Einheit	BGF/Area-m²	USD	USD	z.b.DIN 277
Subsection 1- year 2020							
	Produktion			16.446,00			
	Strom/ Electricity	100,00	kWh/m² a	16.446,00	56,00	92.097.600,00	
	Wärme/ heating	200,00	kWh/m² a	16.446,00	19,00	62.494.800,00	
	Erdgas / Natural Gas		kWh/m² a	16.446,00	15,00	-	
	Wasser / Water	0,10	m³/m² a	16.446,00	0,54	888,08	
	Abwasser / Wastewater	0,10	m³/m² a	16.446,00	2,01	3.305,65	
	Prozessgas /		kWh/m² a	16.446,00		-	
	weitere /		EUR/m² a	16.446,00		-	
	Sicherheit		EUR/m² a	16.446,00		-	
	TFS (Technical Facility Service) / Hard-Service costs		EUR/m² a	16.446,00	14,89	244.880,94	
	IFS (Infrastructural Facility Service) / Soft-Service costs		EUR/m² a	16.446,00	5,93	97.524,78	

Figure 4.7: Cost template to be taken to Nova AVA database.

The fourth column is with the respective unit for operational cost factors, and the fifth column marked with yellow is critical because there is no possibility of creating such a column in Nova AVA as of now, but it can be modified upon request to the software company. The respective area for each type can be taken directly from BIM or from the room book for the project. The last three columns can be used to insert costs per market rates and total energy consumption and organize data as per area codes, e.g., DIN 277, if necessary. Finally, the excel sheet should be converted to .csv format, and then it can be uploaded to the corresponding project in Nova AVA. If the software is available with an additional column to insert areas (upon software development as mentioned earlier), it can be connected with the BIM model. Another possibility is to use the third column, ‘quantity/energy usage/consumption’, for inserting the areas, but the third column should be usage times the area.

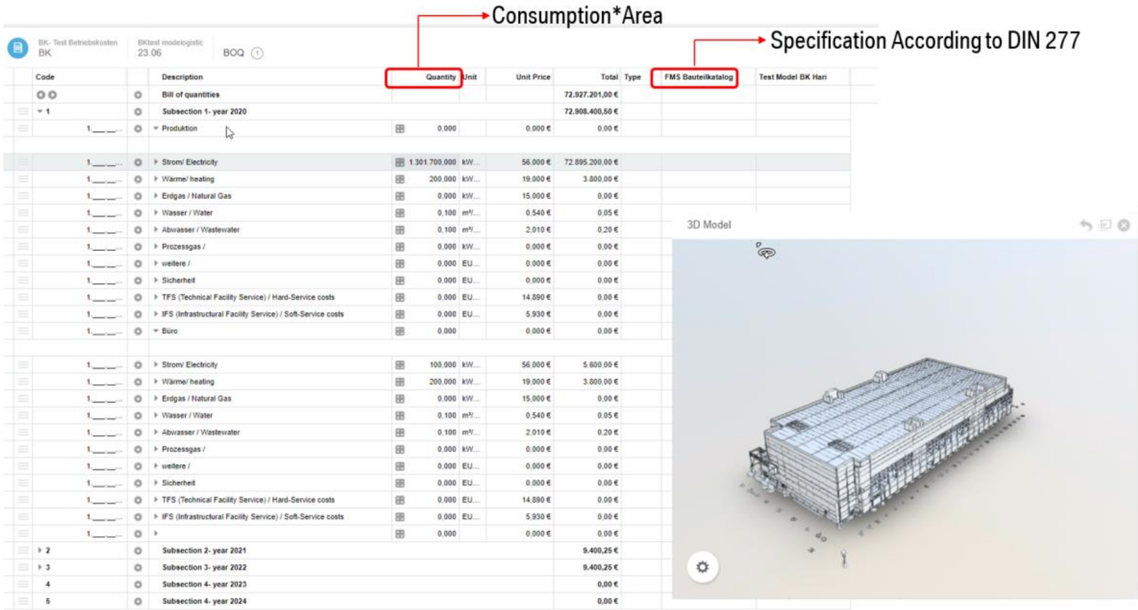


Figure 4.8: Nova Ava interface adapted to suit the operational costs databank concept.

As of now, there is no other way to take operational cost estimation to a central database of costs. The data discussed in chapter 4.2 can be extracted from the BIM model. It can be organized in an excel sheet, as shown in Figure 4.7. The cost for energy consumption can be inserted into it as per the existing market rates. The operational costs can be calculated for one year, and the consumption throughout the lifecycle of the building can be roughly estimated with a factor for the increase in consumption and inflation of prices. Considering a detailed life cycle analysis, the factor should be decided carefully upon.

4.4.2 Compatibility of cost database

From the perspective of an international project owner, the above-mentioned database will have cost data from various projects from different regions with different standards specifications. For example, a German planner will deliver the cost information based on DIN 276 standard specification, but on the other hand, an international planner might deliver the cost information in UNIFORMAT-II or Omni Class, which are known as international construction classification systems (CSI, 2017). The problem is that when this information is taken to the database, it can be confusing if the information is arranged based on different standards. Therefore, a mapping system is needed so that the specifications are mapped and arranged as per the requirement of the project owner.

To solve the mapping problem, IFC IDs or IFCRoot of elements can be used as a filter in Nova ava to match the specification catalog, but this process should be carried out manually for every building element. Another solution is to use CAFM Connect (CAFM- Computer Aided Facility Management), which is "an IFC-based file and content format to exchange data in the construction and facilities management industry" (CAFM, 2020) As CAFM Connect also uses a different coding system, the former will be a better solution for now, but CAFM has another advantage of facility management coding, but this possibility should be researched further to solve the mapping problem with CAFM Connect.

4.5 Test for model-based LCA

For testing model-based LCA, facade systems of industrial buildings were considered. After checking many facade systems commonly used for industrial facilities, Figure 4.9 shows the two different facade systems chosen for the test, with Polyurethane Hard foams and Extruded Polystyrene (XPS) as insulation materials. The insulation material is particularly mentioned here because the other materials are with significantly less thickness, and so the importance should be given to the material with the higher quantity, which might probably have more impacts. The graph on the left depicts the total GWP of sandwich steel facade system (sandwich – 2 layers of 1 mm steel) with lower CO_2 emission of 54,63,62 kg-CO2 äq/m² (äq= equivalent) for Extruded Polystyrene (XPS) and higher CO_2 emission of 325,88 kg-CO_2 äq/m² for Polyurethane Hard Foam (PIR). On the graph on the right side, the same analysis was carried out with a steel sheet facade (only one layer of 1mm steel). Both the facade systems have the same thickness of insulation of 12cm. It's evident that XPS is a better material in this comparison based on the CO_2 emissions on various phases except for the use phase.

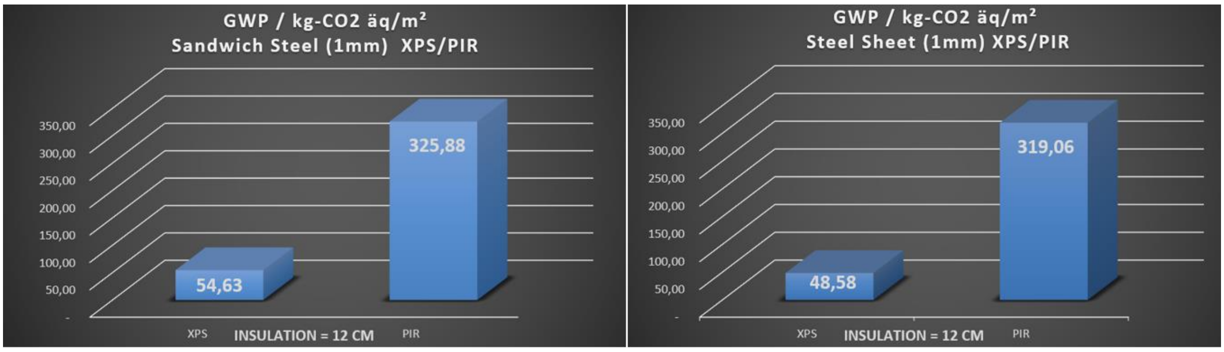


Figure 4.9: Co2 emission of different facade types with PIR and XPS insulation

Figure 4.10: shows the comparison of U-values of the insulation mentioned above materials. As mentioned in chapter 2.7, the lesser the U-value, the better the material's use phase. So here, unlike the case of GWP, PIR is a better material because of its lower U-value.

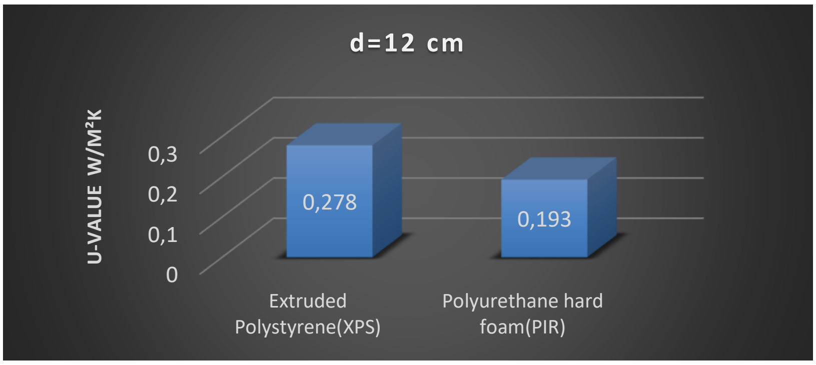


Figure 4.10: U-values of different insulation materials

It cannot be said that PIR or XPS is the best material for the insulation for any façade system as there are many other factors to be considered. On the scope of this thesis, only CO_2 and U-value are considered for tests for sustainability and LCA. On further analysis, it was found that there are many other factors which have a significant influence on choosing the material for insulation on different building parts such as walls, facades, roofs, etc. some of these factors are mentioned below:

- Fire rating/ Inflammability
- Investment costs
- Recycling potential
- Maintenance costs for repair, washing, painting, etc.

4.5.1 Limitations

There are many limitations to the above-mentioned test process, some of them are listed below: -

- Lack of data of some materials used in the construction of industrial buildings in ÖKOBAUDAT Databank.
- No data for green roofing materials.
- eLCA tool not directly connected with BIM authoring tool, the data has to be extracted to excel sheets.
- There is no clear definition of CO_2 emissions in ÖKOBAUDAT/ eLCA for all other phases other than the use phase. For example, in some materials, phase D details are not available, and in some, there is data for the C2 phase but no C1, and for some materials, there is data for B2, which is for the maintenance for use phase, so it has to be organized and calculated to suit the requirement, using manual excel based calculations.

4.5.2 Benefits for cost estimation

As discussed in chapter 2.7, the context of LCA is vast, and it needs a tremendous amount of research to be implemented to its full potential. From the tests conducted, it was evident that many factors are considered while choosing a construction material, which contributes a lot to the facility's sustainability. It's common knowledge that the reduction of CO_2 is beneficial for sustainability, but it is also beneficial in a costs perspective if there is a compensation amount paid for CO_2 consumption. Also, the U-value is a very important factor that decides the energy consumption of a facility, and if the energy consumption is less, then the costs of operations are also less. There is no direct link for model-based LCA to the costs, but there are many indirect links like the factors mentioned above.

5 Conclusions

To conclude, it's crucial to organize the findings for model-based cost estimation as phase adequate exchange requirements. For this purpose, the German “Leistungsphasen (LP)” or phases in construction as per HOAI is considered. The following

Table 5-1 shows the summarized version of these requirements:

Table 5-1: Phase adequate requirements for construction and operational cost estimation-own compilation

Phases of construction (HOAI-LP)	Description of phase adequate requirements for construction and operational cost estimation
LP 1-Basic Investigation & LP 2-Pre-Planning	▪ Basic requirements like geometry, room functions, area, data exchange requirements of model-based construction, and operational costs must be included in the BIM standard of a project according to phases in construction. ▪ Data requirement concept for facility management. ▪ Conceptual material definitions.
LP 3-Design	▪ Model-based room book – clearly defined room names with the net area. ▪ IFC (data format) export must ensure all the geometry, property sets, including name, type, function, IFC-id, dimensions, the performance of relevant equipment (e.g., Heating equipment), etc. ▪ Multi-model Container as an exchange format for construction costs. ▪ Analytical Spaces – MEP Rooms. ▪ Comparison of operational cost calculation (excel based) with energy Simulation
LP 4-Approval Planning	▪ Model check on IFC file to avoid proxy elements. ▪ Total quality checks on model to find the completeness of contents.
LP 5-Execution Planning	▪ Check for design change such as a change in functions of rooms or materials ▪ Comparison of estimated data with data from facility management ▪ Evaluation, correction of operational data, re-simulation ▪ Taking all relevant data to a central database with necessary corrections/ modifications and updates.
LP 8- Object Monitoring	▪ Final quality check and documentation ▪ Taking all relevant data to a central database with necessary updates.

LP 9-Property Care (also use phase)	▪ Comparison of estimated costs with actual consumption costs to enhance the precision of estimations and find performance gaps. ▪ Digital Twin concept, smart buildings supported with artificial intelligence, interoperability with as-built model

5.1 Changes in the early phases and their effects on costs

Often in the early phases, the modeling process starts with a mass model, and then slowly, the details will be defined in the model. A mass model is not enough for cost estimation as proper quantities in volume or areas are needed to estimate the prices. Still, in the early phases, the model requirements for construction costs could be defined, which should be defined in the BIM standards of the project as shown in

Table 5-1.

It is imperative to track the changes that affect the cost estimations to find it and take necessary actions to avoid delay. The most cost influencing factors in -the early phases of a project were analyzed on work in progress (BMW construction projects) projects, and it was found as are shown in Figure 5.1. The factors are arranged in the shape of a pyramid to depict its influence on costs, as shown, when the function of the room changes, it brings drastic changes to the costs as the plan itself must change, and the MEP design has to be adapted, and that might cause a delay in the project. The adapted change must reflect in the data drops to the project client, and it needs a lot of effort and time, which costs money as well. The next factor is the change in material type, for example, if the material of the façade is changed due to some reason, a lot of factors listed in chapter 2.7 and 4.5 has to be checked considering its sustainability aspects which again demands time. As the LOD is not defined to deliver a material description in early phases, these changes go unnoticed, causing design changes in the later phases, increasing the project costs, and delay in the project. The next factor is the change in thickness of building elements, especially insulations considering the factors mentioned in chapter 4.5.1 and also in steel or concrete structural member, which has much influence in costs, but often these changes are tracked and corrected as the design in early phases focus on dimensions and areas of the building. The last considerable factor is the change in areas, in early phases, often this change and only a considerable change which demands redesign (for e.g., change of more than 100 square meters) could be counted as an influential factor on costs.

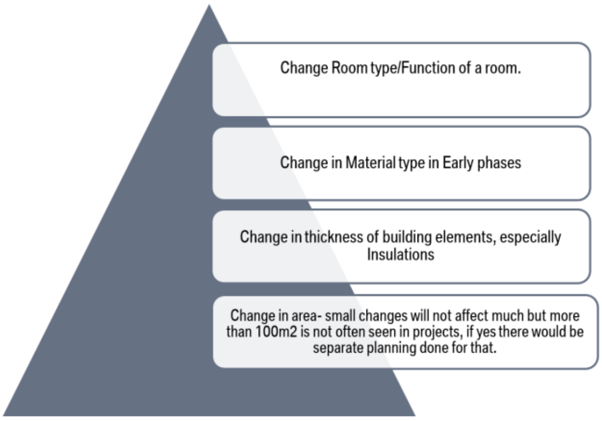


Figure 5.1: Factors influencing operational costs in early phases

5.2 Challenges and limitations of the suggested process

From the literature analysis and various tests, the following challenges were encountered with some limitations:

- Multi-model container of construction costs in the early phases is difficult to deliver. This requires a higher LOD than the international standards in the early phases, hence demanding immense efforts of planners.
- Problems in collaboration with facility management & BIM planning in early phases and sometimes also in the advanced phases.
- The Digital Twin concept remains a mirage because the planners are not so advanced with enough skilled people to turn the concept into reality.
- Insufficient key figures for energy simulations in the planning phase.
- Not every required detail for operational costs can be obtained from BIM.
- Static energy simulations are rough and cannot be close to real values as much as a dynamic energy simulation.
- Industrial buildings, especially with production areas for automobiles, have huge consumption of energy which cannot be calculated by any simulation software with its default values or characteristic reference values. These consumption data must be verified with data from facility management, and further re-simulations consume a lot of time.
- Databanks do not exist which has both construction and operational costs. The importance of binding both these costs to the model and keeping it in a central

database is not yet realized by the industry, and hence there is the unavailability of tools that can make such a databank.

- The difficulty of implementing sustainability measures to industrial buildings: As stated in the LCA part of the thesis, many crucial factors in LCA should be kept aside because of limitations with the availability of data and software competence. There is also conflict between economic, ecological, sociologic, and lawful (e.g., fire protection rules) aspects of sustainability in industrial buildings. Compromises on any element of sustainability cannot be made on industrial buildings as in other types of buildings

5.3 Benefits of the suggested process

- **Transparency:** Building model connected with construction and operational costs in the central database.
- Smooth exchange of model-based cost data with the **multi-model container**.
- Possibility of integrating existing data of projects (which does not use BIM-5D) with BIM in Nova AVA.
- Exchange of information in the use phase of a building with the help of a digital twin.
- **Optimization of operational costs of a building with data comparison:** Finding the performance gap between energy simulations and actual energy consumption will help improve the quality of data in cost estimation.
- **Sustainability with BIM:** CO2 calculator using material data from BIM improves a simple solution for choosing the best material.
- Early integration of sustainability aspects in a project.
- **Phase adequate requirements: to make the entire cost estimation process as smooth and transparent as possible, considering the practical challenges of** implementing total model-based cost estimation processes.

6 Summary and Outlook

With this work, it can be inferred that the model-based cost estimation process is very complex with multiple horizons, and hence it should be carefully done in the early phases with appropriate checks. The perspective of this work, which was based on the employer's point of view, gave a holistic understanding of model-based cost estimation. Comparisons of model-based cost estimation to conventional cost estimation methods and real-time values are always good for realizing the challenges and improving the characteristic values. The suggested process improves data transparency and makes it easier for the stakeholders to shift from conventional methods to BIM-based methods. Since data transparency is high, the optimization possibilities are also high with comparing different types of solutions. Also, since the tests were on industrial buildings (the methodology is tested and portrayed using a generic test model as well), the challenges encountered, and outcomes derived were very specific. As the major focus point was operational costs, all the necessary information related to the operations of a building was extracted as much as possible from BIM in the test phase of this work. The requirements for model-based operational costs were arranged according to the phases. As BIM for operations is a new topic and highly under research, the following section below is the outlook derived and understood from the tests in this thesis for building operations.

6.1 BIM for Operations - future expectations based on tests and evaluation

It’s essential to define the important factors considered while planning operations of the building; as discussed in the previous sections, it was evident what the requirements are. The following are the details that can be expected or should be researched upon with BIM, static/ dynamic simulations for model-based construction and operational costs:

Model-based Room Book

- Room costs -rent, utilities, space, etc.
- Personnel costs -number of employees in the room
- Use of the space - functions
- Repairs / maintenance -materials, FM relevant equipment, etc.
- Cleaning costs-cleaning area

Model-based user fit-out

- Furnishing, room equipment, evaluations

Model-based Maintenance Rooms (MR) for assets relevant to operations

- Information for operations - room number, associated system/plant, utilities, accessibility, energy performance, etc.
- MR for fire dampers
- MR for volume flow controllers
- Maintenance area, e.g., around central air handling units
- MR for heat exchanger (ventilation technology)
- MR for switch cabinets
- MR for electrical sub-distribution
- MR for shafts and shaft entrances
- MR for sprinkler heads

Model-based asset register for Facility Management (FM)

- FM relevant assets -list and information, operating costs, maintenance costs, maintenance intervals, manufacturer, type, serial number, etc.

Model-based Facility Management

- BIM-supported CAFM system
- Centralized FM data and models
- Digital twin - optimization of process and operating costs
- Model-based warranty, maintenance, and repair management
- Model-based building automation (intelligent building operation)
- Model-based service provider management
- Model-based security management
- Model-based relocation management

Model-based KPIs (Key Performance Indicators)

- Cost benchmarks through the life cycle of the building.

6.2 Outlook

The findings from this work should be realized while planning any type of construction because operational costs are obviously the highest in a project in its life cycle, but the same is the least considered in the early phases of the project because of technical compatibility issues and difficulty in implementing. Following the suggested workflow is the best possible solution for the current challenges within model-based cost estimation and the data acquiring process.

Furthermore, extensive research must be done to minimize the performance gap between actual energy consumption values and simulations, transfer of operational costs with a multi-model container, database concept for construction and operational costs, and to use the digital twin for continuous data updates.

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Affirmation

Hereby I declare to have written the Master Thesis autonomously. Only the cited sources and means have been used. Verbally or semantically transferred intellectual property I distinguished as such.

Further I assure not to have handed in the Thesis for another examination.

München, 14. Dezember 2021

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