MSc Construction Management and Engineering
Thesis

Enhancing Cost Estimation Processes In Industrial Construction Through BIM

Thom Kooke

Supervisor: Prof. Dr. Ir. A.M. Adriaanse (Arjen)
Second supervisor: Dr. Ir. F. Vahdatikhaki (Farid)
External supervisor: Emergo, Ing. T.J. Borst (Tobias)
External Advisor: TNO, Ing. T. van Ee (Tim) EngD.

5th May 2024

Department of Civil Engineering and Management,
Construction Management and Engineering,
University of Twente

UNIVERSITY OF TWENTE.

Preface

With pride and gratitude, I am pleased to present my final thesis to complete my master's degree in Construction Management and Engineering. This research marks the culmination of my studies at the University of Twente, where I pursued this master's program since February 2022. This journey concludes with the completion of this research, conducted from October 2023 to March 2024 at Emergo, an industrial construction company in Almelo. I eagerly anticipate the next chapter in my career and life, grateful for the opportunity to pursue my interests in Civil Engineering and Management through this Master's program.

Emergo proved to be the ideal setting for conducting my master's thesis. Their vision for affordable housing is inspiring, and it was enlightening to explore the organisation of the industrial and modular construction industry. I extend my sincere thanks to every member of the Emergo team for fostering a positive working environment. Additionally, I would like to express special appreciation to Tobias Borst and Jean-Pierre de Comarmond, whose support and guidance were invaluable throughout my research.

I would also like to extend my gratitude to Farid Vahdatikhaki from the University of Twente. Farid provided guidance as a BIM expert, and his expertise greatly contributed to the core topic of my thesis. Furthermore, I wish to thank Tim van Ee from TNO, who conducted his EngD research at Emergo. His knowledge and enthusiasm for the subject matter were inspiring and helped steer me in the right direction. Lastly, I am deeply grateful to Arjen Adriaanse, the supervisor of this research. Despite his busy schedule, he generously made time for me, providing guidance that ensured I remained focused and on track.

Finally, I would like to express my gratitude thanks to my family. Their unwavering support throughout my academic journey has been invaluable, and I am proud to share this achievement with them.

I hope you enjoy reading this thesis.

Thom Kooke,
Zwolle, May 2024

Contents

Summary

This research delves into the current cost estimation processes within Emergo, an industrial construction company, aiming to explore the potential integration of Building Information Modeling (BIM) methods for enhanced accuracy, efficiency, and automation. Through a thorough analysis of existing processes and the identification of key challenges, the study proposes BIM-based scenarios tailored to Emergo's specific needs, considering its two core branches: PreFab and PreModu.

For PreFab, the study designs two primary BIM scenarios. Firstly, Scenario 1 involves the implementation of BIM tools such as Information Takeoff (ITO) tools to extract information from BIM models delivered by clients. Secondly, Scenario 2 entails the development of a prototype parametric roof modeler, enabling the automatic generation of roof elements for integration into subsequent processes. These scenarios aim to enhance the cost estimation process by improving accuracy, automation, and process lead time, though their success hinges on the development of standardised procedures and the quality of BIM models industry-wide.

In contrast, three scenarios are devised for PreModu. The first mirrors PreFab Scenario 1, utilising information takeoffs for cost estimations, with potential expansion into fully automated estimations through library standardisation. The second scenario focuses on automated estimations using Dynamo to integrate databases, allowing for dynamic cost calculations despite design changes. The third scenario represents Emergo's desired state, implementing a web-based house configurator for client-driven designs, leveraging a conceptual kit-of-libraries and cost database linked via Dynamo. Standardisation is pivotal for PreModu, with library development being a key condition for enabling automated cost estimations.

Additionally, the research provides roadmaps for implementing these BIM-based scenarios, offering strategic guidance for Emergo's short-term and long-term objectives. For PreFab, the roof generator (Scenario 2) is prioritised, followed by ITO (Scenario 1), due to its reliance on external BIM models. Conversely, PreModu can immediately implement ITOs (Scenario 1) for project-specific information, with subsequent development options including dynamic cost estimations (Scenario 2) or the configurator (Scenario 3), depending on priorities and resource allocation.

The roadmaps suggest that despite being in development, PreModu may soon surpass PreFab, achieving its desired cost estimation state sooner and offering greater value potential. By focusing on standardisation in design, PreModu aims for comprehensive control and standardisation throughout Emergo's supply chain.

In summary, this research offers strategic insights into Emergo's cost estimation process, particularly regarding the "Author cost estimate" BIM application. Future research should translate conceptual scenarios into actionable strategies and contribute to the broader construction industry's understanding of integrating BIM methods into cost estimation processes, offering practical re-

commendations for efficiency, accuracy, and overcoming industry-specific challenges.

Chapter 1

Problem Identification

In this chapter, broader challenges in the construction industry and direct issues in cost estimation process are examined. The developments of industrial construction and BIM, and their contributions to the challenges are discusses. Finally, Emergo is introduced as problem owner, where their challenges are summarised in a problem statement and the research gap.

1.1 Dutch construction industry

1.1.1 Housing shortage

The Netherlands continues to grapple with mounting pressure due to a shortage of residential properties. In 2022, 90,127 houses have been constructed. Still, The projected housing deficit in 2023 is projected to rise even further, from the current 3.9% to 4.8% (ABF Research, 2023). In absolute numbers, this shortage (4.8%) corresponds a deficit of 390,000 houses. The prospected increase of housing shortages this year is primarily attributed to population growth, with an additional 225,000 residents, largely stemming from migration issues. Additionally, factors such as household fragmentation and the trend of elderly individuals living at home for extended periods contribute to the challenge (ABF Research, 2023).

The forecasts of ABF Research (2023) underscore that the pace of residential construction can barely keep up with the burgeoning number of households. Consequently, the current housing and mobility plan falls short in addressing the situation in accordance with these projections. In a letter to the House of Representatives, De Jonge (2023) (Minister for Housing and Spatial Planning of the Netherlands) suggests reevaluating the initial building goal. Specifically, the target of constructing 900,000 houses by the end of 2030 is proposed to be elevated to 981,000 houses. This revised goal necessitates the construction of an additional 891,000 houses, spread over the next eight years.

Besides the increase in figures, De Jonge (2023) also explicitly mentions the imperative nature of the housing crisis. He emphasises that the housing construction process must unfold seamlessly, minimising the interruptions. This goal entails expediting the pace of construction, providing more effective leadership, and ensuring affordability. Yet, Despite a brief cooling period in 2023, Experts predict that housing prices of The Netherlands will rise even further. The expensive material and construction costs, tight housing market, and robust population growth, is contributing to rising prices and increased competition among buyers. In fact, the median request prices of new homes has raised from €440.000 in 2020 to €550.000 in 2022 (NVM, 2023). On top of that, external factors such as climate change put pressure on the quality of construction process and outputs as well. Besides producing affordable houses in an efficient manner, sustainability has become a crucial factor, resulting in additional requirements but also in the challenge of making the current housing stock energy neutral. In essence, the Dutch house-building industry faces a substantial challenge marked by noticeable pressure, necessitating prompt, efficient and concerted action.

1.1.2 Fragmentation in the construction industry

The existing state of the construction industry appears to be incongruent with the revised objectives set within the house-building sector. The construction industry is characterised by project overruns, a low productivity, slow technological adaptions and a lack of industrialisation (Hossain and Nadeem, 2019). A key factor contributing to this landscape is the fragmentation within the construction industry, which. refers to the circumstance where the multitude of involved construction entities operate independently. Moreover, the traditional construction approach is known for it's "*Over the wall syndrome*", indicating a sequential manner throughout the project life cycle (Figure 1) (Nawi et al., 2014). The resulting division of the industry into distinct entities limits the integration of construction expertise and overall project performance (Mohd Nawi et al., 2014).

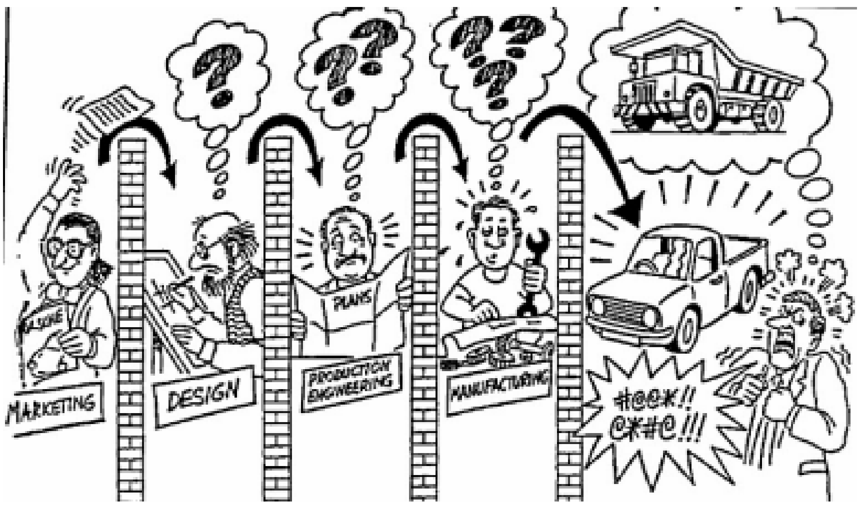


FIGURE 1: Over the wall syndrome of construction industry (Nawi et al., 2014)

Adriaanse (2014), identifies three forms of fragmentation prevalent in the Architecture, Engineering, and Construction (AEC), contributing to already described characteristics of the construction industry, project overruns and low innovation. According to Adriaanse (2014), the three forms of fragmentation are:

1. Vertical fragmentation: Indicates the clear division of the construction process into phases, distinct management and execution of tasks across different phases is common. This division fosters limited collaboration between phases, such as between the design and construction phases.

2. Horizontal fragmentation: This form arises due to the specialised nature of different segments within the construction industry. Given the complexity within the construction industry, firms tend to specialise in specific tasks, concentrating on optimising these functions. Each entity develops its unique methodologies, and the integration of knowledge and data across entities remains restricted

3. Longitudinal fragmentation: This variant highlights the lack of reusing accumulated experiences, knowledge, and skills from previous projects. The project-based nature of the construction industry leads to constantly changing collaborations, where often unique outputs are produced. Consequently, projects are managed individually rather than in a collective manner

1.1.3 Challenges in cost estimations due to the fragmentation

Fragmentation, characterised by isolated components and a sequential approach to operations, impacts the effectiveness of various processes within construction projects, among others, project design and cost estimations (Riazi et al., 2020). This study's primary focus is on cost estimations, as they are identified as a crucial process by the research's problem owner, offering substantial potential for improved process outcomes. Cost estimation is a crucial preliminary process step in any construction project, determining the completion and success of a project (Elfaki et al., 2014). Nevertheless, even though budgeting is acknowledged as a critical step, the construction industry faces several obstacles that hinder the efficiency of estimating project costs. These challenges are primarily rooted in the industry's fragmentation.

The sequential nature of construction process results in a lack of collaboration among various parties involved. This over-the-wall-syndrome shown in Figure 1 represents the traditional sequential construction approach, which leads to coordination gaps between construction phases, referred to as vertical fragmentation. When collaboration and coordination are lacking among construction participants, it adversely impacts the quality of the design process and cost estimations (Nawi et al., 2014). The absence of an holistic view of a construction product can result in inaccurate cost estimations, originated by the lack of collaboration and coordination between the separated construction phases.

Inaccurate information sharing is another obstacle in the realm of budgeting and cost estimations. Horizontal fragmentation brings about a multitude of involved parties, different contracts, and multiple information exchange points, complicating information integration. This communication approach can introduce incomplete or inaccurate information for cost estimations, resulting in missed costs, misunderstandings and discrepancies between expenses and cost estimations are the results (Al-Ashwal et al., 2011). Moreover, the greater the number of project participants within a team, the more varied software applications and systems are employed, hindering data exchange due to interoperability issues(Grilo and Jardim-Goncalves, 2010).

Additionally, the traditional construction industry's lack of standardised routines and consistent partnerships across projects contributes to longitudinal fragmentation. This fragmentation type constrains learning curves, innovation, and process optimisation, including cost estimations (Dave and Koskela, 2009). Each project's unique nature and discontinuous project team configurations hinder the reutilisation of cost information and previous supplier experiences (Dubois and Gadde, 2000). The inputs for cost estimation processes aren't standardised as they are originated from multiple involved construction parties. As a result, benchmarking design-related costs against industry standards or similar projects is limited, impacting the efficiency and reliability of cost estimations.

1.2 Industrial construction

1.2.1 Definitions

To potentially standardise construction processes, one promising approach is to industrialise construction processes. **Industrialised construction**, drawing inspiration from manufacturing, significantly reduces on-site activities to create a streamlined process, ultimately enhancing key project objectives, including cost, quality, time, and safety (Goh and Loosemore, 2017). This construction approach relies on advanced technologies, lean principles, automation, and standardised methodologies (Björnfot and Stehn, 2004)).

There is a hierarchy within industrial construction, categorised by the extent to which construction processes are shifted to factory environments. Goh and Loosemore (2017) have proposed four levels of industrialisation, as outlined in Table 1.1. Level 0 represents conventional construction methods where basic materials are manufactured off-site and assembled on-site. Level 1 introduces limited use of prefabricated elements, such as roof trusses or floor slabs. Currently, the majority of construction projects incorporate a combination of levels 1 and 2. Industrialisation level 2 involves prefabricated elemental or planar components, such as framing systems. Level 3 extends to include volumetric 3D elements, in addition to planar elements. Finally, level 4 relies entirely on manufactured building systems procured from a single source and based on multiple modules or prefabricated elements. In summary, higher levels of industrialisation indicate a greater degree of reliance on prefabricated components. Specifically, levels 1-2, level 3, and level 4 encompass a proportion of prefabricated elements of 10-25%, 30-50% and 70%, respectively (Lawson et al., 2014).

Level	Components	Description	Examples
0	Materials	Basic materials for on-site construction	*Concrete,* *bricks*
1	Components	Manufactured components for on-site construction	*Precast concrete slabs,* *Cladding panels,* *Timber roof trusses*
2	Planar	2D, linear components for assembly of structural frames or wall panels	*Structural steel frames,* *Timber framing,* *Structurally insulated panels*
3	Volumetric	3D, modular components to create major parts of buildings, which can be combined with level 2 components	*Prefabricated plant rooms,* *Modular stairs or lifts,* *Bathroom pods,* *Modules placed on podium level*
4	Complete building systems	Complete building systems, including fully finished modules before they are transported to the site	*Fully modular buildings*

TABLE 1.1: Multiple levels of building technologies in the context of industrial construction

Modular construction stands out as one of the most advanced off-site manufacturing (OSM) technologies, developing 3D or volumetric units. These units are prefabricated and fully finished within controlled factory environments before being transported to the construction site for assembly, serving as either complete structures or significant building sections (Lawson et al., 2014). This approach revolves around the utilisation of project-independent, pre-engineered standardised modules and interfaces to craft project-specific solutions. In the context of industrialised construction, modular construction typically encompasses levels 3 and 4. For instance, the prefabrication of modularised components like bathrooms, stairs, or roof assemblies aligns with level 3, while the assembly of modular units such as hotel rooms falls within the purview of level 4 industrial construction.

1.2.2 Benefits

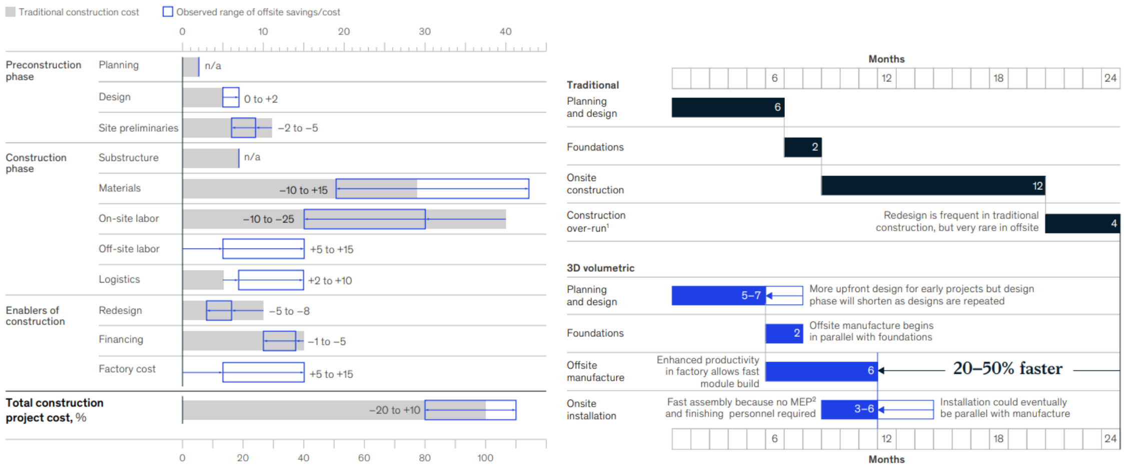
Industrialised and modular construction hold promise for addressing the housing shortage in The Netherlands, since the scarcity of both workers and homes drives the potential for modular construction to gain traction (Bertram et al., 2019). Modular construction offers several advantages over traditional building processes, particularly in project objective outcomes, measured in terms of cost, quality, time, and sustainability (Ogden et al., 2014).

First of all, as depicted in Figure 2b industrial construction has the potential to accelerate the process by up to 50%, caused by off-site fabrication and on-site assembly (Bertram et al., 2019). The reduction of construction times is caused by standardised designs and high production pace of industrial construction (Ofori-Kuragu and Osei-Kyei, 2021). Also, factory-based production reduces on-site activities, avoiding potenial hinderances such as weather conditions (Building Societies Association; Goulding et al., 2012). Delays are reduced drastically, for example, KPMG refered to a case of Portakabin Group, a modular building manufacturer and contractor, achieved a successful 99.7% completion rate in all projects compared to avereage of the industry of 40%.

Secondly, Figure 2a illustrates that costs could be reduced by as much as 20% (Bertram et al., 2019). Industrialised construction is aligned with standardised products, opening the door for economy of scale and manufacturing principles. Also, design costs are reduced, which is performed upfront instead of project-dependent. Offsite and standard solutions are more predictable (Ofori-Kuragu and Osei-Kyei, 2021), which can lead to fewer defects, rework, and associated costs (Building Societies Association; Goulding et al., 2012)

Industrial construction methods also tend to enhance social aspects of the industry. Industrialised construction be more safe, where OSM can reduce safety risks by 35%. Operations experience improved work conditions as they are performed within a controlled factory, instead of a dangerous site environment and site congestion. (Chen et al., 2010). Besides, it reduces nuisances for local residents drastically, especially in a dense area. (Building Societies Association; Goulding et al., 2012).

Also, negative environmental impacts are effectively reduced while circularity is increased by implementing industrial construction methods. Waste is reduced and emissions on-site and in use are decreased. Recycling or reusing possibilities are increased through the ability to dismantle modules effectively (Chen et al., 2010; Lawson et al., 2014). (Ogden et al., 2014).



(A) Potential benefit of costs (B) Potential benefit of speed

FIGURE 2: Productivity potentials of modular construction Bertram et al. (2019)

1.2.3 Disadvantages/Barriers

Industrial and modular construction, while offering various advantages, come with their share of barriers and disadvantages.

First of all, shipping large prefabricated units to the construction site can be expensive, especially if the site is far from the factory. Specialised transportation is often required, especially for oversized products. These oversized components can result in delays or additional costs. Transportation is also a limitation for the entire construction process as engineers need to consider the transportation within their engineering process. For example, an element size could be restricted by the capacity of the transportation methods a company uses (Navaratnam et al., 2022; Subramanya et al., 2020).

Additionally, industrial and especially modular construction often relies on standardised designs, components and processes. Establishing coordination and the transition from one construction phase to another is key for achieving success in terms of time, quality and costs. Compared to traditional construction methods, prefabricated components are more complex and these methods often require more accurate planning and coordination between departments. Accurate planning and excessive need for coordination are often mentioned as disadvantages for prefabricated construction (Navaratnam et al., 2022; Subramanya et al., 2020).

Furthermore, although costs in terms of expenses are considered as a benefit on the long term, others argue that it can be a barrier on the short term. Hong et al. (2018) conducted a cost-benefit analysis to explore cost composition of prefabrication. They examined previous studies, which consistently identified higher capital costs as an obstacle for prefabricated construction. Factors influencing the financial performance of prefabricated construction include additional costs for highly skilled workers, design changes, initial investments in new machinery, fabricate molds, and factories, as well as logistical processes. While some cost aspects like labor expenses for checking, counting, and sorting raw materials and the need for components storage space are less frequently mentioned, they still directly impact the economic viability of prefabrication (Hong et al., 2018).

Finally, Other disadvantages of prefabricated or modular construction that are mentioned in the examined studies are: Modular construction may require a different set of skills compared to traditional construction, limiting the availability of skilled labor in some regions. Standardisation within modular construction can limit architectural creativity and the ability to create unique or highly customised buildings. Also, lingering negative perceptions by the public or experts within the construction industry have been reported (Navaratnam et al., 2022; Subramanya et al., 2020).

1.2.4 Opportunity for standardisation

Besides the direct benefits industrial and modular construction entails, these approaches provide a window of opportunity to implement standardisation and optimise the product, process and supply chain domains (Jiao et al., 2007) within the construction industry (Bertram et al., 2019). Modular construction uses a combination of standardised elements and interfaces, resulting in a standardised, yet project specific product. All kinds of construction processes could potentially be standardised in the transition to Make-To-Order (MTO) or Assembly-To-Order (ATO) principles. The process domain includes standardisation within the industrial, repetitive manner of producing modules. By prioritising standardisation, modular construction maximises the potential for achieving economies of scale, employing industrial methodologies (Salama et al., 2018). At last, standardisation in supply chain domain should support the other two domains. Within industrial construction, the supply chain is more fixed, integrating the coordination between departments by standardising information exchanges.

Through adoption of standardisation in all domains, information can be reused across construction phases, project parties and projects. As long as standardised information libraries and management approach are handled, standardisation is able to contribute to the three forms of fragmentation (vertical, horizontal and longitudinal) (Sivard, 2001; Adriaanse, 2014). Standardisation of information could result in several benefits, such as cost reduction, improved efficiency, enhanced collaboration, less project conflicts, less interface and improved certainty of project outcomes (Alaloul et al., 2018; Aapaoja and Haapasalo, 2014)

Similarly, cost estimations tasks could benefit from standardisation benefits by adopting modular and industrial construction approaches, as these approach increases the certainty and predictability of project outcomes (Ofori-Kuragu et al., 2022; Smith, 2016b). This certainty mainly originates from the repetitive nature of modular industrial construction. Modules, components and materials are standardised and can be replicated across projects. This standardisation simplifies the cost estimation process since these components and their associated costs are well-defined and consistent across different projects (Constructing Excellence). Accordingly, historical data from similar modular projects can be stored within the cost libraries to provide insights into cost patterns, making estimations more precise. Modular construction processes generate valuable data from previous projects, in comparison to traditional unique constructions, where there is a lack of information in order to estimate project costs (Cheng et al., 2010).

1.2.5 Future developments, towards industry 4.0

Modular construction is often seen as an unconventional choice in many countries, where the advantages are not considered as a straightforward proposition (Bertram et al., 2019). These advantages are namely dependent on a company's ability to align their industrial and modular methods with the complexities of the construction process, from design to assembly. However, indications are increasingly strong that a widespread transformation is underway, especially by the industry's embrace of of digital technologies (Bertram et al., 2019).

Industrialising and digitising the construction industry is in line with the appearance of industry 4.0 (IR 4.0), the fourth industrial revolution. Industry 4.0 is characterised by integration of digital technologies into manufacturing and industrial processes (Alaloul et al., 2018). Digital technologies catalyses the construction industry towards their own version of the fourth industrial revolution as it foster design versatility and capabilities, enhance precision and productivity in manufacturing, and facilitate streamlined logistics. These digital technologies includes among others AutoCAD, BIM, ERP, cloud solutions, analytics, drones, and hand-held tech and Linked Data (Maskuriy et al., 2019). In construction industries, BIM has been developed as a central storehouse of digital information, ensuring data continuity across the supply chain. Consequently, BIM plays a pivotal role in advancing the digital transformation and is integrated at the core of projects embracing Industry 4.0 within the construction sector (Maskuriy et al., 2019; Alaloul et al., 2018; Bilal et al., 2015). Therefore, this research also centers around BIM as a fundamental concept, with a specific focus on its application within the study's context.

1.3 BIM

Building Information Modeling (BIM) entails a systematic approach to information management across all phases of a building's lifecycle. Its primary objective is to streamline project workflows and execution by promoting collaboration and integration. Unlike 3D CAD technology, which is limited to graphical representations without embedded data, BIM technology facilitates the creation of intelligent digital models containing comprehensive building elements and systems, alongside contextual information such as physical attributes (Lu and Korman, 2010). While BIM often involves 3D object-oriented models, its core emphasis lies in effective information management, ensuring seamless coordination of information throughout every stage of the project and the building's lifecycle (Bew and Underwood, 2010).

The adoption of BIM aligns with the construction industry's objectives, particularly in the context of industrial and modular construction (Goulding et al., 2012). Industrial and modular construction methods enhance project delivery speed and quality, while BIM facilitates scaling and modeling efficiency. BIM models contain extensive information about building components, crucial for streamlining modular construction processes and integrating with other information systems (Ezcan et al., 2013). Consequently, the synergy between BIM and modular construction can enhance information coordination, effectively mitigating horizontal, vertical, and longitudinal fragmentation.

To unlock the full potential of BIM, there are crucial steps that Emergo, the problem owner of this research, must take. Emergo's representatives highlighted the utilisation of BIM in their processes but expressed a desire for more effective application of linked data. Based on an position paper[1] that reveals the priorities of Emergo, their interest lies in harnessing specific BIM applications. Among others, Emergo wants to focus on *Author Cost Estimate*, which employs BIM for automatic cost estimations based on standardised cost libraries, objects, and processes. Additionally, the concept of *Linking and Extending* within BIM holds potential for Emergo's cost estimation process, focusing on establishing linkages between supply chain databases and the ERP (Enterprise Resource Planning) system. Besides the cost estimations, these uses simultaneously affect other construction processes of Emergo. Standardising data within object libraries and link databases to each other opens the door for applications that ensure increased efficiency all over the supply chain, such as parametric modelling or automatic construction planning. Consequently,

[1] *BIM uses in Modular Construction and at Emergo (working paper) (Ketabi, 2023)*

the problem owner seems important benefits in using BIM and connecting databases, with cost estimation processes as their priority.

1.3.1 Potential of BIM for cost estimations

Author Cost Estimate is thus considered as a priority BIM application by Emergo, holding potential to enhance cost estimation efficiency by leveraging life-cycle project data. Contractors and engineers recognise BIM's capacity to improve budgeting and cost estimating capabilities (Goulding et al., 2012), which can be achieved through various manners. Important Cost estimation related BIM uses that follow from literature are:

Information/ Quantity TakeOffs (ITO/QTO)

Information- or Quantity Take Offs (ITO/QTO's) are fundamental to construction processes and estimations, involving the measurement and quantification of building elements to estimate costs, workloads, and organise workflows. Traditionally, quantifying elements relied on manual tasks based on manual measurements of 2D schematics, which are prone to errors and time-consuming (Valinejadshoubi et al., 2024; Olsen and Taylor, 2017; Monteiro and Poças Martins, 2013).

BIM has revolutionised data management and decision-making in the construction industry, with BIM-based QTOs emerging as a prominent feature (Hartmann et al., 2012; Monteiro and Poças Martins, 2013). BIM models, enriched with data and attributes, allow users to extract semantic and geometric information for analysis and calculations. BIM-based QTOs are lauded for their simplicity, automation potential, and ability to enhance cost estimation accuracy (Nadeem et al., 2015; Sattineni and Bradford, 2011). While various software tools, such as Autodesk Revit, Vico, Bentley, and others, facilitate BIM-based QTO and estimates, the quality of BIM models remains crucial for accurate QTOs (Valinejadshoubi et al., 2024; Monteiro and Poças Martins, 2013; Olsen and Taylor, 2017).

BIM-based estimation software

Furthermore, several BIM-based cost estimation software tools have been developed to automate the process of ITO's, such as Innovaya Visual Estimating, Winest Design Estimation prov, Tokmo production system, Timberline extended, Succes Design Exchange and Vico Office (Lee et al., 2014). These tools are able to conduct an ITO and automatically connect it to cost data. For example, Staub-French et al. (2003) propose an innovative cost estimation system leveraging Industry Foundation Classes (IFC) data, automating cost estimation by directly utilising information from IFC files and applying appropriate pricing based on component geometries and properties (Staub-French et al., 2003).

Consequently, these automatic cost estimations can also be expanded in the range of the cost estimations. Fu et al. (2004) develop a system tailored for life-cycle cost assessment, extracting data from IFC files during the design phase and seamlessly integrating it into the life-cycle cost assessment process. This approach enhances accuracy and efficiency, eliminating manual data entries and allowing direct consideration of design changes' cost effects (Fu et al., 2004).

Another approach to achieving automatic cost estimations involves using BIM for parametric cost estimation models. These models utilise a range of geometric and non-geometric parameters from the BIM model to estimate the costs. The model employs formulas that relate to these extracted parameters from the BIM model. Parametric models can be particularly efficient for modular construction, where elements are often repeated (Yang et al., 2022). However, it's important to note that this method relies on estimations rather than exact cost calculations.

Integrated cost estimations (5D BIM)

The intersection of BIM and automated cost estimation, particularly the integration of the fifth dimension (5D), is a topic of growing interest, driven by the desire to enhance the accuracy and speed of project expense predictions (Parsamehr et al., 2023; Hasan and Rasheed, 2019). 5D-BIM adds cost as a dimension alongside traditional 3D modeling and time (4D). Achieving a fully integrated BIM environment with 5D BIM is considered Level 3 BIM. Despite the potential benefits, challenges exist, such as underutilisation of software tools, implementation costs, and data sharing difficulties (Parsamehr et al., 2023).

Standardisation plays a crucial role in facilitating the flow between different dimensions and automating cost estimations. Mukkavaara et al. (2016) emphasise the importance of standardised building components and associated attributes, stating that "Automation begins with standardisation." However, achieving integrated 5D cost estimations requires significant investment in new data structures, cloud utilisation for cost and object data, and implementation costs (Mukkavaara et al., 2016; Matejka et al., 2018).

Quality checks of BIM models

In addition to automatising cost estimations, BIM can enhance accuracy within the cost estimation process by facilitating clash detection. BIM models integrate various building systems and components into a cohesive model, enabling dynamic examination of how these elements interact in three-dimensional space. This allows for early detection of clashes or conflicts between different building systems, such as HVAC, plumbing, and structural elements. Early clash detection enables project teams to proactively address issues, preventing costly rework and delays. A clash-free design not only ensures smoother project execution but also contributes to more accurate cost estimates by minimising unexpected modifications and change orders. Thus, 3D visualization and clash detection powered by BIM foster precision and efficiency in the estimation process (Savitri et al., 2020).

Standardised data libraries

Lastly, BIM can be utilised to standardised information libraries, especially in modular and industrial construction, which revolves around standardisation. BIM supports this data standardisation by assisting in the establishment of fixed component and cost libraries, enabling automatic generation and modification of cost estimations. The repeatability inherent in modular construction enhances the reliability and efficiency of cost estimations over time (Smith, 2016a).

1.3.2 Standards and developments of BIM

Several factors influence the standardisation within BIM applications, affecting BIM-based cost estimations. Firstly, the use of open standard classes (IFC) for information exchanges between software data losses during conversion (Valinejadshoubi et al., 2024). Secondly, the LOD [2] in Building Information Models (BIM) depends on the designer, with LOD ranging from generic representations (LOD 100) to detailed as-built objects (LOD 500) (Olsen and Taylor, 2017; Monteiro and Poças Martins, 2013). Each category of LOD is shown in Figure 3. Additionally, BIM modeling is a manual task, which can introduce errors and affect the quality of BIM models.

[2] Level of Development (LOD), originally founded by AIA and adopted by BIMForum

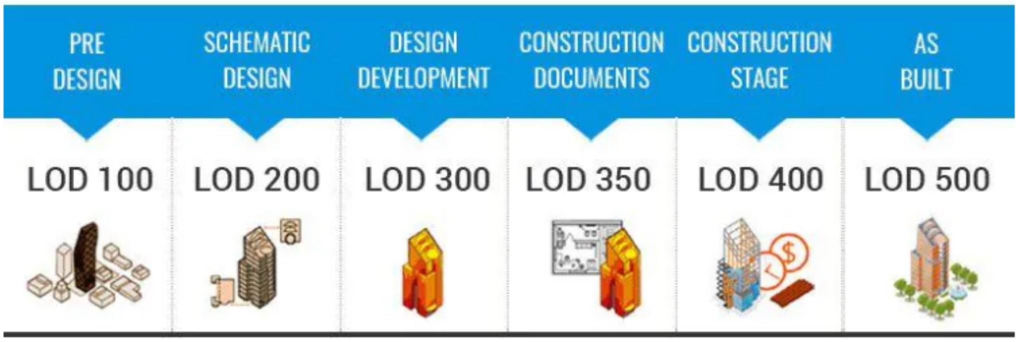


FIGURE 3: Level of development, derived from American Institute of Architect (AIA)

The latest standard, ISO 19650-1:2018[3], enhances LOD into Level of Information Needs (LOIN). LOIN defines the specific information requirements of project parties at different phases of the construction process. It complements LOD by focusing on the information needs of project parties, ensuring alignment with professional requirements (ukbimframework, 2020). LOIN encompasses four facets: Purpose, Content, Form, and Format. Parties specify their information needs using this framework, detailing the purpose, geometrical and alphanumerical information required, and the format of documents (ukbimframework, 2020). LOIN is crucial for defining the exact information needed for cost estimations.

1.4 Emergo as problem owner

Taking center stage in this research is Emergo, functioning both as the case study and the problem owner. Emergo is an industrial construction company with expertise's in prefabricated construction components and modular houses.

1.4.1 Emergo's concepts

Emergo's core business is located in manufacturing custom Engineer-to-Order (ETO) prefabricated elements such as walls, facades, and roofs. These, elements are specifically designed and engineered according to the unique requirements and specifications of a particular project. Subsequently, the elements are prefabricated within their factory and brought to the construction site as one planar element, aligned with level 2 of industrial construction, shown in Table 1.1. Collectively, this product lines is commonly referred to as **PreFab** products within Emergo. PreFab elements are mainly considered as planar 2D components, .

Emergo has ventured into the modular housing realm with their innovative modular housebuilding system, **PreModu**, positioned between levels 3 and 4 of Table 1.1, addressing a high level of industrialisation within the construction industry. This transition marks a shift from Engineer-to-Order (ETO) strategies to an Assemble-to-Order (ATO) or Make-to-Order (MTO) approach, streamlining design and engineering processes by standardising engineering components within the PreModu concept. This proactive embrace of modular construction signifies Emergo's commitment to standardisation, repetition, and efficiency, diverging from traditional methods. Central to this evolution is the PreModu concept, which replaces conventional design, engineering, work planning, and construction approaches with standardised designs and processes, establishing a production line designed for repetition and reuse. This approach minimises the need to start each

[3] ISO 19650-1 2018

project from scratch, enabling immediate configuration of solutions based on standard design options. Emergo aims to further standardise processes in the future, supported by comprehensive information libraries encompassing design-related and semantic data, facilitating tasks such as structural calculations, schedules, and purchase statements

1.4.2 Challenges of Emergo

Emergo's emphasis on standardisation and industrialised construction opens doors for improved information management systems that could enhance efficiency in project processes and cost estimations. Subsequently, the modular and industrial vision offers a promising future characterised by efficiency, speed, cost-effectiveness, and productivity, possibly contributing to the overarching challenges within the construction industry.

Nevertheless, there are challenges within Emergo to achieve efficient cost estimations within PreFab as well as in PreModu processes. While interconnected, these processes have distinct characteristics. The challenges associated with the PreFab process are elaborated first, followed by an exploration of the issues related to cost estimation processes within the PreModu framework.

PreFab components lack standardisation since the elements are engineered according to variable and unique project demands. Each project includes specific requirements by unique housing designs. This variance between projects hinders the ability reusing solutions and designs. Hence, the traditional fragmented nature of the industry is clearly visible in Emergo's PreFab product line. For instance, each party involved in preFab projects adopts individual work methods, systems, and software. These interoperability challenges contribute to inconsistency in designs and thus in the inputs for cost estimation processes. Also, each project consists of variable project parties, where each different client uses their own methods and systems. Therefore, due to the unique character of PreFab projects, the lack of standardisation hampers the development of an information system capable of reusing data, forcing Emergo to manually link project designs and cost estimation software for PreFab processes.

On the other hand, the concept of PreModu has the formula that has the potential to adopt standardisation of the three domains: Product, process and supply chain. In this case, standardisation originates by introducing uniform building components, limited design variations and standard production routines. Product, process and supply chain standardisation could potentiality reorganise fragmented data. However, the absence of complete design standardisation and uniform information management approaches within the PreModu framework hinders further solutions that contribute to the data fragmentation. The disability to unlock the full potential of the concept are mainly caused by utilising various disconnected data storage systems. Similar to PreFab, the link between cost estimation software and 3D BIM models remains incomplete, necessitating manual efforts to connect building elements with the cost library. Furthermore, achieving an uniform data structure across the PreModu process has proven to be challenging for Emergo. Not all information is standardised, where data is also scattered between multiple systems, libraries and databases, resulting in inefficient information management or inconsistencies. Additionally, the level of detail in the model is at the object level, resulting in some manual interventions to incorporate each single component into cost estimation processes. For example, mountings of objects are not modelled but are manually added in cost estimation processes by employees of Emergo.

Both processes (PreFab and PreModu) are linked in Emergo's quest to enhance the connection between project models and cost estimation software. BIM, serving as a central storehouse of information within various construction phases, offers the potential to integrate and manage data seamlessly across different systems and project stages. BIM's capabilities, such as authoring cost estimations through standardised information libraries, facilitate the integration of diverse systems. Emergo is actively examine multiple ways and manners in which BIM can drive efficiencies throughout the industrial construction phases. They have identified several specific BIM applications to focus on, but the challenge lies in determining how to effectively implement these applications within their operational methods. In light of these challenges, the following problem statement has been established, tailored to Emergo's specific context:

Problem Statement

Emergo seeks to optimise construction processes through modular and industrial construction approaches. Yet, the cost estimation processes are considered inefficient, where challenges arise from the disconnect between (3D BIM) models and cost estimation software, as well as lack of complete and standardised data libraries, resulting in unnecessary manual labor. Emergo questions which cost estimation related BIM applications suits the the company in the future and how these applications can be implemented step-by-step.

1.5 Research Gap

This study focuses on the intersection of modular and industrial construction with BIM to optimise cost estimation processes. Despite the construction industry's growing interest in modular and industrial methods to boost productivity, there remains a notable gap in understanding how to seamlessly integrate these approaches with advanced technologies (Kordestani Ghalenoei et al., 2022). Currently, there's limited in-depth research on the practical implementation of BIM solutions within the industrial and modular construction sector. While there are numerous potential solutions and applications categorised as BIM, their precise implementation, impact, feasibility, and future direction remain uncertain. This lack of implementation knowledge poses challenges for modular and industrial construction firms like Emergo in achieving standardisation across the product, process and supply chain domain. Variations within these domains leads to process inefficiencies, particularly in cost estimation.

This research addresses this critical research gap by investigating how the incorporation of BIM can optimise cost estimation processes within Emergo's Prefab and Premodu frameworks. The aim is to provide valuable insights and practical strategies for streamlining and taking decisions about cost estimation practices within the context of modular construction, harnessing the potential of BIM. This examination aligns with broader industry objectives of improving data integration, enhancing interoperability among various systems and disciplines, standardising inputs through 3D/BIM models for cost estimation processes, leveraging 5D-BIM for cost control, and fostering enhanced collaboration and communication within the construction sector.

Considering the challenges identified at Emergo, which are addressed in this study, the following statement emerges:

Research Gap

In the modular and industrial construction sector, there is a lack of effectively aligning and implementing the right BIM solution, which has resulted in non-standardised and inefficient cost estimations. This study aims to address this gap by investigating which combination of BIM solutions can be most valuable to cost estimations in industrial and modular construction, under what conditions they can function effectively, and how they can be gradually introduced to industrial and modular construction. There is a need for better insight in potential BIM solutions and the needed guidance for decision making about the (stepwise) implementation of these BIM solutions.

Chapter 2

Research Design

2.1 Research Goal

This research aims to enhance operational efficiency and synergy within Emergo's project workflows through the adoption of BIM. This enhancement necessitates leveraging or developing BIM models specifically for cost estimation purposes, benefiting both Prefabricated processes and the innovative PreModu concept. By harnessing the capabilities of BIM, Emergo stands to achieve heightened efficiency across their cost estimation and related processes. However, it is imperative to determine the precise utility of BIM, identify necessary developments or conditions, and examine how it can enhance both cost estimation processes.

As discussed, BIM encompasses a broad spectrum of applications, with each specific implementation referred to as a BIM use. Examples include 5D BIM or Information Takeoffs (ITO), as well as the development of a complete component library. These BIM uses often interact synergistically, with advancements in one area complementing another. A combination of multiple BIM uses within a specific context constitutes a BIM scenario. It is pivotal to examine which potential BIM scenarios, comprising various combinations of BIM uses, are applicable for PreFab and PreModu. Furthermore, this research aims to reveal the underlying benefits and barriers associated with each scenario. The goal is not only to outline how a scenario operates but also to delineate the benefits and conditions of full deployment. This understanding will equip Emergo with insights into how each scenario functions and, more importantly, the benefits and conditions associated with its comprehensive implementation.

Subsequently, This research aims to develop a roadmap outlining a sequence of potential BIM scenarios over time, providing Emergo with a visual representation of strategies for BIM implementation. The roadmap encompasses steps, decisions, conditions, and benefits associated with each scenario, allowing for an assessment of their impact on Emergo's current operations. By highlighting pathways for improvement and identifying associated benefits and barriers, the roadmap serves as a guide for Emergo to achieve their desired objectives. It enables informed decision-making and strategic actions to enhance the efficiency, accuracy, and quality of their cost estimation processes in both the short and long term. Through an exploration of how BIM scenarios operate, the research seeks to empower Emergo with actionable insights to optimize their project outcomes.

The following research objective has been established according to the structure of Wieringa (2014):

Research Goal

- Enhance strategic decision-making capabilities for Emergo's business developers
- By crafting a roadmap detailing potential BIM-based solutions, their associated value, and requisite conditions
- That guides Emergo towards an optimised cost estimation process, including standardised and integrated data
- In order to facilitate Emergo in their mission to efficiently produce high-quality, affordable housing

2.2 Research Questions

The research goal is broken down into sub-questions, logically structured to achieve the final research outcome. Four overarching questions (1,2,3, and 4) guide this investigation, each comprising a series of sub-questions. Initially, the study thoroughly examines Emergo's design and cost estimation processes, aiming to uncover the underlying challenges. By comparing the PreFab and PreModu processes, the first main question establishes the current state of Emergo's cost estimation procedures. Subsequently, the focus shifts to future prospects, outlining the necessary requirements and scenarios for streamlining and improving cost estimation processes. Specific BIM-based scenarios are then explored to enhance these workflows, with each scenarios workings, conditions, and values analysed. Conditions represent the prerequisites for successful scenario implementation, while values denote the direct and indirect benefits each scenario offers in the short and long term. Finally, based on the established scenarios, a roadmap is developed, outlining the sequential steps Emergo can take to refine their cost estimation processes for both PreFab and PreModu. Through evaluation and assessment, this roadmap guides Emergo towards optimised cost estimation practices.

1. **What are Emergo's current cost estimation processes and challenges for PreFab and PreModu?**
    (a) How do the current calculation processes for Emergo's PreModu and PreFab projects operate, including the sequence of activities, input sources, needs and desired output?
    (b) What are the primary challenges, bottlenecks, and areas of improvement within the calculation processes of both PreModu and Prefab projects?
    (c) What are the key differences and similarities between the calculation processes of PreModu and PreFab projects?
2. **What are the needs and treatment requirements of potential scenarios for both cost estimation processes?**
    (a) What are the anticipated requirements and expectations for the desired calculation processes of PreModu and PreFab projects?
    (b) How can the data generated within the calculation processes be effectively utilised in other phases of the project life-cycle, contributing to an overall improved efficiency and decision-making?
3. **Which BIM-based scenario's can be used and adapted to achieve desired requirements?**

(a) Which BIM uses can be be harnessed to address the challenges and improve the efficiency of the calculation processes within both Premodu and Prefab projects?

(b) What are the necessary conditions and challenges to facilitate BIM and which value come with the successful implementation of these solutions?

(c) To what extent do the proposed scenarios align with the identified design requirements and effectively mitigate challenges in cost estimation processes for both PreModu and PreFab projects?

4. **What are useful criteria for assessing the BIM scenarios and how are these translated to a roadmap for Emergo?**

   (a) How can the scenarios be assessed to evaluate the feasibility, benefits, and potential challenges of the derived scenarios in the context of PreModu and PreFab projects?

   (b) How can a strategic roadmap be designed to guide Emergo in the successful implementation of BIM solutions to enhance the efficiency and integration of the calculation processes for both PreModu and PreFab projects?

2.3 Research Strategy

Given the research questions, this study adopts a design research approach to seek innovative solutions through creative thinking and practical experimentation, aligning with the methodology outlined by Wieringa (2014). This approach is chosen for its efficacy in achieving tangible outcomes with the potential to drive positive changes across various domains. The primary objective is to enhance Emergo's operational efficiency by crafting BIM-based scenarios that strengthen the connection between design data and cost estimation processes. In addition to scenario design, a strategic roadmap is developed to evaluate and sequence the derived scenarios effectively.

The design cycle proposed by Wieringa (2014) serves as the framework for this design research, comprising problem investigation, treatment design, treatment implementation and treatment validation stages, as depicted in Figure 4. In this study, the treatments correspond to the roadmap and the integrated BIM-based scenarios tailored for Emergo's cost estimation processes. While scenario design falls within the scope of this study, implementation is deferred due to its extended timeline. Instead, a proof of concept is developed to simulate the implementation phase and validate the effectiveness of the proposed solutions.

A design approach is thus adopted within this study, following the design cycle of Wieringa (2014). In fact, the design cycle is applied twice in two separate phases of this research. Namely, once for the design of the BIM-based scenarios that enhance the efficiency of cost estimation processes (Phase 1), and once for the design of the roadmap (Phase 2). Figure 5 shows an overview of the organisational structure of this study

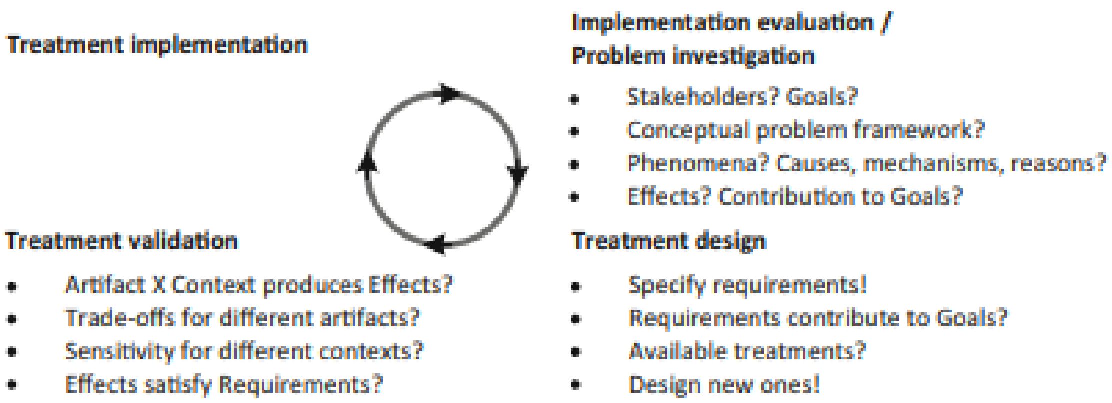


FIGURE 4: Design Cycle (Wieringa, 2014)

2.4 Research Approach

Figure 5 reveals the organisation of this study, where the research is divided into two phases. The scheme reveals the research strategies that are selected for answering each research question. Each phase is further divided into multiple stages, according to the phases of Wieringa (2014) (problem investigation, treatment design and treatment validation). In the following subsections, an elaboration per data collection method is provided.

2.4.1 Strategy for question 1

Question 1 delves into the **problem investigation** phase, offering an in-depth analysis of current processes and challenges faced by stakeholders. This investigation employs a multi-faceted approach utilising document analysis, observations, and interviews as primary data collection methods. These strategies collectively provide a comprehensive understanding of Emergo's cost estimation processes, offering insights from various angles.

Document Analysis

The documant analysis involves systematically reviewing relevant documentation, including flowcharts, process descriptions, project records, and historical documents. Additionally, specific attention is given to cost estimation documents and applications to discern the underlying structures of these processes.

Observations/ hands-on experience

in collaboration with with PreFab and PreModu cost estimators, prior projects of Emergo are recalculated step-by-step. This hands-on approach fosters an immersive understanding of Emergo's cost estimation practices. Researchers actively participate in the cost estimation departments, witnessing real-time operations. This method unveils practical challenges and bottlenecks as they occur during daily operations. Researchers can observe practices that may not be evident through documents alone, gaining insights into how decisions are made, data is collected, and calculations are performed, providing valuable insights where interventions are required.

Interviews

Scheduled interviews with key stakeholders, including the head of the PreFab cost estimation department and cost estimators for both PreFab and PreModu, provided invaluable insights. These interviews delved into the challenges and nuances encountered by individuals during cost estimation, covering topics such as daily activities, client coordination, and current threats to accuracy and efficiency.

Moreover, interviews were extended to stakeholders that interacted with cost estimation processes, including a development engineer for PreFab, a concept manager of PreModu and application managers. These interviews gained insights into broader process workflows and software utilisation. Through these engagements, a comprehensive understanding of Emergo's operational landscape was gained and any disparities between documented procedures and actual practices, enhancing the exploration of cost estimation dynamics.

2.4.2 Strategy question 2

The second main question sets up the requirements for the design of the scenarios, contributing to the **treatment design** phase. Later on, the derived requirements form a manner to validate the design. Therefore, this question also contributes to the **treatment validation** phase in an indirect manner. Interviews are utilised for identifying and understanding the stakeholder needs, which are converted to treatment requirements, according to the methodology of Wieringa (2014).

Interviews

Interviews were conducted with key stakeholders, including the head of the PreFab cost estimation department and cost estimators for both PreFab and PreModu, to gain firsthand insights into their perspectives and needs. Through open-ended discussions and targeted questions, stakeholders were encouraged to articulate their vision for the future of cost estimation processes. Areas for potential improvement were explored, alongside identifying which changes would have the greatest impact. Additionally, stakeholders from other departments, such as development engineers for PreFab, concept managers for PreModu, and application managers, provided valuable insights into how data generated during these processes could enhance project efficiency and decision-making. Overall, the interviews unveiled desired enhancements for PreFab and PreModu, as well as additional preferences for standardised procedures.

2.4.3 Strategy question 3(a) & (b)

The strategy for addressing questions 3(a) and (b) involves designing scenarios, which contributes to the **treatment design** phase. Designing scenarios is a creative endeavor, supported by literature analysis, expert interviews/workshops, and focus groups. Initially, potential scenarios are identified based on a literature review of relevant BIM uses. These scenarios are then refined and validated through consultations with a BIM expert and further development guided by literature, tutorials, and workshops. Subsequently, the scenarios are tested and refined in collaboration with stakeholders during focus groups. This combination of literature review and workshops enables researchers to design scenarios while considering the practical aspects and implications of BIM implementation within the unique context of Emergo's projects.

Literature/ Desk research

A thorough literature review serves as a foundational element in examining and understanding potential BIM uses, supplemented by insights from the *"BIM uses in modular construction"* paper. The search terms for the literature are shown in Appendix B. During the design phase, literature providds insights into global best practices, latest developments, and case studies related to specific BIM uses, utilised as input for the design of scenarios. Additionally, literature offers a comprehensive view of background conditions and potential side effects associated with implementing BIM solutions in cost estimation, aiding researchers in anticipating challenges and opportunities.

Expert interview/ workshops

Expert interviews and workshops played a crucial role in scenario design, with sessions arranged with a BIM expert to discuss and evaluate projected scenarios. On top of that, online tutorials and workshops are followed to gain skills in BIM software, such as Solibri, Revit and Dynamo. Input from BIM experts, along with online tutorials on BIM-based software, provides valuable guidance on how potential scenarios can be implemented in cost estimation processes for both PreModu and PreFab projects.

Focus groups

Finally, focus groups involving Emergo employees test and refine the designed scenarios, ensuring alignment with the context of cost estimations within the organisation. Adjustments are made based on the expertise of these employees, finalising the outline of the scenarios.

2.4.4 Strategy question 3(c)

Strategy question 3(c) focuses on validating the different scenarios, thereby falling under the **treatment validation phase**. The scenarios need validation to ensure they meet the expectations of stakeholders, which involves a combination of requirements checks as verification, and focus groups as validation to assess the scenarios from multiple perspectives.

Requirements check

The requirements check involves a systematic review and assessment of the design requirements against the designed scenarios. The stakeholders that were involved were asked if all treatment requirements were covered, enabling a direct comparison, identifying any gaps or deviations between the designed solutions and the specified requirements. Meeting the requirements verifies the scenarios, indicating that the scenarios are on track to effectively address challenges in cost estimation processes.

Focus groups

In focus groups, a qualitative approach is taken to validate scenarios through open discussions and conversations. These sessions involve practical demonstrations of the scenarios based on the designed proof of concept, allowing participants to observe their functionality. Participants are encouraged to share insights, concerns, and suggestions, enabling a thorough exploration of how effectively the scenarios address challenges in cost estimation processes. Additionally, identified conditions to facilitate the scenarios' functionality and the resulting values they offer were discussed. Thus, the scenarios are promptly evaluated during the sessions, allowing for the identification of additional conditions, risks, or challenges that need to be addressed.

2.4.5 Strategy question 4

Question 4 is conducted in phase 2 of the research, following a similar design approach but on a smaller scale. 4a involves **problem investigation**, examining frameworks of roadmaps and translating stakeholder needs into treatment requirements. Subsequently, question 4b encompasses the design and validation of the roadmap, finalizing the **treatment design** and **treatment validation** phases. The roadmap is designed and evaluated to ensure it satisfies the defined requirements.

Interviews

Initially, the key stakeholder, the business developer of Emergo, was interviewed to streamline the expectations of this research. This interview, conducted at the start of the research, aimed to discuss Emergo's desires. The roadmap was identified as the final treatment to be designed, combining the scenarios. Questions regarding the information to be incorporated in this roadmap helped define the treatment requirements.

Literature

A literature review was conducted to understand roadmapping, its value, and the key components that should be included in Emergo's strategic roadmap. This review ensured that the treatment design was informed by existing knowledge and best practices. The key components of the selected roadmap framework identified in the literature were captured as treatment requirements.

Focus groups

Initially, a roadmap template was designed based on the framework found in literature and the derived treatment requirements. Subsequently, the evaluated scenarios were assessed against the characteristics of the roadmap during focus groups that also validated the scenarios. Using the outputs of these focus groups, the scenarios were initially placed in the timeline of the designed roadmap template. In another meeting with the business developer, the initial design was collaboratively refined into a final design. During this session, the preferred order of scenarios and projected implementation dates were determined, validating the designed roadmaps.

Requirements check

Finally, the designed roadmaps were checked against the requirements by multiple stakeholders to verify their design for both PreModu and PreFab. Respondents were asked if the design of both roadmaps corresponded to the established treatment requirements.

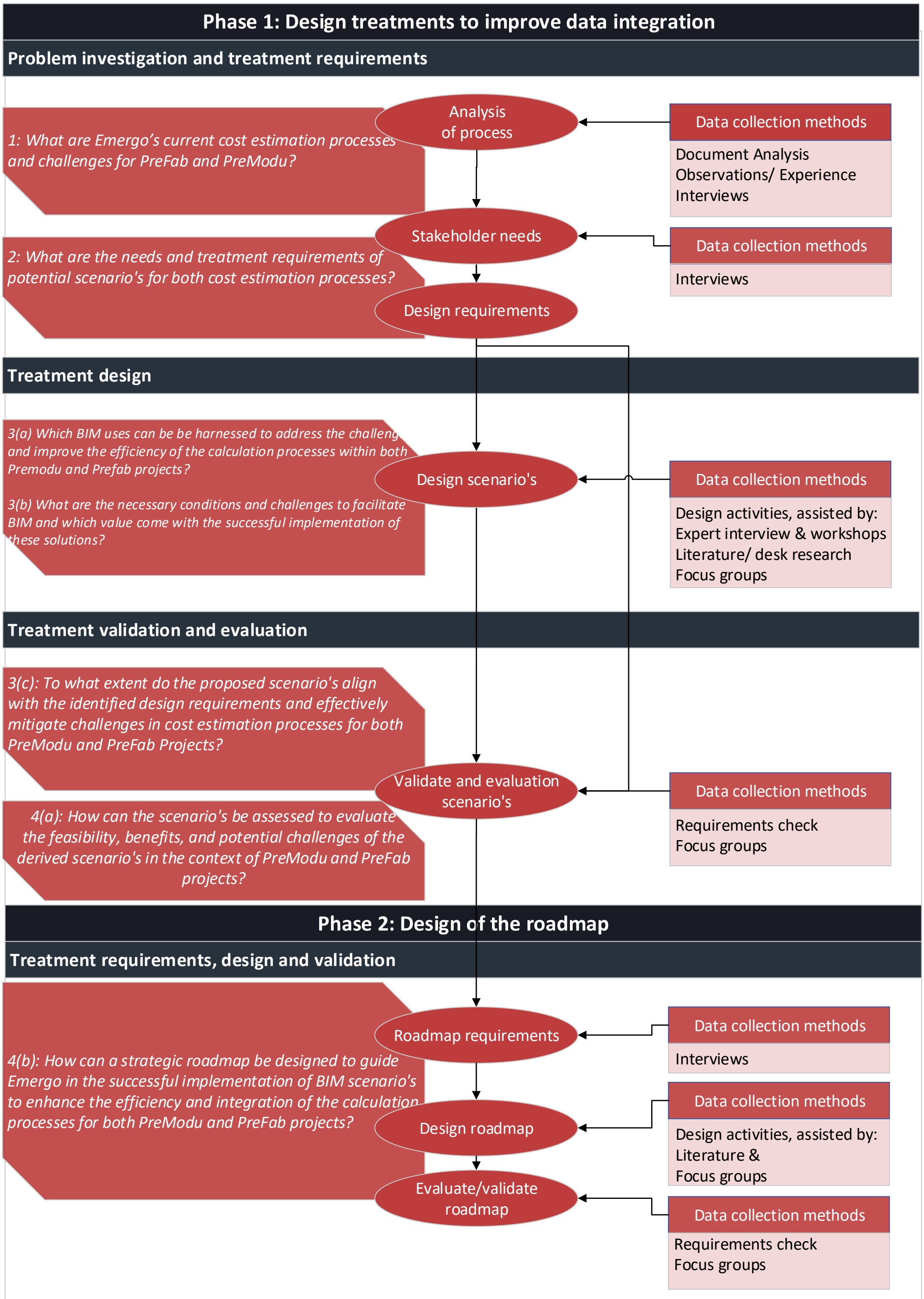


FIGURE 5: Flowchart of research approach

Chapter 3

Process Identification

Both Prefab and PreModu cost estimation processes have been examined in order to reveal highlight the current problems within both cost estimation processes. This chapter thus contributes to the problem investigation phase of the design cycle of Wieringa (2014). The following questions were answered in this chapter:

1. **What are Emergo's current cost estimation processes and challenges for PreFab and PreModu?**
    (a) How do the current calculation processes for Emergo's PreModu and PreFab projects operate, including the sequence of activities, input sources, needs and desired output?
    (b) What are the primary challenges, bottlenecks, and areas of improvement within the calculation processes of both PreModu and Prefab projects?
    (c) What are the key differences and similarities between the calculation processes of PreModu and PreFab projects?

The current calculation processes are examined through document analyses, interviews and practical observations. The cost estimation processes of PreFab and PreModu projects are are highlighted in a flowchart according to the Business Process Model and Notation (BPMN) [1]. Additionally, input data is listed according to the Unified Modeling Language (UML)[2], which is established by analysing the cost estimation processes.

Additionally, the observations and the interviews led to the current issues of the cost estimation processes. These were visible during the observations and later on confirmed and supplemented during the interviews. The issues are summarised in a table for PreFab and PreModu

Finally, the results of question 1a en 1b were considered input for the comparison, as similarities and difference became visible while examining both processes. These comparisons are supplemented and confirmed during interviews.

3.1 Process Description

Initially, the processes are examined in a general way, elaborating on the structure of both cost estimation processes. PreFab's cost estimation process is unraveled first while PreModu's cost estimation process is examined subsequently. Besides the textual description, a flowchart per process and tables that include necessary data entries are derived.

[1] Business Process Model and Notation
[2] Unified Modeling Language

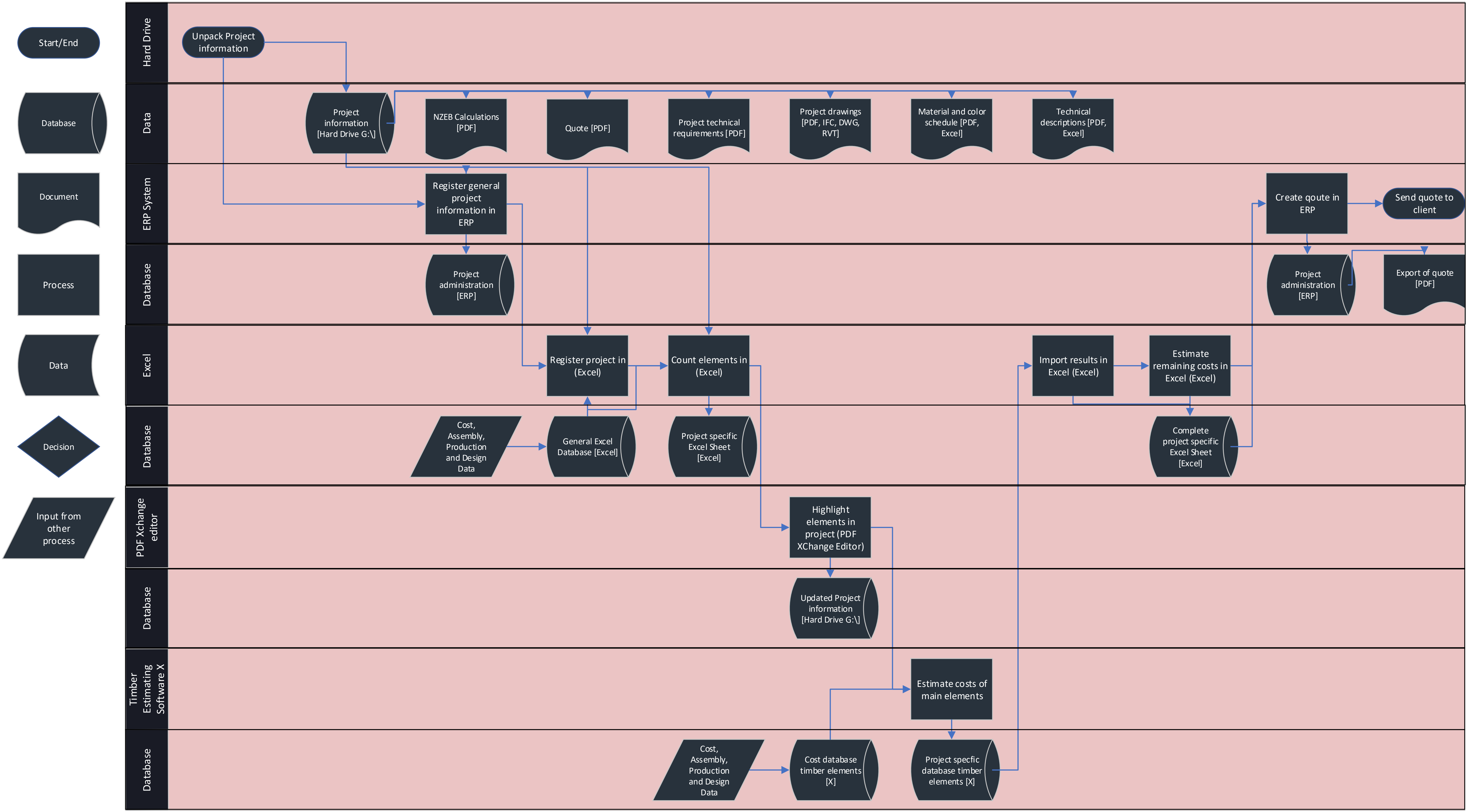
3.1.1 PreFab's cost estimation process

In the PreFab concept, Emergo delivers timber-framed components as a subcontractor, with the roof being the primary component. For cost estimation processes, the contractor seeks a price for the delivery and assembly of the roof and/or other timber-framed construction elements, which could lead to a contract.

Contractors request quotes from Emergo for timber-framed construction elements, often for multiple houses. Emergo's team initiates the cost estimation process to provide an indicative price to the contractor. PreFab projects vary, ranging from one-time clients to established network clients. Additionally, in the PreFab context, Emergo's suppliers are considered network partners, providing specific components not available in-house, such as windows. Despite employing standard materials, partners, and procedures, the unique design of each project results in distinct, specially engineered PreFab components. As a result, Emergo's core process, the PreFab branch, maintains an Engineer-to-Order (ETO) character. However, some standardisation is achieved through limited material variations and streamlined production routines, enhancing efficiency within Emergo's factory. Furthermore, the company is committed to minimising its supplier base, for example, having selected three potential window suppliers, with one being the preferred choice. In conclusion, Emergo uses standardised solutions for PreFab projects but still relies on an ETO character.

In the upcoming subsections, each phase of the PreFab process is elaborated upon, collectively forming the comprehensive PreFab cost estimation process. Per phase, required data entries are listed, gathered and established on behalf of this research. A simplified flowchart of the cost estimation process for PreFab is presented in Figure 6. For a more detailed version of this flowchart, including a breakdown of work tasks and data entries per phase, please refer to Appendix A.

FIGURE 6: Overview of PreFab Process



PreFab Phase 1: Administration

The process begins with the receipt of a quote request, typically containing a ZIP file containing project drawings, ranging from 2D PDF files to IFC and 3D Revit files. Additionally, the ZIP file includes design specifications presented in tabular form, detailing preferred materials, colors, and technical requirements. Moreover, PDF documents provide final project details such as Near Zero Emission Building (NZEB) calculations and quote details. The completeness and quality of these documents vary depending on the client.

Upon receiving a quote request, a new project is generated in Emergo's Enterprise Resource Planning (ERP) system, referred to as the ERP system in this research for privacy reasons. The initial project information is provided by the assigned cost estimator. As the project is initiated in the ERP system, a corresponding project folder is automatically created on Emergo's hard drive for storing project documents.

PreFab Phase 2: Counting & measuring, highlighting and initial constructability calculations

Emergo has developed an Excel checklist model to streamline the work of cost estimators in this phase. Beginning with the receipt of project drawings in various formats within a ZIP file, such as 2D PDF files, IFC data, or 3D Revit files, the process proceeds with entering general project details into the Excel file. The cost estimator then quantifies project elements and objects by counting and creating an inventory, detailing specifications such as roof tiles, knee walls, and interior roof coverage plates. This meticulous process extends to various elements like walls, floors, solar panels, dormers, and roof cladding, ensuring accurate assessment based on project specifics. The necessary data for quantification and specification are examined and established in Table 3.1. This data is implemented in the Excel model or utilised by the cost estimator for this phase of the cost estimation process

General Information	**Data type**	Frame width [mm]	*<integer>*
Blocks in project	*<integer>*	Frame height [mm]	*<integer>*
Houses in block	*<integer>*	Assembly included?	*<boolean>*
Roof Information	**Data type**	**Floor Information**	***Data type***
Qv10-value in roof [(dm3/s)/m2]	*<float>*	Beam distance [mm]	*<integer>*
Rc-value in roof [(m2 K)/W]	*<float>*	Span distance [cm]	*<integer>*
Roof tiles	*List of 3x <string>*	Beam strength	*<string>*
Roof decking plates	*List of 3x <string>*	**Solar Panels Information**	***Data type***
Optional roof decking plates	*List of 3x <string>*	Max power per panel [WP]	*<integer>*
Rafter heights [mm]	*<integer>*	Number of solar panels	*<integer>*
Roof curb present?	*<boolean>*	**Roof Window(s) Information**	***Data type***
Gutter brackets present?	*<boolean>*	Window width [mm]	*<integer>*
Knee walls present?	*<boolean>*	Window length [mm]	*<integer>*
Wall Information	**Data type**	Window height [mm]	*<integer>*
Qv10-value in roof [(dm3/s)/m2]	*<float>*	Roof slope [degree]	*<float>*
Rc-value in roof [(m2 K)/W]	*<float>*	U-value glass [W/(m2K)]	*<float>*
Sound resistance wall [dB]	*<float>*	Window count in block	*<integer>*
Fire resistance wall	*<float>*	**Roof Dormer(s) Information**	***Data type***
Wall width [mm]	*<integer>*	Roof trim	*<string>*
Wall decking plates inside	*<string>*	Roof outside cladding	*<string>*
Wall decking plates back	*<string>*	Frame opening material	*<string>*
Frame opening(s) Information	**Data type**	Dormer decking plates	*<string>*
Frame type	*<string>*	**Roof Cladding Information**	***Data type***
Frame count per block	*<integer>*	Cladding material/type	*<string>*
Frame material	*List of 2x <string>*	Cladding count [m]	*<float>*
Frame location	*List of 3x <string>*		

TABLE 3.1: Derived overview of necessary data addressing initial frequency and dimensions, implemented in Excel

Subsequently, the cost estimator highlights these objects on technical project drawings. This step is essential for preventing misunderstandings by demarcating project boundaries through the use of color-coded annotations on the technical drawings in PDF files. In cases where specific details are lacking, standard Emergo details are incorporated into the project documents. The cost estimator uses the data from Table 3.1 as well as the experience a cost estimator has to know which products Emergo offers.

Moreover, the cost estimator subdivides each house into individual timber-framed elements with provisional IDs based on predetermined size rules and logical reasoning. This segmentation ensures the final products are transportable and assemblable, enhancing process efficiency. Similar elements are grouped with similar names, to enhance the efficiency by specifying the frequency of an element. The division process generates project-specific data crucial for accurate cost estimation. Per element, the produced data is shown in Table 3.2, where this data is later used to estimate the costs of these elements. This data is thus produced by the cost estimator by manual measurements, and implemented in the Excel model.

Element Information	**Data type**	Element Width [mm]	*<integer>*
Element ID	*<string>*	Element Length [mm]	*<integer>*
Element Type	*List of 3x <string>*	Element Slope [degrees]	*<float>*
Element Height [mm]	*<integer>*	Element Count	*<integer>*

TABLE 3.2: Derived overview of produced data for a division of timber-framed elements, implemented in Excel

Lastly, the cost estimator utilises an online calculation tool[3] for construction bracket and material determination, simplifying calculations based on roof dimensions and ensuring compliance with deflection limits. Information in Table 3.3 is gathered by the cost estimator and input for the cal-

[3] CIBIS Roof calculations

culation tool, resulting in the the determination of the allowed deflection, roof trusses type, roof trusses distance and bearing capabilities of knee walls. The results are included in the Excel model

Furthermore, specific elements requiring structural engineer attention are identified and counted, with associated engineering costs considered in the estimation process. These specifc elements are shown in the right column of Table 3.3, under construction elements. These elements are counted and this exact data is noted in the Excel model

Construction Information	Data type	Construction Elements	Data type
Roof Ridge Length [mm]	*<integer>*	Rafter Roof Count	*<integer>*
Roof Angle [degrees]	*<float>*	Purlin Roof Count	*<integer>*
Distance (Knee Wall & Roof Ridge) [mm]	*<integer>*	Dormer Count	*<integer>*
Distance (Knee Wall & Roof Trusses) [mm]	*<integer>*	Hip Rafter Count	*<integer>*
		Glulam Beam Count	*<integer>*
		Walls Count (per height)	*<integer>*
		Floor Count (per level)	*<integer>*

TABLE 3.3: Derived overview of input data for the initial construction calculations and frequency of construction elements

PreFab Phase 3: Estimating costs of timber-framed construction elements

In the third phase of PreFab, Emergo estimates the costs of its primary timber-framed construction elements using an external calculation tool developed within Microsoft Access, referred to as Timber Estimating Software X. This software primarily focuses on estimating roof components and knee walls, with less frequent use for walls and floors. The process begins with the cost estimator manually inputting the base dimensions of the elements, and selection of predefined timber-framed material bundles.

Customisation of materials bundles is often necessary to meet project-specific requirements, such as modifying roof bracket types and quantities. Emergo applies surcharges for rare or complex elements to account for additional complexity. Project-related costs, including transportation and engineering expenses, are also factored into the estimations per element. The resulting costs are automatically calculated through a price database within Timber Estimating Software X, and the data can be exported via a .CSV file, providing a detailed breakdown of costs per item. This .CSV file is then imported into the ERP System, effectively concluding the process within Timber Estimating Software X

Several datasets are utilised during this sub-process. Data from the division of elements (refer to Table 3.2) is used, alongside the corresponding predefined composition of the element, which must be selected manually. This composition is adjusted as needed for project-specific requirements. Additionally, input data for selecting the proper composition for a specific element is specified in Table 3.1. These compositions may require manual adjustments per element type, such as incorporating special construction elements from Table 3.3 into fixed material compositions, resulting in additional construction costs.

The data listed in Table 3.4 is manually implemented within Timber Estimation Software X by the cost estimator. While some data entries are duplicated from prior tables, the need for manual implementation necessitates their repetition. Additionally, new data entries, such as estimating the type and number of trucks necessary, are introduced in this phase.

Base Information per element	**Data type**	C.O.C. Size Roof Trusses [mm]	*<integer>*
Element ID	*<string>*	C.O.C. Size Roof Tile Battens [mm]	*<integer>*
Element Count in Block	*<integer>*	C.O.C. Size Roof Lath Battens [mm]	*<integer>*
Element Width [mm]	*<integer>*	Add/Adapt any Additional Article	*<list>*
Element Heigh [mm]	*<integer>*	Add/Adapt Any Additional Task	*<list>*
Element Compostion	*<list>*	**Additional Cost Information**	***Data type***
Discount Assembly [%]	*<integer>*	Construction/ Engineering Costs [Euro]	*<integer>*
Discount Machine Hours [%]	*<integer>*	Distance to Project [km]	*<integer>*
Element Area Oblique Elements [%]	*<integer>*	Type of Truck	*List of 2x <string>*
Additional Information Per Element	***Data type***	Number of Trucks required	*<integer>*

TABLE 3.4: Derived overview of necessary data that is manually implemented in Timber Estimation Software X

PreFab Phase 4: Estimating remaining and/or additional costs

After completing the calculations in Timber Estimation Software X, the cost estimator returns to the Excel model to estimate the costs of any remaining or additional elements that couldn't be calculated within this software. These elements typically include windows, dormers, framings, and other additional items. The Excel model is equipped with built-in formulas to facilitate this estimation process, operating in a semi-automatic mode. While the Excel model handles most calculations automatically, some dimensions or values must be manually input by the cost estimator. Additionally, certain estimations rely heavily on the estimator's knowledge and experience, particularly when assessing special products, assembly hours, and transportation requirements.

Although the structure of this phase mirrors the initial Excel phase, focusing on elements such as roof windows, dormers, assembly operations, and roof cladding, it delves deeper into the specifications and details of each element. The dataset necessary for this phase is specified in Table 3.5, which provides more detailed information compared to the data in Table 3.1. For instance, it includes specifications for dormer materials and skirting boards, which are relatively minor cost items but require precise estimation. This phase demands a higher level of expertise from the cost estimator due to the intricacies involved in estimating these detailed costs.

Roof Window Selection Information	**Data type**	Roof Anchors in Roof	*<integer>*
Window Brand	*List of 3x <string>*	Glulam Beam in Block	*<integer>*
Window Brand Type	*<list>*	Stairwell in Knee Walls	*<integer>*
Window Frame Opening Type	*List of 3x <string>*	**Cladding Information**	***Data type***
Window Additional Costs	*<float>*	Cladding Material	*List of 4x <string>*
Dormer Selection Information	***Data type***	Cladding Thickness [mm]	*<integer>*
Dormer Width [mm]	*<integer>*	Cladding Length [mm]	*<integer>*
Dormer Height [mm]	*<integer>*	Cladding Width [mm]	*<integer>*
Dormer Depth [mm]	*<integer>*	**Skirting Boards Information**	***Data type***
Material Dormer Roof	*<list>*	Standard Houses in Block	*<integer>*
Material Dormer Cheeks	*<list>*	Cross Gable Roof in Block	*<integer>*
Material Dormer Cheeks	*<integer>*	Perpendicular End Unit in Block	*<integer>*
Assembly Information	***Data type***	**Glulam Beam Information**	***Data type***
Number of Houses in Block	*<integer>*	Building Wall Type	*List of 2x <string>*
Height of Roof [mm]	*<integer>*	Glulam Beam Count in Block	*<integer>*
Number of Trucks required	*<integer>*	Length of Glulam Beam [mm]	*<integer>*
Floor Levels per Element	*<integer>*	**Solar Panels Information**	***Data type***
Type of Roof	*<list>*	Solar Panel Row Count in Solar Panel Field	*<integer>*
Valley Rafter Included	*<boolean>*	Solar Panel Row Count in Solar Panel Field	*<integer>*
Hip Rafter Included	*<boolean>*	House Count in Block	*<integer>*
Roof Gutters Length [m]	*<float>*	Window Count in House	*<integer>*
Elements in House	*<integer>*	Less Panel Count in Solar Panel Field	*<integer>*

TABLE 3.5: Derived overview of necessary data to conduct the calculations in Excel, relying on previous collected data and experience of the cost estimator

PreFab Phase 5: Quote composition

In PreFab Phase 5, the quote composition occurs within the ERP system, continuing the semi-automatic process. Costs from Excel are manually inputted into the ERP system, while costs calculated in Timber Estimation Software X can be imported through a .CSV file. Initially, an automated draft quote is generated based on predefined rules. The employee's role involves reviewing, modifying, and finalising the quote by confirming the presence or absence of project elements. This meticulous process ensures that the quote accurately identifies the products Emergo can supply, establishing crucial terms for the contractual relationship with the contractor. Once the annotated PDFs and quote are sent to the contractor, the cost estimation process concludes.

Following quote approval, the cost estimator may further engage in negotiating project options with the client. Although recalculations might be necessary, the project then transitions to the account manager, buying department, and engineer for further action.

3.1.2 PreModu's cost estimation process

In PreModu projects, Emergo collaborates with a diverse range of clients, including investors, house-building corporations, and contractors, who typically seek a (sub)contractor for residential construction in new developments. While many projects involve assembling multiple houses with similarities, variations can arise due to different house types and design options. Initial meetings are conducted to assess the feasibility of integrating PreModu into a project. If there is mutual interest, the cost estimation process begins to provide an indicative price. Clients can select from predetermined options and solutions offered within PreModu, but Emergo also allows for limited unique solutions to accommodate client preferences. Nonetheless, the majority of the design is standardised and predefined, with Emergo estimating their standardisation level to be 85%

Emergo is currently expanding the standardised components, moving towards MTO or even ATO strategies. However, the remaining 15%, which includes unique client adjustments, still relies on an ETO strategy. Therefore, cost estimations may include uncertainties due to the inclusion of unique or varying components that have not been previously calculated. Achieving 100% standardisation could lead to more accurate cost estimations.

During the cost estimation process, a preliminary BIM model is created by an internal or external architect using standardised design specifications and PreModu concepts. Once an agreement is reached on the estimated price, the design is further developed and refined to determine detailed design options, technical solutions, and specifications, leading to the establishment of a technical design and production plan. As the project progresses, actual costs become clearer, often deviating from the initial estimate. Thus, the current cost estimation process primarily aims to provide clients with a cost indication, recognising the iterative nature of design and decision-making in PreModu projects. The process leading to the estimated costs is illustrated in Figure 7, whereafter the client can decide to continue or terminate the project. Further details are elaborated in subsequent sections.

PreModu Phase 1: Project start-up

The project initiation phase commences with one or more meetings aimed at assessing the feasibility of integrating PreModu into a specific project. These discussions cover essential aspects like house types, the quantity of houses, and project locations. Emergo indicates a rough price for houses from their catalog during these discussions. If both parties acknowledge the potential of utilising PreModu for the project, Emergo proceeds to develop a more detailed pricing structure.

To systematically manage the project and monitor its progress, a dedicated project folder is established within Emergo's ERP system. This folder contains essential project information, including client details and project location. Additionally, a corresponding folder is created on the hard drive to store comprehensive project documents, such as drawings.

PreModu Phase 2: Preliminary design

After reaching an agreement on the rough cost estimation, Emergo directs either an internal or external architect to create the preliminary design. This design plays a pivotal role in the subsequent cost estimation process as it combines the selection of house types and options, providing a tangible representation of the project. Leveraging standardised objects and predefined house designs, which potentially are already incorporated in Revit Families. Thus, the architect has a solid foundation to develop the preliminary BIM model and the design process builds upon existing modular house types rather than starting from scratch. Yet, not all the components of PreModu are included in Revit families already, necessitating additional modeling tasks. Emergo oversees this coordination, particularly when the design is outsourced.

The preliminary design encompasses essential elements needed to convey the initial concept and feasibility of the project. Serving as a foundational point for discussions and decisions, this design allows for flexibility in revisions based on client feedback and the need for further detailed planning.

PreModu Phase 3: Cost estimation process in Excel

The cornerstone of cost estimation in PreModu is an Excel model, serving dual purposes. Firstly, it acts as a platform for both automated and manual calculations, entailing predefined cost estimation formulas. While the Excel model automatically processes project options into standardises costs, the cost estimator also manually calculates unique components that are not covered by component and costs libraries. Secondly, Excel functions as a central database for maintaining estimations from various sources. It combines costs that are partly imported from Timber Estimating Software X or the ERP software. Timber-framed construction elements are calculated and updated in Timber Estimating Software X per house type, and then copied within the the Excel sheet. The ERP system includes exact material and labour cost items, such as the costs to deliver and assemble a frame opening. Due to the wide range of objects within PreModu, the cost items are significant, which are manually updated every quarter.

The process begins with indicating the frequency of each house type, including the characteristic if the house is between other houses or at the corner of the block. Then, the cost estimator fills in standardised components, which are incorporated in a list of Excel, such as dormer type, bathroom type and facade finishing type. Standardised Excel formulas automate fundamental calculations on the background for these universal, project-independent modules. For example, formula's for bathroom types include a list of cost items corresponding to the bathroom and house type. Updates involve refreshing article prices and verifying formulas, conducted every quarter or when new house types are introduced. Thus, the cost estimator initially focuses on specifying all the standardised elements, with the model generating estimations for total costs of standard elements

Subsequently, the cost estimator focuses on project-dependent elements, which may vary across projects. These components are determined to be varying with a reason, namely, they impact the aesthetics of a house and project, including a level of flexibility in the design. Examples are the roof tiles, facade finishing materials and framing materials. In Excel, these options are predefined but rely on manual input from the cost estimator, where the material and quantity has to be specified per house type. The quantity is manually measured from drawings while material types are limited and standardised. After the material and quantity is specified, the model automatically estimates the costs of the project-dependent options. Similar to the previous step, the formulas are predefined, and articles are updated quarterly.

Finally, the cost estimator needs to include costs that are unique and not defined within the Excel model. These estimations are entirely manual due to the uniqueness of the product or the fact that it hasn't been predefined before. These costs are primarily determined by special client requests or elements included for engineering purposes. The cost estimator assesses these costs manually, drawing from their experience. Examples of such costs include the delivery of a loft ladder, roof attachments, and floor/roof recesses, which are belonging to the unique costs that are not typically reused between projects. Moreover, the cost estimator has the freedom to adapt certain cost items if these are prospected to differ in the project. For example, if a project is large of size, the cost estimator can increase architectural costs for the design of the project, which obviously cost more time due to the fact that it is a large project.

Emergo indicates that 85% of PreModu consists of standardised components, with the remaining 15% being project-specific. The cost estimation process primarily focuses on selecting options from predefined lists and then, estimating project-specific elements. An overview of the necessary data to estimate to costs per PreModu project is derived ans shown in Table 3.6, distinguishing between standardised and project-specific information. Standard elements are calculated based on predefined parameters, while project-specific details require manual adjustments and measurements or include the additional 'special' costs, used for the unique components that are included based on the preferences of clients and/or buyers.

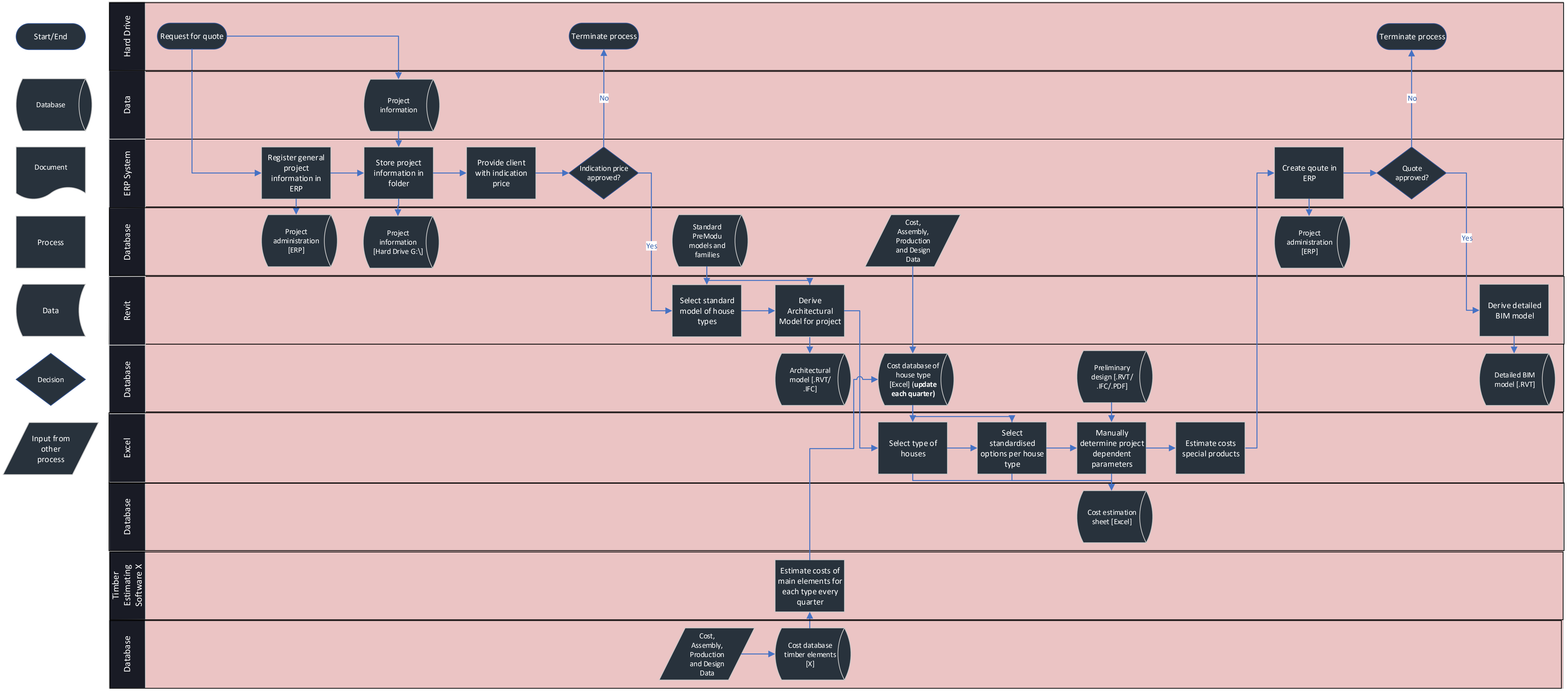
Standardised Information	**Data type**
Corner or inbetween house	*List: 2x <string>*
Option of base configuration	*List: 15x <string>*
Option of front facade	*List: 4x <string>*
Option of back facade	*List: 2x <string>*
Option of head facade (IF corner house)	*List: 4x <string>*
Option of facade finishing	*List: 4x <string>*
Option of roof finishing	*List: 2x <string>*
Option of heating installation type	*List: 3x <string>*
Option of solar panel type	*List: 2x <string>*
Option of solar panel field size	*List: 26x <string>*
Option of kitchen implementation type	*List: 4x <string>*
Option of floor finishing	*List: 3x <string>*
Option of wall finishing	*List: 3x <string>*
Option of sanitary facilities	*List: 3x <string>*
Option of roof window type	*List: 9x <string>*
Number of roof windows	*<integer>*
Number of sun blinds	*<integer>*
Number of ventilation units	*<integer>*
Option of dormer types	*List: 3x <string>*
Number of dormer types	*<integer>*
Option of canopy types	*List: 3x <string>*
Number of canopies	*<integer>*
Option of gutter types	*List: 3x <string>*
Option of sewage type	*List: 3x <string>*
Project-Specific Information	**Data type**
Material of Roofing Tiles in House	*<string>*
Quantity of Roofing Tiles per Material	*<float>*
Material of Facade Finishing/Cladding in House	*<string>*
Quantity of Facade Finishing/Cladding per Material	*<float>*
Material of Framing Area in House	*<string>*
Quantity of Framing Area per Material	*<float>*
Unique Information	**Data type**
Unique costs for unique components	*<float>*

TABLE 3.6: Derived overview of necessary data per PreModu cost estimation process, distinguishing standardised, project-specific and unique costs.

PreModu Phase 4: Development order

Within the Excel model, a comprehensive overview of all costs, including total project expenses and optional prices for additional elements, is compiled. Subsequently, a project development order is generated in the ERP system. This order is then forwarded to the client for discussion and approval. The client's approval of the development order represents a critical decision point. If the client rejects it, the project is terminated. However, if approved, the project advances according to the initial schedule, and a development agreement is formalised. It's important to note that the nature of these development agreements is indicative, and the price remains flexible, subject to adjustments in subsequent project stages. Additionally, certain matters, such as optional prices and the delineation of responsibilities, require further discussion and clarification during this phase

FIGURE 7: Overview of PreModu Process



3.2 Process Analysis

In this section, both cost estimation processes are analysed and evaluated, building on the previously process description. A comparative examination sheds light on the key distinctions between the two routines, providing insight into their respective strengths and weaknesses. Furthermore, interviews were conducted to glean perspectives on the comparison between these processes, enriching our understanding of their intricacies

By revealing the characteristics of each cost estimation process, their unique features and operational nuances are exposed. These insights are instrumental in identifying current challenges and areas for improvement. Interview feedback underscores specific issues inherent to each process, offering valuable perspectives on potential enhancements.

Finally, determined issues are placed within the existing structure of each flowchart, highlighting the improvement area's per process.

3.2.1 Comparison between both processes

In Emergo's construction landscape, PreFab projects represent a cornerstone of revenue generation, characterised by established routines and consistent performance. Conversely, PreModu, while still in its developmental phase, carries significant potential according to Emergo's vision. Despite its current status as a work in progress, Emergo anticipates a future where PreModu could potentially outperform PreFab in revenue and demand.

While both PreFab and PreModu projects share the overarching goal of delivering residential constructions, their cost estimation processes exhibit distinct approaches. The following comparative analysis dissects key aspects, shedding light on both similarities and differences observed during the process description phase and interviews. By examining these aspects, insights into the strengths, challenges, and areas for improvement per process is pursued.

Firstly, Table 3.7 highlights aspects that are handled similarly across both processes, providing a foundation for further exploration. Subsequently, Table 3.8 delves into the specific differences observed between the two processes, offering deeper insights into their respective methodologies and workflows.

Overlapping activities

Both PreFab and PreModu cost estimation processes exhibit significant similarities in their overall execution, utilising comparable software, tools, and methodologies. Automation is central to both processes, streamlining workflows by enabling cost estimators to input selections or dimensions, with subsequent calculations automated by Excel or Timber Estimation Software X. These models share foundational structures, relying on similar formulas for computations. Manual interventions are necessary for handling project exceptions, albeit to varying extents.

Furthermore, both PreFab and PreModu rely on the same price databases. The ERP system forms the basis for the Excel-based database composition, while Timber Estimation Software X is utilised for estimating timber elements. Consequently, the estimation of timber-framed construction elements follows a similar methodology in both processes, albeit with different calculation frequencies: quarterly for standardised PreModu concepts and project-based for PreFab. Notably, resulting prices in both processes remain provisional, subject to adjustments after clients finalise decisions or technical designs reach completion.

As a result, both PreFab and PreModu cost estimation processes provide indicative values, laying a solid foundation for subsequent project phases such as planning, budgeting, and engineering. Rather than recalculating every component, adjustments to cost calculations occur in later stages, reflecting a pragmatic and iterative approach. This shared characteristic underscores the flexibility and adaptability of both processes, enabling responsiveness to evolving project dynamics.

Similar aspects	Explanation
Systems used	*Both processes utilises similar ERP systems and calculations models (Excel and Timber Estimation Software X)*
Process phases	*Similar approach to projects: Administration, cost estimations and then quote composition*
Project Variations/ Manual efforts	*List of options/articles for design variations in combination of manual estimations for special exceptions.*
Data sources	*For the standard components, PreFab and PreModu use similar databases like article prices, labor hours and project information*
Implementation of timber-framed construction elements	*Both processes include the implementation of timber-framed construction elements, where costs are similarly estimated, via Timber Estimation Software X. In fact, employees mention that PreFab is a part of PreModu, but then with standardised timber-framed components.*
Price derivation	*Similar formulas and dimensions used (article price, quantities, labor cost, etc.)*
End of process (result)	*Indicative price + optional prices, where the final price still can change after decisions have been made*
Automated process	*Besides unique cost calculations, the formulas are predefined, resulting in (semi-) automatic cost estimations that converts the input of the cost estimator into estimated costs*
Quality Control Measures	*Model in Excel is error-prone as errors are hard to detect and the model can be changed by anyone. Manual steps are considered as checks of the cost estimation process. Measuring quantities is human activity and hence, error-prone*
Effect on other processes	*Cost estimation process is the beginning of entire workflow, providing a solid base for other activites.*

TABLE 3.7: Similar aspects in PreFab and PreModu processes

Differences between both processes

Although both PreFab and PreModu cost estimation models share similarities in construction and utilize identical systems and price databases, differences emerge in broader organizational and project workflows. As detailed Table 3.7, the fundamental structures of the cost estimation processes overlap, relying on comparable models, tools, and price databases. However, the distinctive nature of typical PreFab and PreModu projects introduces variations that set these processes apart.

This disparity is explicitly highlighted in Figure 8, derived to showcase the profound difference in the conceptual visions of both approaches. In PreModu projects, design intricately ties to standardised components and object libraries, despite ongoing library development. Conversely, PreFab components are engineered for unique designs, offering flexibility despite standard material usage. PreModu components maintain standardised dimensions, while PreFab components vary in size to match design needs. This difference serves as the cornerstone distinguishing the two processes, giving rise to dissimilar aspects detailed in Table 3.8. Different aspects are listed with a score for PreFab or PreModu that reveals the applicability of the aspect, argued in the last column. Scores vary from - - until ++, ranging from not relatable to matching, respectively.

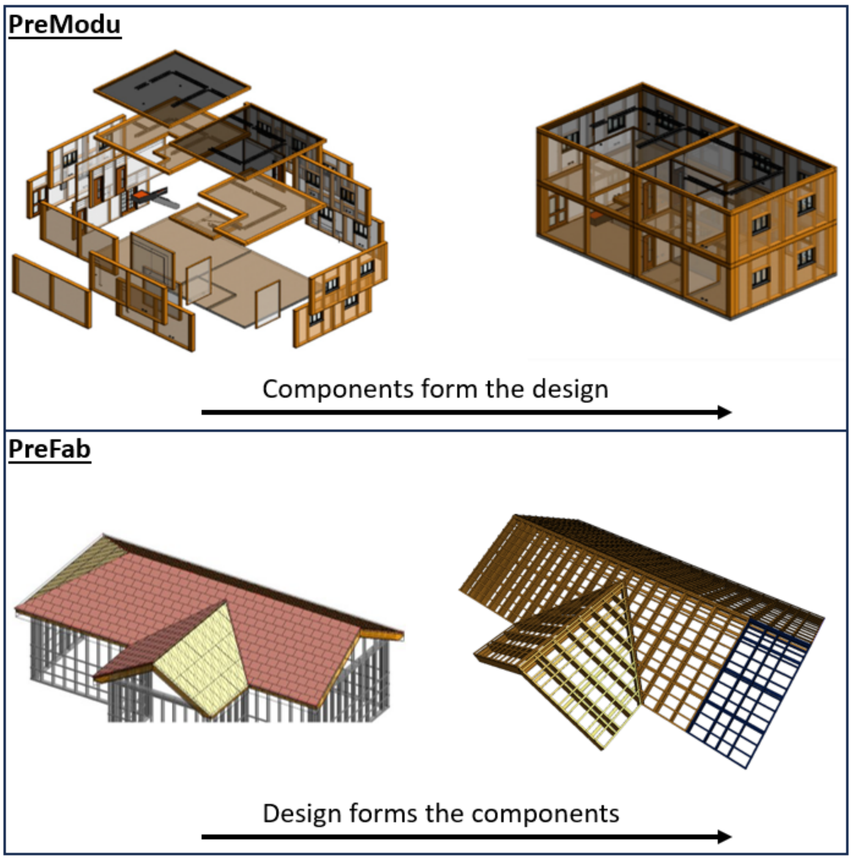


FIGURE 8: Difference in organisation between both concepts

One evident difference arising from distinct design philosophies shown in Figure 8, is the management of design components. PreFab adapts standard materials based on design specifications, while PreModu relies on a greater number of standardised components and modules. This variance is reflected in the initiation phase. PreModu begins with a feasibility check, with clients choosing preferences from fixed options, whereas PreFab starts directly with a quote request, adapting components based on client needs.

The accuracy of PreFab cost estimations is higher due to the limited number of components used, each precisely counted rather than estimated. This approach results in exact cost estimations by connecting a list of component types and their frequencies directly to prices. The range of products used within PreFAb is considered low, where PreFab projects mainly focus on roof-related components. Standardised material compositions are adaptable to match unique designs, necessitating specific engineering for each project and making the process more time-consuming

In contrast, certain components of PreModu are estimated quarterly, with fixed dimensions or modules. While the selection of design options relies on standard choices, the object library is not yet complete, leaving around 15% of components variable or project-dependent. Consequently, the costs for these components are estimated rather than fixed, reducing estimation accuracy. For instance, concrete floors may come in multiple variations, resisting standardisation and leading to estimated prices. Additionally, PreModu encompasses a wide range of products, from bathroom modules to roof components to Mechanical, Electrical, and Plumbing (MEP) installations, increasing reliance on suppliers and resulting in price variations and uncertainties. Currently, Emergo is refining its estimations and working toward establishing a standardised object and more accurate cost library, aligning with its vision to transition to ATO/MTO.

Different aspects	PreFab	PreModu	Explanation
Client interaction:	-	++	*Prefab client interactions are used only to streamline uncertainties while PreModu client interactions are necessary to decide the project feasibility and design options*
Standardisation efforts in the design:	-/+	++	*Prefab relies on adapting standard articles to unique designs while PreModu persuade a combination of standardised components to realise project-specific solutions*
Project Management efforts:	- -	+	*PreModu compares cost estimation and cost realisation for their learning curve and cost estimation capabilities while PreFab is already well-established and quite accurate.*
Reliance on ETO:	++	-/+	*PreFab relies on ETO while PreModu shifts towards ATO/MTO*
Design Influence:	-	++	*PreModu cost estimation process are derived after and during the conduction of the preliminary design on behalf of Emergo while PreFab cost estimations are conducted after the design has been established on behalf of the client. Only technical specifications can be adapted due to Emergo's expertise*
Acceptance of requests:	++	- -	*PreFab starts with direct quote request while PreModu starts with a feasibility check to implement PreModu*
Accuracy:	++	-/+	*PreFab is detailed and accurate in terms of counting products and entails a complete cost overview of the material/components that are used. PreModu relies more on prices of suppliers and face incomplete cost libraries. Currently, PreModu is considered less accurate but Emergo is aiming to obtain standardisation within costs in the future, through completion of cost libraries*
Process lead time:	-	+	*PreModu is faster due to repetitive calculations where only the modifications need to be calculated. PreFab cost estimations are unique and not project exceeding*
Usage of BIM during calculations:	- -	-	*Technical drawings for PreFab projects are created by Emergo after the work is accepted, and preliminary BIM models from the clients are unused during cost estimation. For PreModu, BIM models are conducted on behalf of Emergo but only used in a limited manner*
Adaptability of Design:	++	-	*Changes does not affect PreFab projects as much as it effects PreModu workflows, therefore PreModu design changes is considered almost zero*
Project-specific calculations:	++	-	*This aspect is dissimilar since each component has to be recalculated for each PreFab project while most PreModu components are calculated on quarterly base*
Required Data:	++	-/+	*Compared to PreModu, PreFab cost estimation processes requires more data to estimate the costs of projects. This can be seen if one reviews Table 3.1-Table 3.6*
Risk Management:	-/+	+	*Risks at PreModu are currently greater due to a less accurate process. Both processes include a risk percentage on some prices, yet PreModu is more uncertain.*

TABLE 3.8: Deviant aspects in the current PreFab and PreModu processes

3.2.2 Process evaluations

Upon a comprehensive description and comparison of both processes, a nuanced understanding of their characteristics emerges, resulting in the ability to evaluate both processes. Figure 9 summarises the key strong and weak points for PreFab while Figure 10 provides the findings for PreModu. Each figure will be further elaborated in the upcoming section. The results are thus derived based on the process identifications, comparisons and interviews and are validated during a group session.

Evaluation of PreFab's cost estimation process

The strength of PreFab's current cost estimation process lies in its well-established nature. Emergo has been handling these projects for a considerable period, making it a core aspect of their business. Given Emergo's extensive knowledge as a subcontractor for delivering timber-framed construction elements, the cost estimation process has become routine work. This expertise ensures that cost estimators are well-equipped to address challenges and find solutions during cost derivation.

Standard and limited material compositions and established routines contribute significantly to the precision of cost estimations. The limited range of products allows for project-specific quantities and dimensions, resulting in highly accurate estimates. These characteristics present opportunities for future enhancements. Since tasks are project-dependent but similar, implementing automated models could streamline the process. While estimations may vary, the underlying steps remain consistent, enabling the development of models tailored to these steps, thus reducing time consumption.

Furthermore, the use of standard material compositions only requires to adopt this material composition to the unique design. This minimises design flexibility and enhances the possibility for standardisation. For instance, dividing a roof into multiple elements is currently a manual process based on the cost estimator's experience. However, this step follows a set of rules and utilises a limited range of materials, making it ripe for automation.

On the other hand, The unique and client-dependent nature of designs poses a challenge in the cost estimation process. Each project requires a separate estimation, leading to repetitive steps and manual measurements. This manual and repetitive approach contributes to the time-consuming nature of the process and increases the likelihood of errors, such as counting and measurement mistakes.

Furthermore, the use of multiple tools for estimating costs necessitates manual data transfers, adding complexity and potential for errors. Emergo faces threats in this regard, particularly concerning dependency on client deliverables. Document deliveries vary widely among clients, ranging from comprehensive to nonexistent, which limits Emergo's control and hampers the implementation of potential solutions.

Moreover, information provided by clients vary in terms of standardisation, quality and completeness. The type of documents that a client delivers is different per client such as the appearance of a BIM model, which is not included in many projects. On top of that, BIM models are varying in quality and development. Each client or architect designs these BIM models according to their preferences, undermining the reliability and utility of BIM models for cost estimations.

Finally, while PreFab cost estimation processes are currently well-established and routine, there is a risk of stagnation and obsolescence if advancements in efficiency cannot be realised, especially if Emergo fails to keep pace with emerging technologies. This situation aligns with the potential threat posed by the rise of PreModu, which Emergo anticipates could surpass PreFab in the future.

In conclusion, key findings of PreFab's cost estimation process evaluation are summarised in Figure 9

Evaluation of PreFab	
Strong Points	**Weak Points**
• **Accuracy:** Quantity measurements are quite accurate due to well-defined designs. Components are exactly counted and connected to a price, resulting in detailed cost estimations • **Routine work:** Repeatable process with known challenges, solutions, defined workflows and reliable fixed partners. Materials and components that are used are known and unique solutions are rare • **Adaption of standard materials:** Even though designs are unique, tasks have a repetitive nature, such as adapting standard material compositions into flexible designs. This increases the potential for automated cost estimation models • **Low range of product variety:** PreFab mainly focuses on the roof components and related components, which consist of limited and fixed material and components possibilities	• **Unique designs:** Designs are often unique and vary between projects. Clients are in control of this model and Emergo is dependent on these design • **Time-consuming:** Some steps are time-consuming such as manual dimension measurements or manual division of elements and the composition of the quote • **Disconnected databases:** Manual configurations are necessary to transfer data between databases • **Error-prone:** Counting or measuring errors by cost estimator due to manual measurements • **Old-fashioned:** The risk of not adapting to emerging technologies could hinder Emergo's ability to optimise and enhance the efficiency of the Prefab cost estimation process • **Quality of information depends on clients:** Emergo is dependent on client for BIM models, project information and design quality, threatening the possibility to increase efficiency

FIGURE 9: Derived summary of weak and strong points of PreFab's cost estimation process

Evaluation of PreModu's cost estimation process

PreModu, a relatively new concept, holds immense potential for Emergo. Its strength lies in the implementation of standardisation, both in components and costs. This allows for the emergence of designs from standardised components, enabling project-independent estimations. Modules can be estimated quarterly to account for price fluctuations or supplier updates, streamlining the process and minimising the need for project-specific recalculations. Standardised costs for standard modules or components make the cost estimation process relatively fast, relying on pre-calculated options.

Emergo's success in completing PreModu libraries could unlock massive potential compared to PreFab. Automated design and cost estimations are among the many applications that could become central to Emergo's business with PreModu. BIM models are always modeled during the cost estimation process, on behalf of Emergo's coordination. Integration with BIM presents a significant opportunity, as it can be utilised during the cost estimations

Designs are tailored to the features and component library of PreModu, enhancing Emergo's influence over house development. Clients must adhere to PreModu requirements, reflecting Emergo's vision towards MTO/ATO strategies. Emergo's control over PreModu concept puts it in a position to capitalise on these opportunities and establish PreModu as a core aspect of its business.

Weaknesses in the current PreModu process include incomplete object and price libraries, with an estimated varying percentage of 15% per project, which have not been standardised yet and do not contain an exact price tag. Also unique requirements by clients results in resistance to standardisation and leads to unique adaptions per project or even per house, which are calculated manually. Besides, the wide range of products and suppliers for PreModu realises a level of price uncertainty within the cost database. Based on these three aspects, the cost estimation process of

PreModu is considered to be inaccurate.

Additionally, cost estimations rely on multiple disconnected databases, where manual data transfers are required. Fist of all, designs are conducted in Revit, and are not connected to cost data at all. Secondly, cost items are originally stored in the ERP and in Timber Estimation Software X, which are manually copied and maintained in the Excel Model that is used.

The incomplete libraries result in unavailable prices for certain component variations and necessitating manual cost estimations for new or unique project requirements. The time required to complete these libraries to cover all client design options can be significant. requiring manual data transfers.

Moreover, the learning curve and potential applications of PreModu could overwhelm Emergo. Unclear implementation steps and slow development may hinder the realisation of benefits. This issue also resulted in the ignition of this research, clarifying on the improvement directions Emergo could undertake to enhance cost estimations. Insufficient overview in this development undermines the potential that PreModu entails. Reliance on customised components or designs threatens to undermine the benefits of PreModu, as manual efforts remain necessary without sufficient standardisation.

In conclusion, key findings of PreModu's cost estimation process evaluation are summarised in Figure 10

Evaluation of PreModu	
Strong points	**Weak points**
• **Standardisation:** Standardised designs and objects are project exceeding and not unique per project. • **Relative fast cost estimation process:** Options are precalculated and updated every quarter, avoiding the need to recalculate per project. • **Possible process optimisations:** Further developing and finishing object libraries will standardise and improve cost estimation process in terms of efficiency • **BIM integration:** BIM models are always accessible, resulting in an opportunity to integrate or use BIM models during cost estimations • **Influence:** Emergo oversees deriving a preliminary BIM design. Hence, they can control the BIM model, enabling the possibility to manage data from the start	• **Accuracy:** Due to incomplete object and price libraries and dependency on suppliers, the accuracy in current cost estimation processes is considered relatively low • **Incomplete libraries:** The component and cost library of the concept of PreModu is still incomplete, disabling complete standardised cost estimations. • **Multiple disconnected databases:** Manual work is necessary to connect data between systems • **Dependency on suppliers:** Due to the range of products, Emergo is dependent on the reliability of supplier prices • **Resistance to standardisation:** Currently, unique components are used based on client or buyer preferences, resulting in the need of manual cost estimations. • **Development stage:** Currently, PreModu is still in its development phase. Developing PreModu and adapting to BIM integration might take some time or is unachievable. Not all benefits are currently exploited

FIGURE 10: Derived summary of weak and strong points of PreFab's cost estimation process

3.3 Conclusion

Within this chapter the first research question (*(1) What are Emergo's current cost estimation processes and challenges for PreFab and PreModu?*) and its sub-questions are answered. Both processes (PreFab and PreModu) are examined through document analysis, observations, and interviews to get familiar with the processes. This examination provided a detailed understanding of the structure and organisation of cost estimations, where Figure 6 and Figure 7 reveal the flowcharts of PreFab and PreModu respectively.

Additionally, PreFab's and PreModu's cost estimation process are compared to each other and different or overlapping aspects are examined. In organisational terms, the cost estimation processes are quite similar, using similar software, systems, and methods to estimated the costs. On the other hand, the main difference is the enhanced control and coordination Emergo has over PreModu. The concept, the design and input for cost estimations is managed in-house, with standardisation adopted as vision. PreFab cost estimations are dependent on documents and varying designs from clients. Figure 8 illustrates the main difference, which has significant impact on the corresponding cost estmations.

Finally, this comparative analysis and interviews provided input to evaluate the strengths and weaknesses of each cost estimation process. Given the research objective, particular emphasis was placed on identifying weaknesses as they present opportunities for process improvement. By combining the process description with the analysis results, specific areas where these issues manifest can be pinpointed. The evaluations highlighted critical weaknesses in both cost estimation processes, which serve as focal points in this research. These identified "issues" represent areas in need of improvement, offering opportunities for enhancements that address or mitigate these challenges. These key issues are labeled for reference in Table 3.9, facilitating their placement within the process flowcharts for a clear visualisation of their locations. Flowcharts featuring these labels are available in Figure 12 and Figure 11.

Label	Weaknesses/ Threats
PreFab	
W1	Unique Designs
W2	Time-Consuming
W3	Disconnected Databases
W4	Error-prone
W5	Old-Fashioned Technologies
W6	Information is dependent per client
PreModu	
W1	Accuracy
W2	Incompleteness
W3	Multiple Disconnected Databases
W4	Dependency on Suppliers
W5	Resistance to Standardisation
W6	Development Stage

TABLE 3.9: Labels of issues for both processes

The issues identified in the flowchart mark the conclusion of the process identification chapter. In the next chapter, treatment requirements will be derived. These requirements are based on stakeholder goals, with a focus on improving the current state of cost estimation processes to meet desired objectives.

FIGURE 11: Issues of PreFab Process

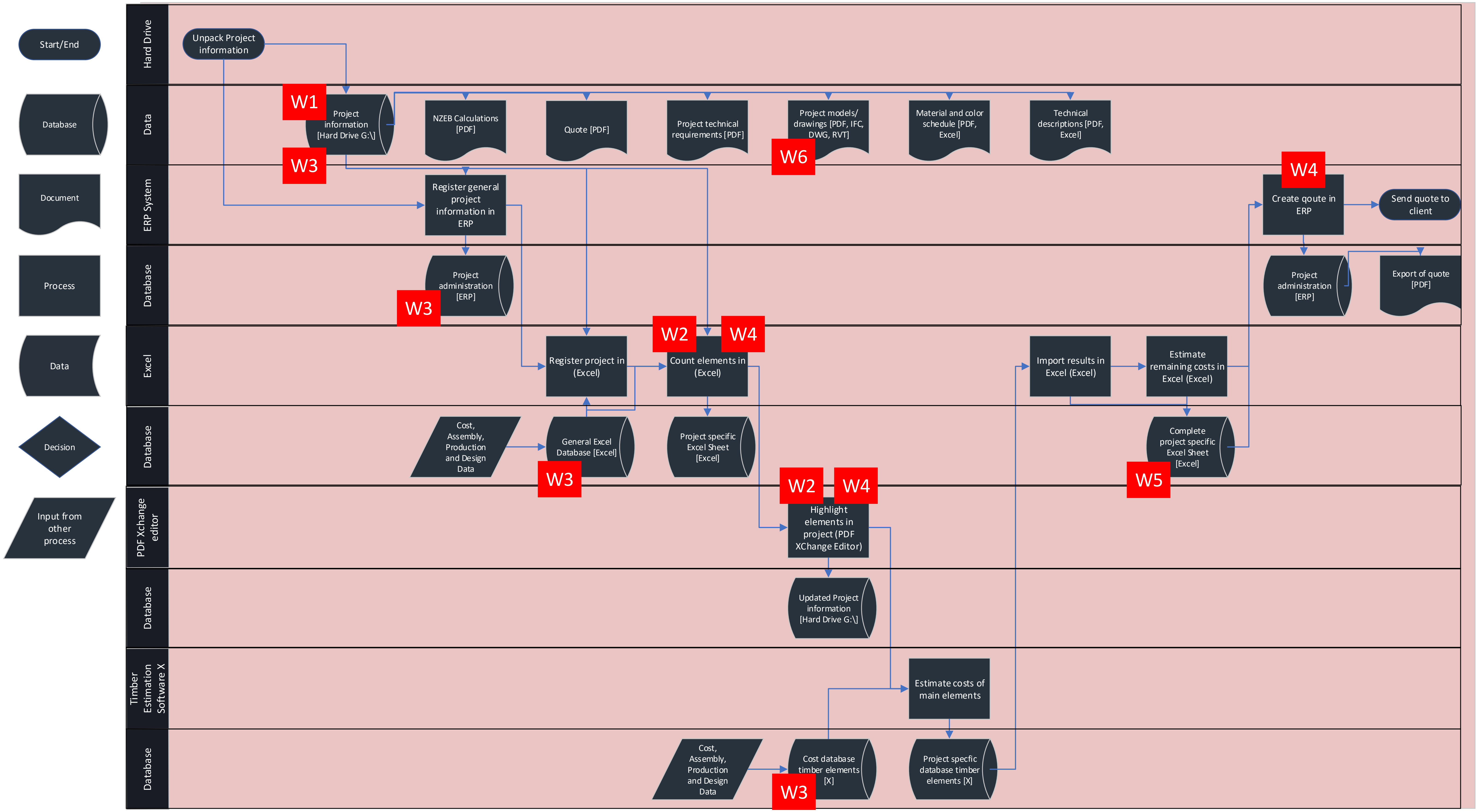
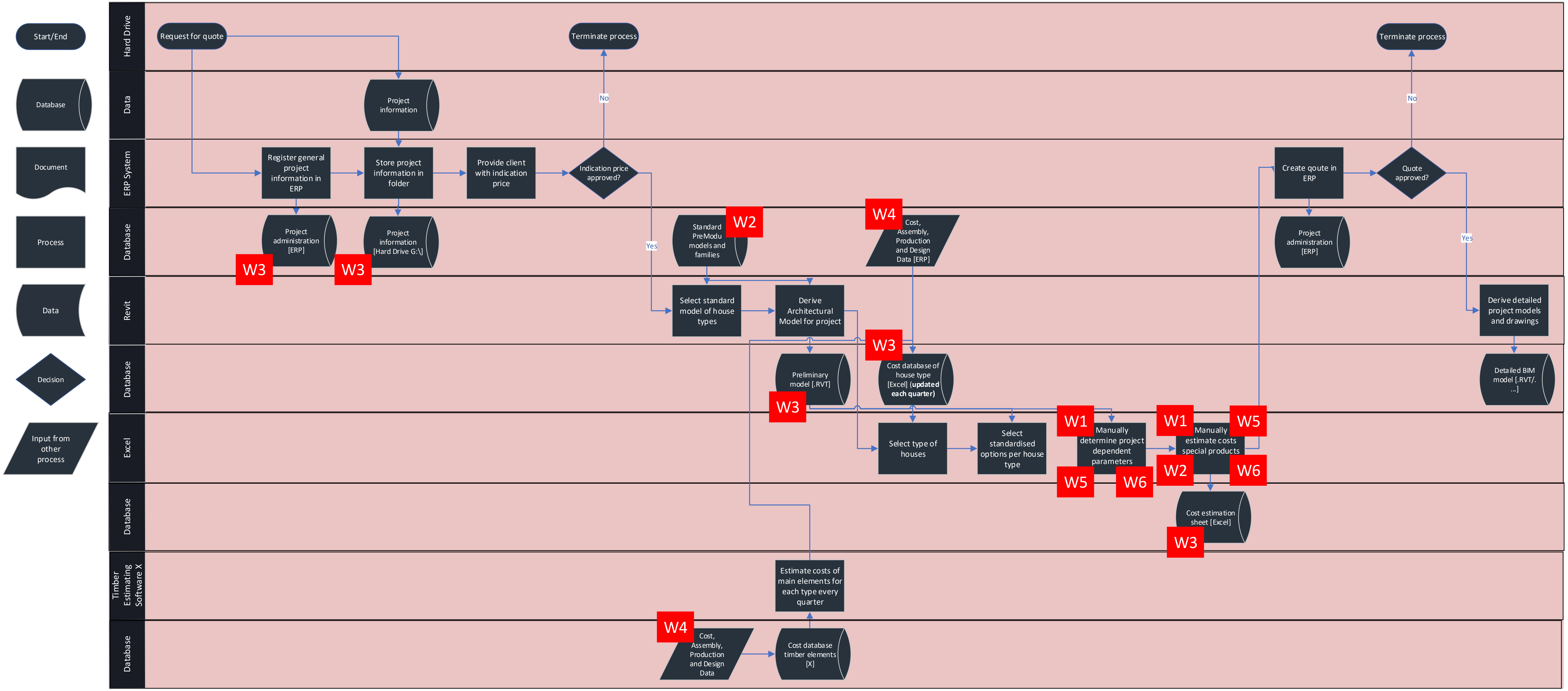


FIGURE 12: Issues of PreModu Process



Chapter 4

Treatment Requirements

Cost estimation processes of PreFab as well as PreModu have been extensively analysed and compared, which resulted in an overview of their strengths and weaknesses. Transferring the research to its second phase, a determination of the stakeholder desires, goals and treatment requirements for potential solutions are necessary. The potential scenarios should eventually enhance the efficiency of cost estimation processes by accomplishing the design requirements. This chapter entails the second phase of the research, which sets the stage for the next chapter, determining the scenarios, which is thus a combination of BIM uses in the context of PreFab's or PreModu's cost estimation processes.

2. **What are the needs and treatment requirements of potential scenario's for both cost estimation processes?**
    (a) What are the anticipated requirements and expectations for the desired calculation processes of PreModu and PreFab projects?
    (b) How can the data generated within the calculation processes be effectively utilised in other phases of the project life-cycle, contributing to an overall improved efficiency and decision- making?

The treatment requirements are derived based on the desires of the stakeholders, captured via interviews. Stakeholder goals are defined, which are the input of the treatment requirements, following the strategy of Wieringa (2014).

These treatment requirements are affecting the cost estimation process in a direct manner. However, other departments can also benefit from a smooth cost estimation process. General statements are made in this chapter while the subsequent chapter reveals detailed derived scenarios, including more specific contributions to the entire life-cycle.

4.1 Stakeholder Desires

The issues (strengths and weaknesses) of both cost estimation processes are identified, which automatically reveals points or areas for potential improvements. These critical points are shown on both process diagrams, Figure 11 and Figure 12. According to Wieringa (2014), stakeholders of the research face different issues or have different awareness of the problems. A stakeholder could be aware of issues and **desire** a potential improvement of the situation by implementation of a treatment. Yet, a desire does not necessarily means that the stakeholder is willing to commit resources to achieve the desire. When a stakeholder is committing resources (time, money and/or other resources), the desire is defined as a **researcher goal** (Wieringa, 2014). These researcher goals can eventually be translated into goals for the potential treatment, which further specifies the treatment and its requirements. The list of desires and goals is provided in Table 4.1, where stakeholders are connected to the issues that they face, and the potential desire or stakeholder goal that they have. These have been derived according to the interviews that have been held with the stakeholders.

Stakeholders PreFab	PreFab's Issues	Desire	Goal?	ID
Clients	**W2, W4**	- Require a reliable and fast estimation of project costs including delivery specifications	Desire	D1
Cost Estimator	**W1, W2, T2**	- Requires accurate, fast and up-to-date cost estimation models to derive costs for unique projects and varying data input	Goal	G1
Cost Estimation department Manager	**W3, W4**	- Needs to have access to accurate cost data from ERP's database to manage and maintain PreFab's cost estimation models.	Goal	G2
		- Persuades quality and reliability in cost estimations by the cost estimators to avoid the need to check and recalculate.	Goal	G3
Timber-Framed Component BIM Engineer	**W4**	- Want to obtain an accurate division of timber-framed elements and details, made by the cost estimator	Desire	D2
Stakeholders PreModu	**PreModu's Issues**	**Desire**	**Goal?**	**ID**
Cost Estimator	**W1, W2**	- Necessitates an (semi-) automatic cost estimation model that automatically calculates the costs based on project parameters and options	Goal	G4
Concept Manager	**W3, W4, T2**	- Have access to all PreModu concepts and variations and cost databases to derive cost estimations for entire modules and options per house type	Goal	G5
Clients	**W1, T2**	- Want to check how PreModu can fit within their development project	Desire	D3
		- Efficient cost estimations, in terms of accuracy and speed	Desire	D4
Project architect/ BIM modeller	**W2, T1**	- Need to have access to the information libraries containing standard PreModu designs, construction details and project documents to derive a project design/ model	Desire	D5
Concept Developer	**W4, T2**	- Desire standardisation across each concept type and	Desire	D6
		- coordination between cost data and design objects to develop and maintain PreModu types	Desire	D7
Stakeholders Both Processes	**Both Issues**	**Desire**	**Goal?**	**ID**
Business Developer Emergo	PreFab: **T1**. PreModu: **T2**	- Wants to enhance business concepts by implementing or developing BIM within the cost estimation processes. The stakeholder is the initiator of the research	Goal	G6
Purchase/ Planning/ Production/ Assembly/ Production Departments	PreFab: **W1, W4** PreModu: **W2, W4, T2**	- Require accurate estimations, including project details and object quantification to conduct their daily tasks.	Desire	D6

TABLE 4.1: Stakeholder desires and goals

Obviously, the stakeholder goals and desires overlap the research goal. In fact, the the stakeholder goals summarise the direct improvements for cost estimation process. On the other hand, the stakeholder desires are more broader aspects that are affected by these improvements, varying from the beginning until the end of PreFab's and PreModu's supply chains. Together, the goals and desires form the research goal as it summarises the improvement of cost estimation processes by implementing BIM to eventually enhance Emergo's overall performance.

4.2 Treatment Requirements

Stakeholder goals are crucial in guiding the research, aligning with the overarching research goal. These goals represent the desired improvements in the cost estimation processes that stakeholders have committed resources to achieve. In contrast, desires reflect broader aspirations that extend beyond the scope of this research and may not involve resource allocation. Following the principles outlined by Wieringa (2014), treatment requirements are derived from these stakeholder goals.

Each primary requirement is further broken down into sub-requirements, each assigned a unique reference number to facilitate cross-referencing. It's acknowledged that certain requirements may overlap, particularly when addressing interconnected issues like accuracy and data library integration.

A comprehensive list of these requirements for the developed cost estimation processes for PreFab and PreModu can be found in Table 4.2 and Table 4.3, respectively.

Process PreFab		
Goal ID	**Requirements ID**	**Requirements**
G1	**R1**	**Cost estimation models must be able to translate varying data input from unique projects into costs by using standard solutions**
	R1.1	The process must have a strategy to receive or generate data input from the unique designs
	R1.2	The process must have a strategy to coop with varying data input
	R1.3	BIM-models must be checked on quality and completeness before utilisation
	R1.4	Cost estimation models or tools must be able to automatically translate unique data input to standard outputs/ solutions
G2	**R2**	**Cost estimation models must have access to accurate datasets**
	R2.1	The cost estimation process must have access to up-to-date cost databases to integrate cost data and cost estimation models
	R2.2	Data exchanges between systems must rely on imports, exports or integration instead of manual exchanges
G3	**R3**	**The process must maintain or reduce error sensitivity**
	R3.1	Errors in dimension measurements must be maintained or decreased
	R3.2	Errors in object quantification must be maintained or decreased
G6	**R4**	**Outcomes of the cost estimation process must be enhanced through BIM**
	R4.1	The process should replace manual cost estimation tasks by automated tasks
	R4.2	The introduced automated tasks must reduce the process lead time
	R4.3	Data integrity between departments or subsequent processes must be kept

TABLE 4.2: Treatment requirements for PreFab's cost estimation process

For the PreFab process, the main requirements revolve around speed, automation, and database integration to reduce reliance on manual interventions. The variability inherent in each design poses challenges, resulting in project-specific datasets that need to be processed uniformly. The current manual extraction of information from project documents is time-consuming and prone to errors due to incomplete data or counting inaccuracies. Therefore, enhancing the PreFab cost estimation process entails automating tasks to accelerate the workflow while ensuring data integration without compromising accuracy.

Process PreModu Goal ID	Requirements ID	Requirements
G4	**R5**	**The cost estimation system must contain complete data libraries to conduct cost estimations**
	R5.1	Cost estimation system must include house types and their variations
	R5.2	Cost estimation system must include standard components, modules or options which the user can select
	R5.3	The cost estimation system must include all cost prices to estimate costs for the possible combinations of project parameters and options
	R5.4	The cost estimation system must automatically calculate the costs according to the chosen options or modules
G5	**R6**	**Process must have complete and integrated connected databases**
	R6.1	PreModu's conceptual process must rely on complete object or module libraries
	R6.2	Each component, module or option must be integrated with cost data from the cost library
	R6.3	Process must be able to handle concept changes
	R6.4	The process must have access to reliable purchase data and coop with supplier price changes
G6	**R7**	**Cost estimation process must have enhanced outcomes**
	R7.1	Cost estimation models or tools must increase in terms of accuracy of the cost estimation
	R7.2	Design changes must be integrated with the cost estimation process
	R7.3	Available BIM models (concept or preliminary project models) must be utilised during the cost estimation process
	R7.4	Process must reuse previous project data to complete cost library and enhance accuracy of cost estimations

TABLE 4.3: Treatment requirements for PreModu's cost estimation process

In contrast, Emergo prioritises accuracy over speed in the PreModu process. The primary focus is on refining and completing the object and price library to optimise cost estimations. Although a significant portion of project elements adheres to standardised solutions, challenges arise with non-standardised elements that vary across projects. Continuous refinement is necessary to address these project-specific challenges, such as facade finishing. PreModu aims to establish database connectivity as the libraries are developed over time, ensuring accuracy and consistency in cost estimations.

4.3 Benefits in the life-cycle

In this chapter, treatment requirements are derived aimed at enhancing the cost estimation process. These requirements not only offer direct benefits but also indirectly improve subsequent processes in the project life-cycle. Since the cost estimation process marks the beginning of each project at Emergo, meeting these treatment requirements could potentially enhance other phases of the project life-cycle.

General relationships with subsequent life-cycle departments are explored in this section, illustrating how these departments interact and utilise cost estimation data. These relationships are summarised in Figure 13, applicable to both PreFab and PreModu concepts. The effective utilisation of data in each department is further elaborated in the following subsections. Additionally, Figure 13 outlines the enhanced activities, such as scheduling activities, achievable through the development of cost estimation processes. Besides the general statements addressing the effective utilisation of cost estimation data, scenarios that are designed in chapter 6 could also impact the entire life-cycle, resulting in effective data utilisation in subsequent departments as well. If this is the case, this will be elaborated in the explanation of the designed scenario, which often results in more specific data utilisation.

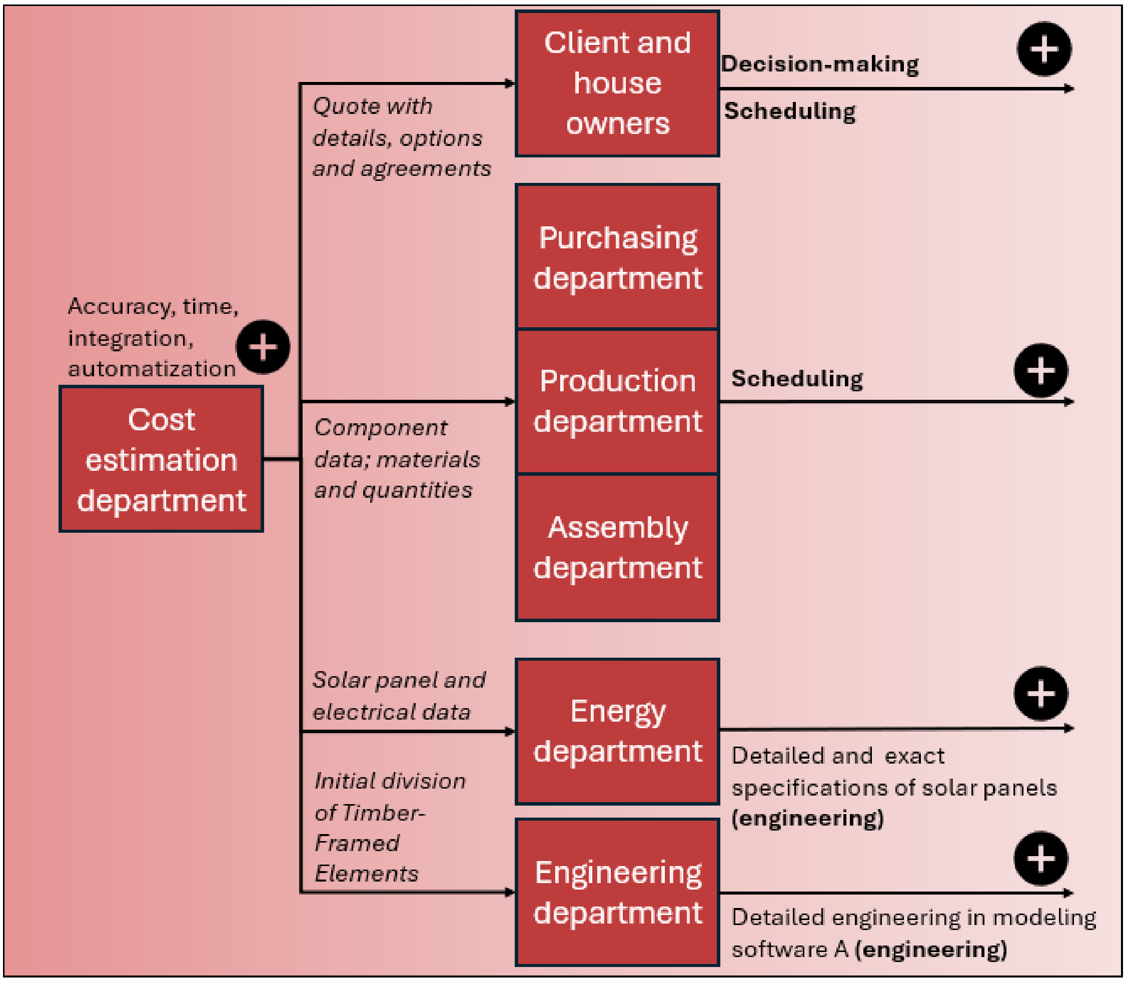


FIGURE 13: Data utilisation in other phases of the project life-cycle

4.3.1 Clients and house owners

For clients and house owners, accepting the initial quote results in a development agreement. This initial quote plays a pivotal role in decision-making processes, providing a crucial go or no-go moment for the clients. It allows them to make informed decisions about their final selections. Furthermore, clients, often acting as the main contractors of the project, can utilise the quote for scheduling purposes, both in terms of costs and time. Improvements in the accuracy and speed of cost estimations can significantly facilitate decision-making and scheduling activities. These benefits are illustrated in Figure 13, where cost estimation data is shown to enhance decision-making processes and scheduling capabilities.

4.3.2 Engineering and energy departments

The engineering and energy departments benefit from the initial cost estimation processes by utilising them as a foundation for their conceptual engineering tasks. In PreFab and PreModu, this involves integrating Navitect, which are Emergo's own developed solar panels. Besides, in PreFab, cost estimators perform preliminary engineering tasks, dividing the roof into elements and conduct intial construction calculations. In PreModu, the process begins with a preliminary design, which is then refined into technical designs within the engineering department for all Mechanical, Electrical and Plumbing components. In Figure 13, the energy department has similar benefits for MEP engineers, namely the conceptual foundation. In summary, engineers verify and develop these initial decisions of cost estimators or BIM modelers. If necessary, the engineer makes adjustments based on their expertise. Therefore, accurate and comprehensive data from cost estimators minimises the need for rework by and improves the overall efficiency of engineers.

4.3.3 Purchasing, production and assembly departments

The purchasing, production, and assembly departments rely on the initial selection of component types, materials, and quantities for their scheduling activities. Typically, orders are placed around five weeks after the final drawings are completed. Production begins in the Emergo factory during the last week of the purchasing timeframe, followed by delivery and on-site assembly the week after production. Improvements in cost estimation accuracy reduce errors in subsequent processes. Additionally, integrating data between these departments could potentially automate scheduling activities. However, this automation relies on the accuracy and completeness of the cost estimation process. Ultimately, efficiency enhancements can lead to improved scheduling capabilities across departments, as illustrated in Figure 13.

4.4 Conclusion

In this chapter, stakeholder goals are translated into tangible treatment requirements that realises enhanced cost estimation processes. Thus, research question *(2) What are the needs and treatment requirements of potential scenario's for both cost estimation processes?* has been answered. For PreFab, the final treatment requirements are shown in Table 4.2 while the final treatment requirements for PreModu are shown in Table 4.3. These requirements are used to select and combine BIM uses into scenarios, and verifying the scenarios after the designing them.

Enhancing cost estimation processes impact the entire life-cycle of a project, where the utilisation of cost estimation data in crucial subsequent departments are highlighted in Figure 13. Additionally, chapter 6 expands this elaboration on effective data utilisation during the explanations of scenarios, and their impact on other departments.

Chapter 5

Selecting BIM scenarios

In this section, potential BIM uses are collected that potentially could contribute to Emergo's cost estimation process. Subsequently, the potential uses are clustered into BIM-based scenarios, which are applicable in Emergo's context. Hence, this chapter is the last step before the design phase ignites, resulting in an overview of the scenarios that need to be designed. The following research questions are thus answered:

3. Which BIM-based scenario's can be used and adapted to achieve desired requirements?
    (a) Which BIM uses can be be harnessed to address the challenges and improve the efficiency of the calculation processes within both PreModu and PreFab project

Research question 3 is not entirely answered in one chapter. Sub-questions (b) and (c) are answered in the chapter 6 for readability.

These BIM scenarios are then further unraveled in their general methodologies, specific working in Emergo's context, and finally, their conditions and values are examined. The conditions are the resources and technologies that need to be established to facilitate the working of each scenario while the value are the direct and indirect benefits on Emergo's cost estimation or connected processes.

Finally, these scenarios are evaluated in consultation with stakeholders from Emergo, verifying and validating the scenarios. If necessary, the working, conditions and values are adapted or further supplemented.

5.1 Potential BIM uses

In exploring solutions aligned with design requirements, potential applications of BIM in cost estimation processes were identified through literature review, where search terms are detailed in Appendix B. These applications, considered primary tools, directly influence cost estimation processes. However, adaptation or development is necessary to tailor them to Emergo's needs. Often, complementary BIM concepts are essential for optimal functionality, such as establishing comprehensive databases or ensuring data quality through model checkers.

Moreover, drawing from previous research[1], Emergo has pinpointed relevant BIM applications crucial to their business strategy. These preferred applications, outlined in Table 5.1, reflect Emergo's strategic directions. As advancements in cost estimation must align with Emergo's plans,

[1] *BIM Uses in Modular Construction*

BIM applications connected to cost estimation processes are of particular interest. For example, Emergo emphasises "Author design" applications, enabling BIM software to create enriched 3D models using parametric modeling or generative design techniques. Thus, BIM applications from Table 5.1 that are affecting or affected by cost estimation outcomes, are considered in exploring potential uses.

BIM Use	Applications
Author Design	Developing 3D-Models, Parametric, and Generative Design
Coordinate Design Model	Clash Detection and Coordination
Automate Creation of Construction Documents	Generating Production Drawings and Instructions
Linking and Extending	Connecting ERP, Calculating, and 3D Configurator, and Buying Processes
Fabricate Product	Quality Control, Production
Author Cost Estimate	Automate Cost Estimations, and Online Selling Process by configurator
Author 4D Model	Instructions

TABLE 5.1: Prioritised BIM uses by Emergo, according to former research

Hence, BIM applications can be categorised into three main types: primary ones directly improving cost estimation, supportive ones aiding data accessibility, and those that interact with cost estimation processes. These relationships are depicted in Figure 14. While primary and some supportive uses stem from literature research, others are recognised through prior research[2] as supportive or influential in BIM's role.

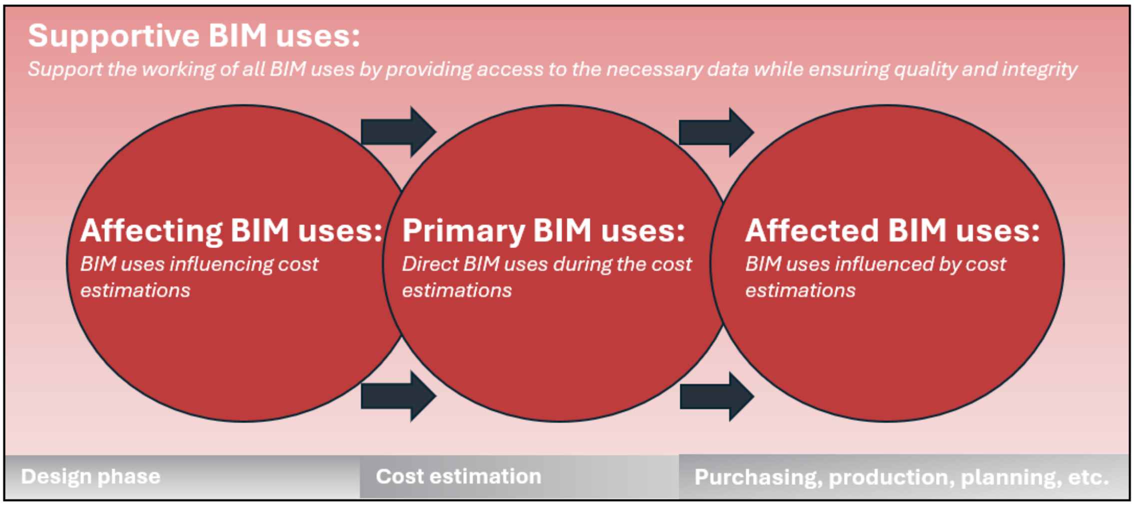


FIGURE 14: A scenario, a combination of related of BIM uses with cost estimation as main environment

In summary, the interconnected BIM applications depicted in Figure 14 play a vital role not only in improving the cost estimation process, but also in broader implementation contexts. These applications can be combined to form scenarios, which may involve a single or multiple BIM uses tailored to the needs of PreFab or PreModu cost estimation. All relevant BIM applications are detailed in Table 5.2. This list is preliminary, and as the scenarios are derived or expanded upon, additional related BIM uses may be identified.

[2] *BIM Uses in Modular Construction and at Emergo (Working Paper)* (Ketabi, 2023)

ID	Name	Description	Source(s)
BIM uses for design, affecting cost estimation			
1	Design Configurator	Develop an interface with predefined design options that reveals a conceptual design and corresponding costs based on a kit-of-parts library (tasveld). This interface can combine multiple concepts and their variations into a project design	(Cao et al., 2021; Farr et al., 2014)
2	Parametric modeller	Develop, generate or change designs by using parameters, internal relationships and/ or formula's	(Wahbeh, 2017; Park, 2011)
3	Generative design	Using BIM software tools to run algorithms and simualate many design options that need to be explored	(Zarzycki, 2012; Ma et al., 2021)
4	Automate creation of construction documents	Automatically generating production models, drawings or instructions based on the architectural model	(He et al., 2021; Deng et al., 2021)
BIM uses for cost estimations			
5	Model viewer	3D Visualisations of BIM models to visualise components for the employee during cost estimation processes	(Jiang, 2011; Wu et al., 2014)
6	Quantity Exports	Translating the BIM model into a simplified initial bill of quantities, which can be converted in excel worksheets or CSV files. All components are extracted	(Jiang, 2011; Wu et al., 2014)
7	Information TakeOff (ITO) Tools	Specialised takeoff tool that extracts and visualises the desired takeoff diagrams, which can be analysed in excel worksheets or CSV files. Only desired and filtered data is extracted	(Jiang, 2011; Wu et al., 2014)
8	BIM-based estimating software	Use a cost estimation tool that is capable of reading and utilising BIM models to perform cost estimations	(Jiang, 2011; Wu et al., 2014; Sepasgozar et al., 2022)
9	5D BIM	Include or connect cost data into or to BIM models, expanding beyond the traditional 3D dimensions (height, length and depth) and time data	(Sepasgozar et al., 2022; Lawrence et al., 2014)
10	Parametric estimation models	BIM-based cost estimation prediction models based on algorithms that are able to predict cost rather than calculate them	(Elmousalami, 2020; Zhao et al., 2020)
11	BIM-based LCC	Estimate all the life-cycle costs, from construction until disposal of a building based on BIM	(Lee et al., 2020)
BIM uses affected by cost estimations			
12	BIM design analysis	Implementing BIM for decision-making processes where designs could be assessed with costs as a criteria	(Lee et al., 2020)
13	Author construction site logistics planning	BIM-based logistics and on-site planning or simulations for scheduling purposes (cost and time), affected by the estimated costs for the construction phase	(Wang et al., 2016)
Supportive BIM uses			
14	Model checking	Check and assess the value of BIM models on the design quality (clashes) and semantic requirements, which could be used to determine if the model is usable for cost estimation processes	(Wu et al., 2014)
15	Convert 2D drawings to 3D BIM models	Tools or softwares that are able to generate 3D BIM models based on imports of 2D CAD files	(Jiang, 2011)
16	Develop cost libraries	Finish and standardise cost libraries to estimate standardised objects and processes to achieve automatic cost estimations	(Sepasgozar et al., 2022; Lawrence et al., 2014; Wang et al., 2016)
17	Develop component library	Develop and standardise a modular object family tree in BIM design software to standardise all components that are used	(Sepasgozar et al., 2022; Wang et al., 2016)
18	Linking and extending	Connect cost databases to design databases or design interfaces.	(Sepasgozar et al., 2022; Lawrence et al., 2014; Wang et al., 2016)

TABLE 5.2: Potential scenarios that influence cost estimation processes

Various BIM applications are examined, all related to the cost estimation process in some way. First, there are **affecting BIM uses**, which influence but are not part of cost estimation activities. For instance, BIM design uses (use 1, 2, and 3) can provide essential data such as components and quantities, impacting cost estimations. Conversely, BIM use 8 offers more design flexibility, indirectly affecting cost estimations by influencing project designs.

Secondly, there are direct **BIM uses for cost estimations** that enhance outcomes or the process itself. BIM uses 5 til 11 are applications from literature that can be directly used during the estimations of costs. BIM use 5,6 and 7 address the uses that are more straightforward than other uses, namely quantity exports, information takeoff tools and using visualisations. These uses looked promising, but considered to have limitations. The uses usually rely on manual interference's and data manipulations (Lawrence et al., 2014; Monteiro and Poças Martins, 2013). Recently examined techniques addressed by (Sepasgozar et al., 2022) focus more on automatic cost estimations through linked data, algorithms or data frameworks. These concepts are more related to 5D BIM, where components are connected to cost data (Sepasgozar et al., 2022).

Additionally, there are **BIM uses affected** by the cost estimation processes, which are influenced by potential improvements. Uses 12 and 13, for instance, rely on cost data for scheduling or optimisation purposes. Improved cost estimations could facilitate cost analysis, planning, or optimisation efforts, enabling better decision-making for projects.

Lastly, there are **supportive BIM uses** that facilitate the functioning of direct BIM uses by providing or automating data exchanges. BIM uses 14 to 18 ensure necessary data availability and data integrity, essential for effective cost estimation processes.

5.2 Combining BIM uses

Potential BIM uses have been examined and in this section, the they are evaluated, selected and clustered into BIM scenario's. The following strategy has been applied to obtain the BIM scenario's:

1. Check which BIM uses are compatible with the characteristics of PreFab's or PreModu's cost estimation process. Incompatible BIM uses can not be selected for the scenario's
2. Check which BIM uses could fulfill certain treatment requirements.
3. Make a selection of BIM uses that collectively ensure that all requirements are met. The least number of BIM uses are pursued
4. Cluster the selected BIM uses into BIM scenario's. The clusters have been determined on the primary BIM tools that are remaining. These tools affect the cost estimations process directly or drastically.

5.2.1 Compatibility check with process structures

First of all, the compatibility to PreFab and PreModu's cost estimation processes. Thus, a certain BIM use have to fit into one of the current cost estimation process, as well as the development plans of Emergo. In other words, the BIM use has to hold on to or exploit the strong points and should reduce or not expand the issues of a process (Table 3.9). A complete overview of the compatibility check is shown inTable C.1 under Appendix C.

5.2.2 Requirement analysis

Secondly, the degree a BIM use corresponds to the design requirements for PreFab and PreModu, noted in Table 4.2 and Table 4.3, respectively. This action reveals the treatment requirement(s) that each BIM use can realise.

5.2.3 Selection and clustering of BIM uses

Finally, the BIM uses are selected based the compatibility and requirements check. Incontrovertibly, the design requirements must be met, urging the need to check which combination of BIM uses meet the requirements. Additionally, incompatible BIM uses are not available anymore, narrowing the possibilities to choose from. Figure 54 and Figure 55 highlight the BIM uses which are chosen according to the compatibility and requirements check. An additional explanation is provided in section C.3.

Subsequently, the list of selected BIM uses (Figure 54 and Figure 55) must be converted to clusters, or in other words, the scenario's. This is done by dividing the primary BIM uses that are directly affecting the cost estimations into separate scenario's. The primary tools are supplemented with the necessary supportive, affecting or affected BIM uses.

For PreFab, BIM use **(7) ITO tools** and **(2) Parametric modeler** are the remaining main tools, both affecting the cost estimation process in a direct manner. Nevertheless, they are not used in similar applications and are derived in different scenarios.

For PreModu, BIM uses **(7) ITO Tools**, **(9) 5D BIM** are considered as the remaining primary BIM uses tools, as these BIM uses are contributing to the cost estimation in a direct manners. This observation already requires two scenario's. One for ITO, exploiting automatic measurements, and one for 5D BIM, more focused on automated cost estimations. Finally, despite that **(1) Design configurator** is not a primary BIM use for cost estimations, it affects the cost estimation process drastically, opening the door for integrated cost estimations. Costs and design could be integrated, which asks for a new scenario, namely, integrated cost estimations. The scenario's are supplemented with the BIM uses that further realise the treatment requirements.

5.2.4 Selected Scenario's

Table 5.3 outlines the scenarios examined within this research for PreFab's cost estimation process. Scenario 0 represents the current state of the process. The other scenarios focus on a single primary BIM use, supplemented with sub-uses to optimise functionality. For instance, merely using an Information Takeoff (ITO) tool isn't sufficient for improved outcomes. It requires support, such as a comprehensive BIM model.

PreFab As-is scenario	
As-is scenario: Using several cost estimation systems (Excel, ERP, Timber estimation software X) that rely on manual measurements and component quantification's, requires manual linking of data to align databases and no usage of BIM models	

PreFab Scenario 1: Information Take Off **Main BIM use**	**Requirement ID:**
ITO Tools: Extracting data out of BIM models delivered by the client and import this data into the cost estimation software to reduce or avoid manual measurements or counting	R1.1, R3.1, R3.2, R4.1, R4.2
Sub BIM use(s)	
Model Checking: Since BIM models can vary in how they are derived, checking BIM models could be useful to determine the usability. A model could be checked on the quality and clashes as well as classification of components	R1.3
Develop cost library: Ensure that costs are estimated using standardised material compositions and thus standardised costs. Avoid the need to manual derive costs for the extracted quantities	R2.1
Linking and extending: Realise that received datasets could be used automatically within the cost estimation process to avoid manual data exchanges	R2.2, R4.1, R4.3

PreFab Scenario 2: Generating Roof Model and Elements **Main BIM use**	**Requirement ID:**
Parametric modeller: Generating BIM models through parametric modelling instead of manual measurements to derive solutions, which could be utilised if the client does not deliver a BIM model or this is insufficient	R1.1, R1.2, R3.2, R4.1, R4.2, R4.3
Sub BIM use(s)	
Quantity Export: Extract data out of the generated roof model, which is then usable for cost estimations	R1.1, R3.1, R3.2, R4.1, R4.2
Develop cost library: Ensure that cost models are able to calculate the derived standardised components and elements	R1.4, R2.1
Develop component library: The parameters that are generating BIM models must consist of a combination of standardised objects	R1.4,
Linking and extending: Realise that the resulting dataset out of the generated BIM models could be applied automatically within the cost estimation processes	R2.2, R4.1, R4.3

TABLE 5.3: BIM Scenario's for PreFab's cost estimation process

The first scenario involves extracting specific information from a BIM model using the ITO tool. This structured approach filters on the desired information without generating a full list of all quantities. However, the extracted information must link to cost data for effective cost estimation, requiring a developed cost library. Smooth integration with cost estimation models and databases is essential, necessitating to include the linking and extending BIM use. Finally, since this scenario deals with external BIM models, a BIM use has to ensure that the models are indeed complete and usable for information takeoff's. Hence, model checking is selected as BIM use as well

In the second scenario, Emergo utilises a parametric modeler to create or adapt roof models automatically, adhering to standardised material compositions. These roof components are composed out of timber-framed construction elements, where automatic element division occurs. Subsequently, the generated roof model needs to be translated into cost estimation language, typically Excel, necessitating quantity exports. Although the quantity export aids in cost estimation, the parametric modeler remains the cornerstone of the process. The results from the quantity exports must be compatible with the cost estimation model. Thus, developing the cost estimation model and library becomes imperative to ensure that each component correlates with a corresponding cost item. Moreover, establishing a comprehensive component library is essential to encompass all material compositions within the parametric modeler. To facilitate interoperability, the results from this scenario need to be transferable between systems using a universal format. Therefore, incorporating linking and extending functionalities becomes crucial to ensure smooth data exchange.

The PreModu cost estimation processes encompass three additional scenarios alongside the as-is scenario. Table 5.4 outlines these scenarios, denoted as Scenario 0 for the as-is state, and Scenarios 1, 2, and 3, which incorporate various combinations of BIM uses and their supporting sub-uses.

PreModu As-is scenario	
As-is scenario: Using an Excel model that includes quarterly pre-calculated components and options in combination with project-dependent manual calculations. Quarterly updates are manually executed and connected. No/limited usage of BIM during cost estimations	

PreModu Scenario 1: BIM Information TakeOff	**Requirement ID:**
Main BIM use	
ITO Tools: Extracting data out of BIM models that are modelled on behalf of Emergo. This data can be used to avoid manual project-dependent measurements for the project-dependent calculations	R7.1, R7.2, R7.3
Sub BIM use(s)	
Develop cost library: Ensure that costs are estimated using standardised components and thus standardised costs calculations that fit the extracted information. Avoid the need to manual derive costs for the extracted quantities	R6.4, R7.4
Develop component library: Realise a component library to ensure the ability of standardised ITO procedures.	R6.1
Linking and extending: Realise that received datasets could be used automatically within the cost estimation process to avoid manual data exchanges	R5.2, R5.3, R7.3

PreModu Scenario 2: Automated Cost Estimations	**Requirement ID:**
Main BIM use	
5D BIM: Integrate or connect cost data with objects or modules, resulting in automatically estimated cost estimations and updates when designs are changed	R6.2, R6.3, R7.2, R7.3
Sub BIM use(s)	
BIM-based estimating software: Software or tool that is able to automatically translate designs/ BIM-models into costs	R5.4
Develop component library: Realise a complete project-exceeding standardised component library, where no components are unknown or unique. This is the input for the cost estimations	R6.1
Develop cost library: Realise a complete cost library, resulting in the fact that all components or modules could be connected to costs. Hence, no manual cost predictions are necessary	R6.4, R7.4
Linking and extending: Connected databases to realise that the estimated costs are dynamic instead of static. Meaning that estimations are up-to-date	R5.2, R5.3, R7.3

PreModu Scenario 3: Integrated cost estimations with design phase	**Requirement ID:**
Main BIM use	
Design configurator: A platform or interface where PreModu house types can be combined, including all variations. The combinations are visualised in conceptual designs including estimated costs of the project.	R5.1, R5.2, R7.2
Sub BIM use(s)	
5D BIM: Integrate or connect cost data with objects or modules, resulting in automatically estimated cost estimations and updates when designs are changed	R6.2, R6.3, R7.2, R7.3
Develop component library: Realise a complete kit-of-parts library to compose each combination of PreModu variations	R6.1
Develop cost library: Realise a complete cost library for these modules so that the cost estimations are predefined instead of manually conducted for every combination.	R6.4, R7.4

TABLE 5.4: BIM Scenario's for PreModu

In the first scenario, similar to PreFab's initial scenario, an information takeoff (ITO) is performed at the component level. This involves extracting component types from the BIM model, along with semantic information and quantity assessment. To achieve standardisation across projects, a component library must be developed. This library streamlines the ITO routines, although not every component requires detailed development; smaller parts like bolts and screws are standardised within larger components like walls and doors. Emergo oversees the derivation of BIM models, which can facilitate the extraction of project-specific quantities such as facade finishing. Currently, these quantities are manual, but automation is feasible with automatic import or integration with the cost database. Then, the cost estimation model must support the imports of the resulting ITO sheets, meaning that develop cost libraries is included as BIM use. Finally, linking and extending functionalities ensures that data can be exchanged automatically, which complements this primary BIM tool.

The second scenario focuses on automated cost estimations, leveraging the standardised nature of PreModu's house types, modules, and elements. 5D BIM is the main uses, connecting cost data with components in an automatic manner. A BIM-based estimating software is required to conduct these estimations, as these software have direct access to BIM models and cost data. By utilising preliminary BIM models, cost estimations per project can be automated. However, this necessitates connecting BIM model information to cost data, requiring complete and integrated component/module and cost libraries. Obviously, linking and extending supports the entire working of this BIM use, ensuring that cost or component data can be exchanged from one to another database.

The final scenario is about integrating cost estimations with design variations through a design configurator, which is also the primary BIM use. This scenario utilised 5D BIM methods to conduct cost estimations. Yet, this scenario is slightly different as cost etimations are shifted towards the design phase. It can be used earlier on, where clients or Emergo's employees are able to make desired house type combinations and receive the projected costs immediately. This scenario is considered to derive conceptual designs, rather than detailed ones. It depends on the accuracy and completeness of component and cost library how detailed this design could be. Clearly, these concept are thus considered as supportive BIM uses. Another value this scenario can have is BIM design analysis, since the design configurator could be used to derive multiple designs and assess them on for example costs. Yet, the BIM use is not further elaborated as it more considered as a benefit, rather than a necessary tool.

5.3 Conclusion

In this chapter, *3(a) Which BIM uses can be be harnessed to address the challenges and improve the efficiency of the calculation processes within both Premodu and Prefab projects?* is answered. The scenario's (combination of BIM uses) revealed in Table 5.3 and Table 5.4 are selected as scenario's that are going to be further examined and designed. These scenario's are considered to be a combination of compatible and suitable BIM uses that cover the treatment requirements. The initially selected scenarios have undergone validation through discussions with multiple stakeholders of Emergo. During these consultations, the established scenarios were collectively agreed upon, with no additional BIM uses identified that were excluded or left unmentioned.

Also, the scenario's have been initially verified in terms of the treatment requirements. However, final verification of the scenario's is conducted after the scenario's have been further developed, providing the verification more input.

Chapter 6

Scenario Design

In this chapter, the design of treatment can be started as the established scenarios are derived. The scenarios are designed including an initial practical proof of concept, resulting in additional insights. This chapter contributes to gain insights per scenario, ensuring the ability to evaluate and assess each scenario. The remaining sub-questions of question 3 are answered while (a) is answered in chapter 5. The following questions are answered, completing research question number 3.

3. Which BIM-based scenarios can be used and adapted to achieve desired requirements?
   (b) What are the necessary conditions and challenges to facilitate BIM and which value come with the successful implementation of these solutions?
   (c) To what extent do the proposed scenario's align with the identified design requirements and effectively mitigate challenges in cost estimation processes for both Premodu and Prefab projects?

The scenarios are devised as interventions, following the framework outlined by Wieringa (2014). This phase of the research demands a blend of creativity and expertise from the researchers. However, it is underpinned by insights gleaned from literature, particularly through real-world case studies, workshops facilitated by a BIM expert, and online tutorials. The insights acquired from these sources are then tailored to suit the specific context of Emergo's cost estimation processes. Simultaneously, the scenarios are tested with real PreFab or PreModu projects from Emergo, which could adapt or finalise the scenarios.

Each scenario is derived and tested in the context of Emergo, including a step-wise plan that reveals how the scenarios work. These step-wise plans are tested with real projects of Emergo, supplementing the theoretical implementation with practical examples as a proof of concept. Based on how each scenario works, the necessary conditions are determined. Additionally, based on the working and practical proof, the value's per scenario can be derived. This entails what benefits each scenario can contribute to. Each scenario should be examined according to a similar structure. The following structure is used to examine the scenarios and their applicability for Emergo:

1. **Working for Emergo**: The approach of the scenario is translated into the environment and processes of Emergo. Practical examples are examined, such as test cases. The BIM use is tested for Emergo's cost estimation processes, resulting in an overview of how the methods can be used for PreFab or PreModu

2. **Conditions**: The general approach and test cases of the BIM scenarios should result in general conditions and specific conditions for Emergo. These conditions support an effective

working of the BIM scenario. These conditions are structured among categories, which could overlap between scenarios. Therefore, conditions are labelled and reused if this is necessary, where Table 7.1 summarises all conditions per category and scenario.

3. **Process changes and value**: The scenarios are examined from a management standpoint to identify necessary process changes and the value they bring. This analysis involves modifying the original flow chart of the cost estimation process to simulate a hypothetical implementation of the scenario. Subsequently, the new flow chart highlights the process changes, while any reduction or elimination of existing issues implies value gained from the scenario.

4. **Summary of the scenario:** Finally, as a conclusion, a summary of conditions and value per scenario is derived in tabular form. Final remarks are made.

The final scenarios underwent validation through consultations with multiple Emergo stakeholders. This iterative process refined the value propositions and conditions, addressing any new findings or adjustments based on stakeholder feedback. Additionally, stakeholders discussed potential implementation challenges for each scenario.

Furthermore, a requirements check was distributed to multiple Emergo stakeholders, with all respondents verifying the derived scenarios. For PreFab and PreModu, the scenarios were evaluated against their intended goals to ensure they indeed represented improvements to current cost estimation processes. Lastly, stakeholders were asked for their preferences regarding specific scenarios per branch, providing input for the subsequent roadmap development.

6.1 PreFab 1: Information TakeOff's

The first scenario focuses on information takeoffs (ITOs) for PreFab, with the term "ITO" chosen to emphasise the inclusion of alphanumerical information alongside materials and quantities. subsection 6.1.1 details how the scenario operates within Emergo, subsection 6.1.2 outlines the necessary conditions, subsection 6.1.3 discusses the required process changes and potential value of this scenario, and subsection 6.1.4 concludes by summarising the conditions and values.

6.1.1 Working in context of Emergo

A schematic overview of how scenario 1 operates is provided in Figure 15, illustrating its workflow. The scenario begins with a developed BIM model as input, with the ITO definition and data processor ensuring that data is accurately extracted and translated into Emergo's cost estimation systems. To examine the possibility to exploit ITO's for Emergo, 3 random real PreFab projects are tested.

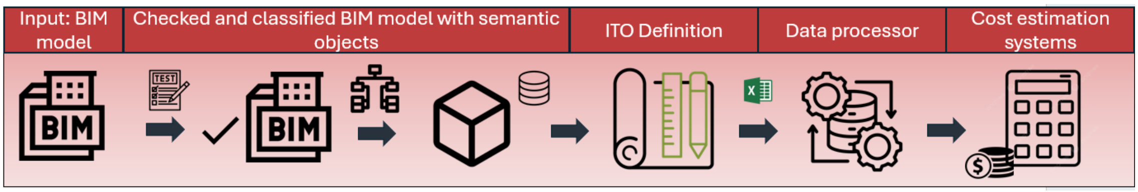


FIGURE 15: Schematics of the working of scenario 1

Step 1: Open BIM model

The BIM models are delivered by the client during quote request, which are shown in Figure 16. Solibri Information Takeoff has been used as the tool to conduct a ITO, which uses IFC as open BIM schemee to import the data.

FIGURE 16: PreFab ITO test BIM models

Step 2: Quality check of the model

This is where BIM use **14: Model Checking** can assist the tool by utilising a standard or custom rule set that checks the BIM model. A model checker can be used to check the quality of the BIM model by reviewing duplicates and overlapping elements, unclassified objects, component information, etc (Pibal et al., 2021). In Solibri, one can test the model on predefined checking structures or one can create their own checks. Identified issues are summarised in a result summary and overview report.

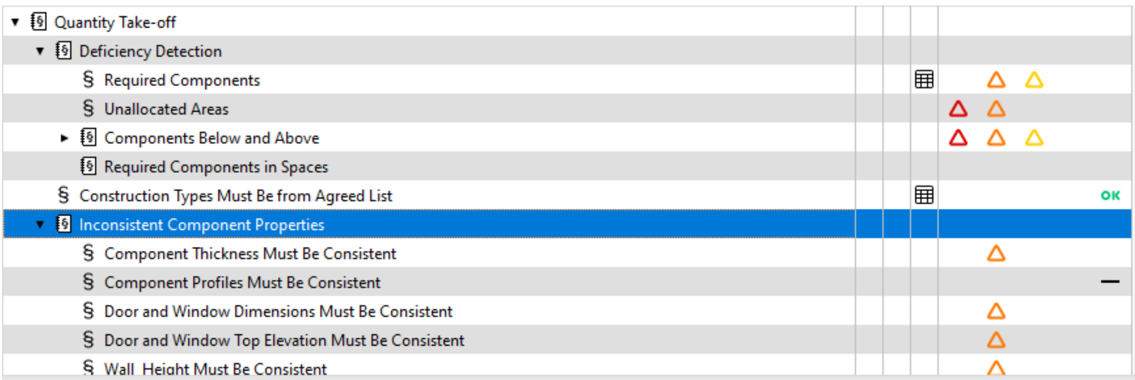


FIGURE 17: Identified issues project 3

For information takeoff's, its especially useful to identify duplicate components, inconsistencies within similar components and unclassified components. The checker provides results in terms of critical components and their locations if clashes occur. Figure 17 reveals the issues for project 3, where no critical issues for roof components were determined. After the checks, one can even classify the unclassified components manually or with a (customised) rule set. This is also done for the test projects, where unclassified components are manually classified to a certain category.

Step 3: Creating a filter to select necessary components

As shown in Figure 16, the BIM models contain all building elements for an entire house while Emergo is only delivering the Prefabricated elements and corresponding attachment or construction materials. Hence, a filter needs to be applied to select the desired components. These filters could be established in various ways. First of all, Emergo could conduct a classification system that classifies and groups components based on a set of rules. Figure 18 reveals such a ruleset, resulting in the classification of components of the BIM model where for example roof and wall components are grouped. The ruleset could be adapted or expanded to group all the components that Emergo needs.

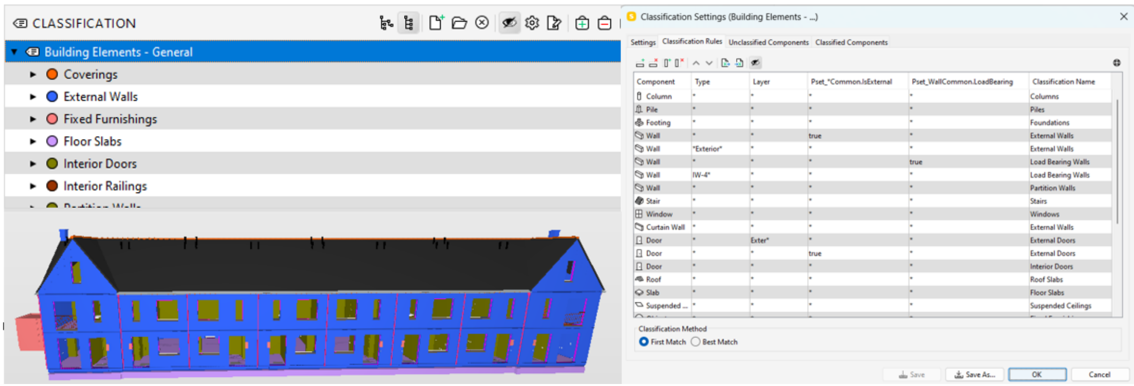


FIGURE 18: Classification rules and divided model into determined categories

Another way to filter or group components is to rely on standardised classification systems such as Uniformat, MasterFormat (Monteiro and Poças Martins, 2013) or the dutch classification system NL-SfB[1]. However, these classification settings are determined by the one that established the BIM model, making Emergo dependent on the client and BIM modeller for correct classifications.

Step 4: Sort and extract necessary data per component

The results can be revealed in multiple ways, dependent on the wishes of the user. The components can be grouped together if certain semantics are similar. For the test cases, the components are grouped on "Type", "Width" and "Height", where components are given the same color if all the attributes are similar. Moreover, "Material" and "Length" are extracted as well, resulting in the material and total length of similar components, which provides the option to calculate the volume. In this stage, the cost estimator can even (de)select specific components, to examine components in an isolated manner. The final components and their predefined or selected attributes can be extracted and exported from Solibri via an excel file (Figure 19).

[1]NL-SfB 4 cijfers codering

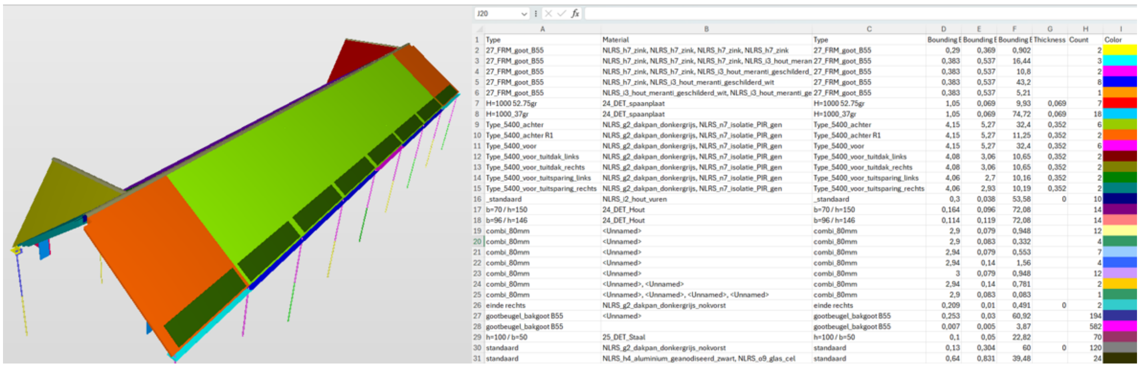


FIGURE 19: Results of QTO, test project 3

Step 5: Import excel to cost estimation system(s)

The results from Solibri in the form of an excel file can be imported into a calculation model of Emergo, the Excel model or even in the ERP system. Since decreasing manual modifications and increasing automatic data transfers are part of the requirements, the results must be automatically imported and processed in the cost estimation system. Relying on automatic imports exploits the BIM use **18: Linking and Extending**. Especially, when these results can be imported in the ERP system, where cost data is stored and maintained actively. Moreover, Emergo must succeed in BIM use **16: Develop cost library**, where cost data can be further developed in order to be connected to the results of the quantity takeoff imports. This use is rather considered as an adaptation of cost data, rather than establishing new data.

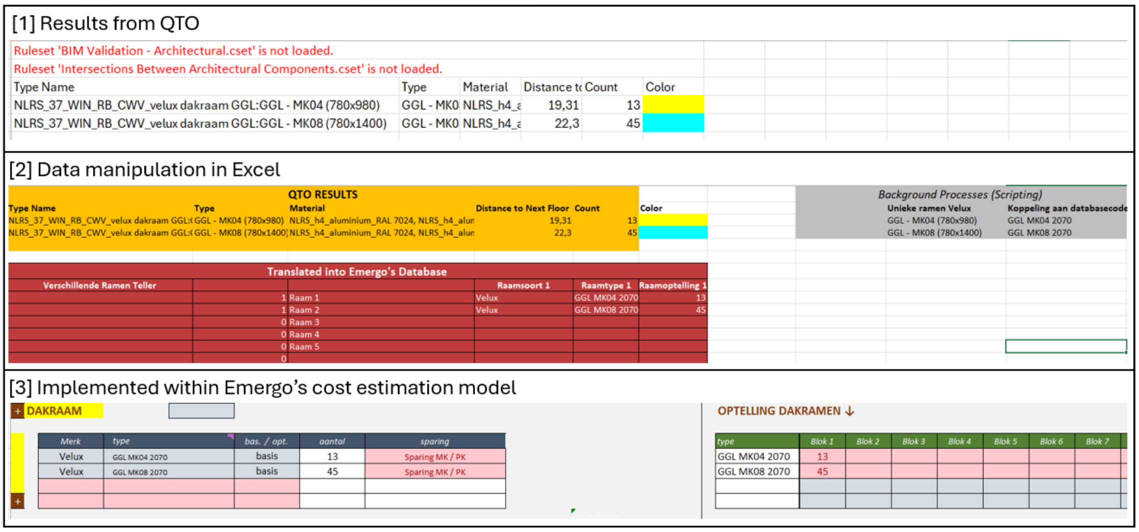


FIGURE 20: Processing results of ITO, test project 3

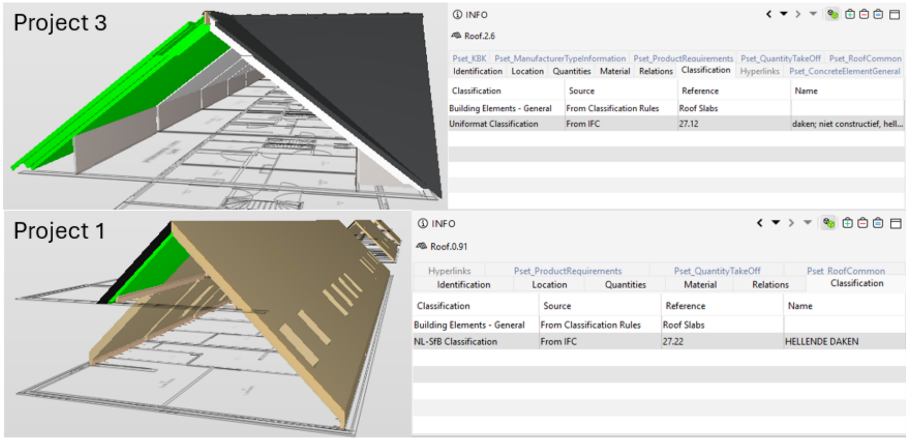
Figure 20 Shows the raw data from the results of the quantity takeoff in scheme [1]. In scheme [2] of the figure, these results are then imported within excel, in a separate sheet of Emergo's cost estimation model. Subsequently, the raw data is translated to terms of Emergo by using multiple formula's and modifications within Excel. Scheme [3] of the figure reveals the resulting data that is directly used for cost estimations and automatically extracted from the import of the results of the QTO. This final step is considered crucial, as it makes the information flow automatic. This example only revealed the automatic information flow for window objects. Yet, this automatic way of information processing needs to be done for every component.

6.1.2 Conditions and developments

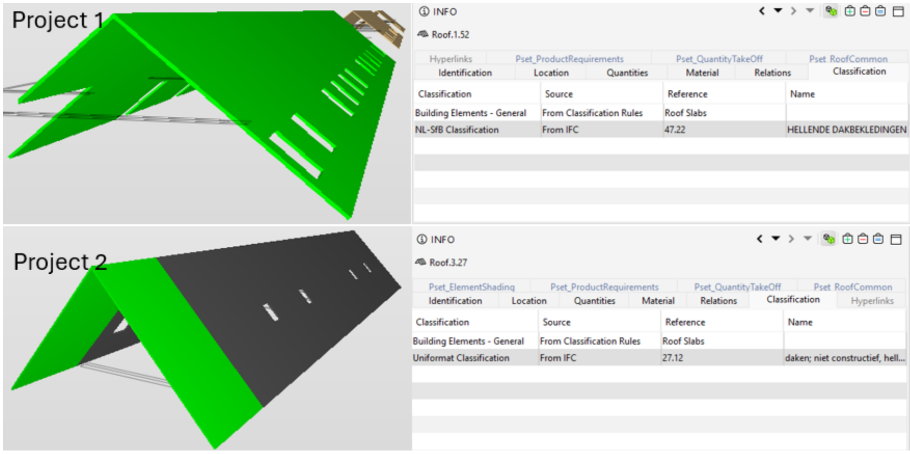
In order to make this BIM scenario realistic, several conditions has to be fulfilled. The derived conditions are derived under the following categories: *Quality conditions for BIM models, Conditions for information needs, according to (ISO 19650-1)* and *Conditions for information takeoff's procedures*. Explicit conditions are derived under the categories below, where all conditions for the scenarios are summarised in Table 7.1.

Quality conditions for BIM models

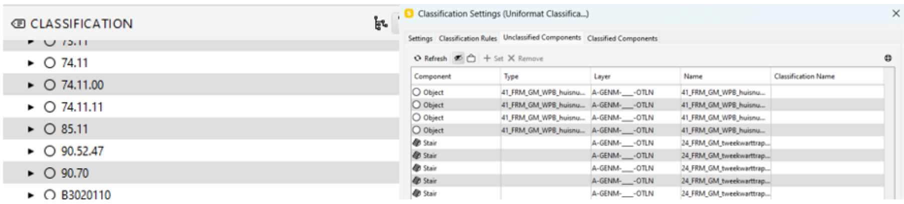
Three issues were identified during the examination of automatic classifications in BIM models from three different projects. Firstly, different classification methods were observed across projects, with some using Uniformat and others using NL-SfB (as depicted in Figure 21a). While related, these systems may yield different results due to variations in their application. Secondly, as shown in Figure 21b, similar components were classified differently across projects, indicating inconsistencies in classification standards. Finally, Figure 21c highlights instances where components were either not classified or assigned non-existent codes, indicating incomplete or erroneous BIM models.



(A) Issue 1: Different classification systems



(B) Issue 2: Different classification for similar components



(C) Issue 3: Wrong classifications or unclassified components

FIGURE 21: Issues of relying on existing classifications within IFC models of the projects

In summary, these issues in current BIM models are undesired and result in the first condition, namely **C1.1: Correctly classified BIM Models**. However, Emergo can also develop their own filter or classifier to classify every component of delivered BIM models. Yet, this seems to be more complex and error-prone due to the fact that they still rely on the quality of the BIM model. For example, if a roof element is modeled as general object, it can already be interpreted differently by Emergo's filters.

Besides the classification systems, models can also include errors that affect the cost estimations. For example, if a roof is modeled as one component or as combination of multiple sub-components can affect the cost estimations. Therefore, there should be no clashes affecting the cost estimation in the BIM model. This can be solved by a quality check of the BIM model, resulting in a need of **C1.2: Correctly modeled BIM** and the possibility to resolve issues.

Finally, there is the possibility that a certain component is not modeled in the BIM-model, which could be present in other documents. These missing components are not checked by the quality check, and do not appear in the quantity takeoff, making the component excluded from the cost estimations. Currently, Emergo states that the PDF drawings leading for the cost estimations in their agreement of the price. However, a complete BIM model is desired, resulting in **C1.3: Complete BIM model**.

Conditions for information needs, according to (ISO 19650-1)

For PreFab, 5 test projects were tested on which data was directly available. Table 6.1 until Table 6.5 reveals the tables that contain the necessary data to accomplish a PreFab cost estimation process, supplemented with two columns. The additional columns reveal if a data entry was available at at least one project or at all projects. Currently, only 22 out of the 114 data categories were available in all test projects, making it currently unlikely to completely rely on QTO's, as these barely reach complete datasets for PreFab's cost estimation process.

General Information	**Data type**	**Any**	**All**	Frame width [mm]	*<integer>*	✓	✗
Blocks in project	*<integer>*	✓	✗	Frame height [mm]	*<integer>*	✓	✗
Houses in block	*<integer>*	✓	✗	Assembly included?	*<boolean>*	✗	✗
Roof Information	**Data type**	**Any**	**All**	**Floor Information**	***Data type***	**Any**	**All**
Qv10-value in roof [(dm3/s)/m2]	*<float>*	✗	✗	Beam distance [mm]	*<integer>*	?	?
Rc-value in roof [(m2 K)/W]	*<float>*	✗	✗	Span distance [cm]	*<integer>*	?	?
Roof tiles	*List of 3x <string>*	✗	✗	Beam strength	*<string>*	?	?
Roof decking plates	*List of 3x <string>*	✓	✗	**Solar Panels Information**	***Data type***	**Any**	**All**
Optional roof decking plates	*List of 3x <string>*	✗	✗	Max power per panel [WP]	*<integer>*	✗	✗
Rafter heights [mm]	*<integer>*	✓	✗	Number of solar panels	*<integer>*	✓	✓
Roof curb present?	*<boolean>*	?	?	**Roof Window(s) Information**	***Data type***	**Any**	**All**
Gutter brackets present?	*<boolean>*	✓	✗	Window width [mm]	*<integer>*	✓	✓
Knee walls present?	*<boolean>*	✓	✓	Window length [mm]	*<integer>*	✓	✓
Wall Information	**Data type**	**Any**	**All**	Window height [mm]	*<integer>*	✓	✓
Qv10-value in roof [(dm3/s)/m2]	*<float>*	✗	✗	Roof slope [degree]	*<float>*	✓	✓
Rc-value in roof [(m2 K)/W]	*<float>*	✗	✗	U-value glass [W/(m2K)]	*<float>*	✓	✗
Sound resistance wall [dB]	*<float>*	✗	✗	Window count in block	*<integer>*	✓	✓
Fire resistance wall	*<float>*	✗	✗	**Roof Dormer(s) Information**	***Data type***	**Any**	**All**
Wall width [mm]	*<integer>*	✓	✓	Roof trim	*<string>*	✓	✓
Wall decking plates inside	*<string>*	✗	✗	Roof outside cladding	*<string>*	?	✗
Wall decking plates back	*<string>*	✓	?	Frame opening material	*<string>*	?	✗
Frame opening(s) Information	**Data type**	**Any**	**All**	Dormer decking plates	*<string>*	✗	✗
Frame type	*<string>*	✓	✗	**Roof Cladding Information**	***Data type***	**Any**	**All**
Frame count per block	*<integer>*	✓	✗	Cladding material/type	*<string>*	?	?
Frame material	*List of 2x <string>*	✓	✗	Cladding count [m]	*<float>*	?	?
Frame location	*List of 3x <string>*	✓	✗				

TABLE 6.1: Checked data in BIM models, PreFab cost estimation process phase 2

Element Information	**Data type**	**Any**	**All**	Element Width [mm]	*<integer>*	✗	✗
Element ID	*<string>*	✗	✗	Element Length [mm]	*<integer>*	✗	✗
Element Type	*List of 3x <string>*	✓	✓	Element Slope [degrees]	*<float>*	✓	✗
Element Height [mm]	*<integer>*	✗	✗	Element Count	*<integer>*	✗	✗

TABLE 6.2: Checked data during the division of elements

Construction Information	Data type	Any	All	Construction Elements	Data type	Any	All
Roof Ridge Length [mm]	*<integer>*	✓	✓	Rafter Roof Count	*<integer>*	✓	✗
Roof Angle [degrees]	*<float>*	✓	✗	Purlin Roof Count	*<integer>*	✓	✗
Distance (Knee Wall & Roof Ridge) [mm]	*<integer>*	✗	✗	Dormer Count	*<integer>*	✗	✗
Distance (Knee Wall & Roof Trusses) [mm]	*<integer>*	✗	✗	Hip Rafter Count	*<integer>*	✗	✗
				Glulam Beam Count	*<integer>*	✗	✗
				Walls Count (per height)	*<integer>*	?	?
				Floor Count (per level)	*<integer>*	?	?

TABLE 6.3: Checked data during the initial construction calculations

Base Information per element	Data type	Any	All	C.O.C. Size Roof Trusses [mm]	*<integer>*	✗	✗
Element ID	*<string>*	✗	✗	C.O.C. Size Roof Tile Battens [mm]	*<integer>*	✗	✗
Element Count in Block	*<integer>*	✗	✗	C.O.C. Size Roof Lath Battens [mm]	*<integer>*	✗	✗
Element Width [mm]	*<integer>*	✗	✗	Add/Adapt any Additional Article	*<list>*	✗	✗
Element Height [mm]	*<integer>*	✓	✓	Add/Adapt Any Additional Task	*<list>*	✗	✗
Element Compostion	*<list>*	✓	✗	**Additional Cost Information**	***Data type***	**Any**	**All**
Discount Assembly [%]	*<integer>*	✗	✗	Construction/ Engineering Costs [Euro]	*<integer>*	✗	✗
Discount Machine Hours [%]	*<integer>*	✗	✗	Distance to Project [km]	*<integer>*	✗	✗
Element Area Oblique Elements [%]	*<integer>*	✗	✗	Type of Truck	*List of 2x <string>*	✗	✗
Additional Information Per Element	***Data type***	**Any**	**All**	Number of Trucks required	*<integer>*	✗	✗

TABLE 6.4: Checked data Timber Estimation Software X calculations

Roof Window Selection Information	Data type	Any	All	Roof Anchors in Roof	*<integer>*	✗	✗
Window Brand	*List of 3x <string>*	✓	✓	Glulam Beam in Block	*<integer>*	✗	✗
Window Brand Type	*<list>*	✓	✓	Stairwell in Knee Walls	*<integer>*	✗	✗
Window Frame Opening Type	*List of 3x <string>*	✓	✓	**Cladding Information**	***Data type***	**Any**	**All**
Window Additional Costs	*<float>*	✗	✗	Cladding Material	*List of 4x <string>*	✗	✗
Dormer Selection Information	***Data type***	**Any**	**All**	Cladding Thickness [mm]	*<integer>*	✗	✗
Dormer Width [mm]	*<integer>*	✓	✗	Cladding Length [mm]	*<integer>*	✗	✗
Dormer Height [mm]	*<integer>*	✓	✓	Cladding Width [mm]	*<integer>*	✗	✗
Dormer Depth [mm]	*<integer>*	✓	✓	**Skirting Boards Information**	***Data type***	**Any**	**All**
Material Dormer Roof	*<list>*	✓	✗	Standard Houses in Block	*<integer>*	✓	✗
Material Dormer Cheeks	*<list>*	✓	✗	Cross Gable Roof in Block	*<integer>*	?	?
Material Dormer Cheeks	*<integer>*	✓	✗	Perpendicular End Unit in Block	*<integer>*	✗	✗
Assembly Information	***Data type***	**Any**	**All**	**Glulam Beam Information**	***Data type***	**Any**	**All**
Number of Houses in Block	*<integer>*	✓	✗	Building Wall Type	*List of 2x <string>*	?	?
Height of Roof [mm]	*<integer>*	✓	✓	Glulam Beam Count in Block	*<integer>*	✗	✗
Number of Trucks required	*<integer>*	✗	✗	Length of Glulam Beam [mm]	*<integer>*	✗	✗
Floor Levels per Element	*<integer>*	✗	✗	**Solar Panels Information**	***Data type***	**Any**	**All**
Type of Roof	*<list>*	✓	✗	Solar Panel Row Count in Solar Panel Field	*<integer>*	✓	✓
Valley Rafter Included	*<boolean>*	✗	✗	Solar Panel Row Count in Solar Panel Field	*<integer>*	✓	✓
Hip Rafter Included	*<boolean>*	✗	✗	House Count in Block	*<integer>*	✓	✗
Roof Gutters Length [m]	*<float>*	✓	✓	Window Count in House	*<integer>*	✓	✓
Elements in House	*<integer>*	✗	✗	Less Panel Count in Solar Panel Field	*<integer>*	✗	✗

TABLE 6.5: Necessary data Excel calculations

Frequently, available data felt under the category of geometric values, such as height, width and thicknesses for components, such as windows. For the roof element, the geometric values were present and could be successfully extracted. Quantities and geometric shapes of the main components were present, such as walls and roof components. However, smaller components were sometimes modeled in a generic way, lacking exact quantities. For example, the F-brackets were modeled generically, making it impossible to quantify these brackets.

On the other hand, these BIM objects were often insufficient developed in terms of information. On occasion, some semantics were utilisable, such as the window brand, u-value for windows, type of roof, dormer material and the type of F-brackets. Still, necessary semantics were often missing, such as the physical attributes ([Qv-value, Rc-value]) for roof elements. In general, information development of these elements were considered insufficient.

Additionally, the level of detail was insufficient as well. Material composition, finishing materials and technical or construction elements were missing or incomplete. For example, the F-brackets were modelled in a generic way, lacking details on number of F-brackets and type of

F-brackets, necessary for constructability issues. Additionally, specific roof finishing materials were not present in the BIM model, such as roof cladding or frame opening materials.

In summary, the current state of BIM models must be developed in terms of completeness, geometry and semantic information. If you examine this the data from Table 6.1 until Table 6.5, BIM models must be developed at fabrication level, aligning with at least LOD 400[2] while currently, the tested BIM models were developed at LOD 200/300. Figure 3 shows the differences per LOD in an illustration. As seen in the tables, crucial information is lacking. First of all, in terms of completeness, all components have to be modeled, including the smaller and technical components. Secondly, a few geometric values were generic or missing, necessitating improvement for geometric development. And lastly, semantic information per component has to be developed, such as physical information of type of materials. Several conditions are necessary that results in the necessary information for Emergo's cost estimation process. In fact, Emergo can exploit the framework of LOIN, included in ISO 19650-1. This lead to three additional conditions for for the information delivery by the client, namely **C2.1: Complete geometric information**, **C2.2: Complete alphanumerical information** and **C2.3: Presence of all documents in the right format**. In fact, these conditions stand for a full development of the data that is currently missing, revealed in Table 6.1 until Table 6.5.

Conditions for information takeoff's procedures

Emergo needs a standardised flow of information, that realise the required information needs in a correct way as well as the processing of the data that realises the cost estimations. First of all, conditions on the quality and completeness of the information are dervied, resulting in multiple conditions. Secondly, conditions have to be derived that ensure that data is automatically processed after the information takeoff.

To start, a standardised model checker has to be developed, checking if the models are indeed correct and complete. Secondly, a quantity takeoff definition has to be developed, ensuring that only the necessary components and data is extracted out of the model. Finally, the raw data has to be readable by cost estimation systems from Emergo, requiring a data processor to translate raw excel data into objects and cost items in terms of Emergo, as shown in Figure 20 as an example. **C1.1** and **C1.2**, can be resolved by a model checker, which reveals errors in the BIM-model and provides the possibility to improve the BIM-model. Still, correct quality and classifications is desired immediately, yet a method should be included that checks the model, highlighting potential issues to the user. **C3.1: A check for classification issues** and **C3.2: A check for quality of the BIM** should be realised to deal with potential issues.

Secondly, LOIN (ISO 19650-1) has to be maintained within the BIM models, which is achievable in cooperation with the client. However, Emergo can establish a document that expresses the information requirements. In order to make it entirely reliable on automatic procedures, the data that is displayed in Table 3.1 until Table 3.5 need to be implemented. Not every data can be implemented within a BIM model, such as the division of timber-framed elements, their names and transportation costs Emergo is taking into account. However, some can be derived in an indirect manner if all the other data entries are consistent and included. In conclusion, Emergo should realise a standard information requirement document that results in the necessary information to conduct a cost estimation, incorporated within Table 3.1 until Table 3.5). This results in the following condition: **C3.3: Establish an information requirement document, according to LOIN**

[2] Level of Development (LOD), originally founded by AIA and adopted by BIMForum

(ISO 19650-1).

Finally, there are the conditions that realise the data processing capability. **C3.4: Standard ITO definitions** has to ensure that the desired data is extracted out of the BIM model. Secondly, data can be expored into a .xlsx or .csv file, which can be imported in Excel or in the ERP system. Hence, **C3.5: Raw data processing algorithms in cost estimation software** are necessary to translate varying data input into Emergo's terms and products. Consequently, Emergo have to achieve standard components and costs items in which the raw data can be translated to, resulting in **C3.6: Standardised and complete component library in cost estimation model** and **C3.7: Complete cost items in cost estimation models** are the final conditions to exploit this scenario.

6.1.3 Process changes and value

Implementing this scenario in the process structures of Emergo's cost estimation process brings several changes and enhancements. Figure 22 reveals these changes.

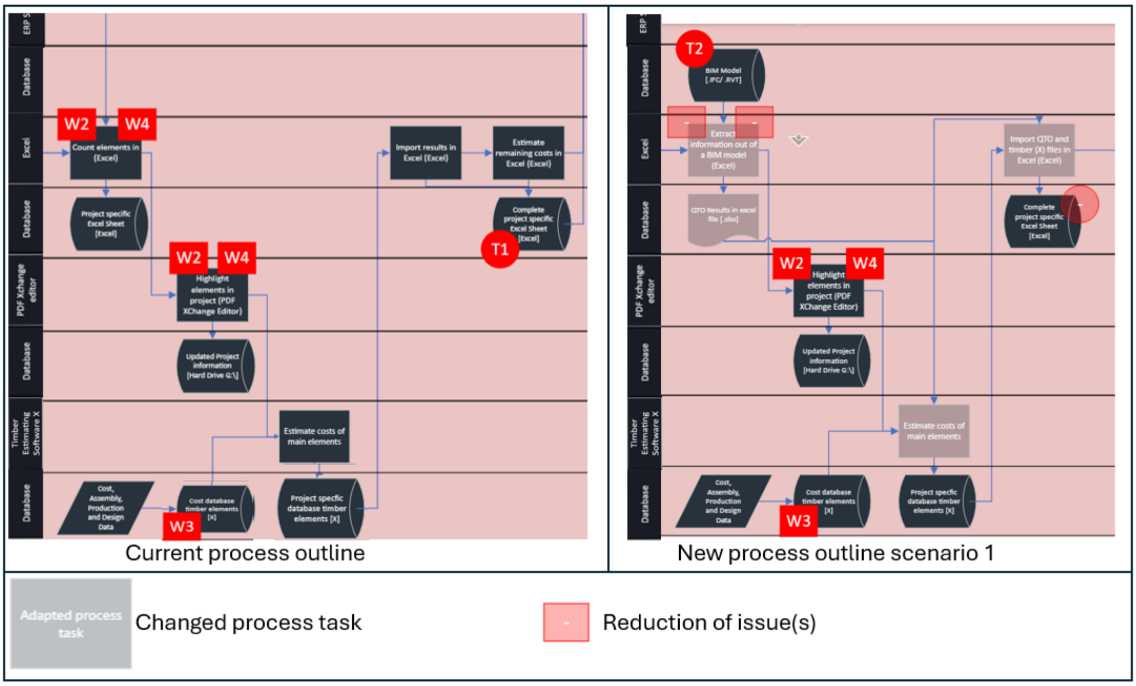


FIGURE 22: Old process outline vs. new process outline, PreFab scenario 1

Implementing this scenario in Emergo's cost estimation process brings several changes and enhancements, as depicted in Figure 22. Instead of manual counting, measurements, and estimations, the process relies on automatic information extraction from the BIM model as its cornerstone. Thus, elements, or information from elements, are automatically measured and quantified, resulting in the value of **Automatic measurements** and **Automatic quantification**. Initially, information within the BIM model is extracted, potentially aiding in element division or timber-framed calculations in Timber estimation software X. However, while this scenario streamlines certain tasks, it cannot fully replace them on its own. Subsequently, the results from the QTO and Timber estimation software X are imported into Excel for cost estimation. This automation reduces the reliance on manual processes, Thereby enhancing **Accuracy** and it makes the process **Potentially faster**.

6.1.4 Summary of scenario

In summary, the resulting value the cost estimation process obtains through implementation of scenario 1, and the conditions a proper working of the scenario can be found in Table 6.6.

Conditions	Value
C1.1: Correctly classified BIM Models	**Automatic measurements**
C1.2: Correctly modeled BIM	**Automatic quantification**
C1.3: Complete BIM model	**Accuracy**
C2.1: Complete geometric information	**Potentially faster**
C2.2: Complete alphanumerical information	
C2.3: Presence of all documents in the right format	
C3.1: A check for classification issues	
C3.2: A check for quality of the BIM	
C3.3: Establish an information requirement document, according to LOIN (ISO 19650-1)	
C3.4: Standard ITO definitions	
C3.5: Raw data processing algorithms in cost estimation software	
C3.6: Standardised and complete component library in cost estimation model	
C3.7: Complete cost items in cost estimation models	

TABLE 6.6: Value and conditions that Scenario 1 entails

The major risk of this method is the components that are not modeled in the building information model, as this method completely relies on this model. In other words, components that are not modeled are not taken into account. Currently, Emergo is dealing with a similar situation where the cost estimator relies on the 2D drawings in PDF. This is also noticed in the quote and during the acceptance of the quote. Similarly, this has to be included when this method is implemented.

6.2 PreFab 2: Parametric roof modeler

The second scenario addresses automatic generation of roof models and elements, divided among two sub-scenarios. subsection 6.2.1 details how the scenarios operate within Emergo, subsection 6.2.2 outlines the necessary conditions, subsection 6.2.3 discusses the required process changes and potential value of the scenarios, and subsection 6.2.4 concludes by summarising the conditions and values.

6.2.1 Working in context of Emergo

Varying data input and quality via client responsibility and thus dependability are threats for conducting PreFab cost estimations. A solution could be to generate data through the automatic modeling ofroof models. In this way, Emergo is control of deriving BIM models and reduces the dependency on the information delivered by the client. Or, this scenario can be implemented whenever there is no BIM model at all, necessitating the generation of BIM models. As not all object can be automatically modeled, the decision has been made to focus on the timber-framed roof, and it's automatic division into elements. Dividing the roof into sub-elements is time-consuming, manually and error-prone and leads to the task of measuring each specific element. Parametric modelling could be implemented to handle the division of elements automatically.

This scenario can be organised into to sub-scenarios, namely modeling from scratch or modeling with a BIM model as an input. *scenario 2(a)* focuses on a start from scratch, where a roof is completely generated by using input parameters. On the other hand, *scenario 2(b)* uses the existing BIM model, extracts the outline of the roof and creates an overlay to derive new roof elements. Scenario a is derived as proof of concept while scenario b is described in theory, due to a lack of time. The scenarios are derived in general context, as it should be applicable for every roof, and thus every project at PreFab.

Thus, this scenario has unraveled itself into two sub-scenarios, shown in Figure 23. The two scenarios distinguish themselves by various input methods, which must be supported by different scripts. The aim and the result are similar. *scenario (a)* uses measured input parameters and starts building a model from scratch while *scenario (b)* creates an overlay of the roof from an existing BIM model.

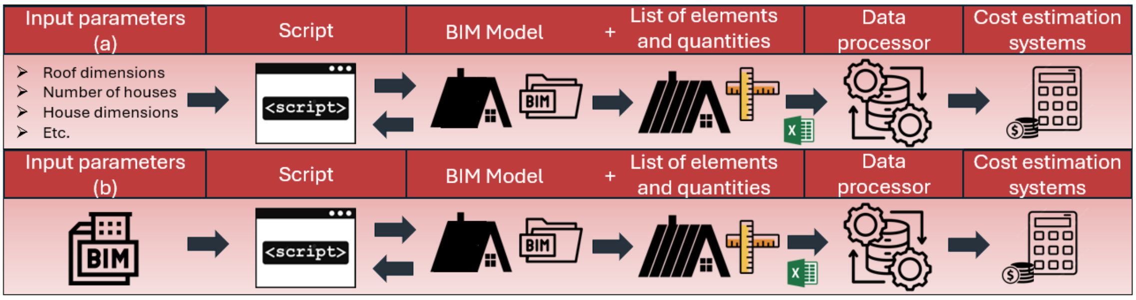


FIGURE 23: Scheme of the working of scenario 2 for PreFab

Step 1: Decide on input parameters

Obviously, the parametric modeler must have some standardised input parameters for generating roof models. These must not be too extensive, as this will only take more time and will eliminate the purpose of the modeler, namely saving time and automating tasks. for *scenario 2(a)*. The data that needs to be collected and filled in by the cost estimator is as following:

- 1) Number of houses
- 2) Width of houses in between [mm]
- 2) Width of houses on the corners [mm]
- 4) Roof depth [mm]
- 4) Roof element height [mm]
- 4) Relative height of the start of the roof [mm]
- 4) Roof type
- 5) Are knee walls present?
- 5) If yes; height of knee walls [mm]
- 5) If yes; Type of knee walls

In contrary to scenario a, *scenario 2(b)* uses an existing BIM model as input. More specifically, the geometry and outline of the roof elements. Yet, the entire BIM model is taken as input the modeler must filter out the roof element(s) automatically. An example of a BIM model in can be found in scenario 1, specifically in Figure 16.

Step 2: Develop Dynamo script that determines the outline of roof elements

For *scenario 2(a)*, a Dynamo script has been created to simulate and proof the concept this scenario, whereas deriving the entire scenario would be too time-consuming for the scope of this research. The script is able to translate the determined input parameters into the desired roof model.

In this proof of concept, A BIM model consisting of the base of the roof and the knee walls are generated, where each component type consists of multiple elements. In reality, roof elements are also divided among the intersections of houses. Therefore, roof components are divided into elements that each cover one house. Additionally, the houses on the edge vary in size from the houses that are in between, which is modeled as well. Obviously, Prefabricated roofs can vary in size and shape that is beyond the possibilities that can be generated with this script. Yet, this roof generator proves the concepts as it is able to generate a 3D model that consists of roof and wall components, that divides these building components into a desired number of elements and that supplements the elements into correct relative coordinates.

For *scenario 2(b)*, a similar script can be created as well. However, instead of input parameters that have to be manually provided by the cost estimator, the script must be able to read an IFC model. In Dynamo this is possible, and the script can also extract desired roof elements from the BIM model as well. A possible workflow of such a script can be as follow:

1. Create a Dynamo node that allows you to select a file from your hard drive
2. Create a script that extracts the roof element(s) from the BIM model
3. Translate the roof elements into points, polygons, or polysurfaces containing coordinates
4. Create new roof elements based on these extracted points in your coordinate system, which can be adapted

Step 3: Develop object library and add this to the script

This step is similar for *scenario 2(a)* and *(b)* and is necessary to translate roof elements into Emergo's standard material compositions. Within Revit, an object family can be created, which is aligned with **(17) Develop component library** since this considers standard type of elements or materials. Emergo can create a library with their standard material compositions for timber-framed construction elements. Subsequently, the cost estimator can select these element types for the generation of the model. Currently, the proof of concept is limited to the generic roof types to cover **(17) Develop component library**. Figure 24 reveals that material compositions can be included as input to determine the material of the generated roof elements. Yet, Emergo does not have a Revit family containing their standard material compositions for PreFab, which results in the need to implement standard revit roof compositions into the script.

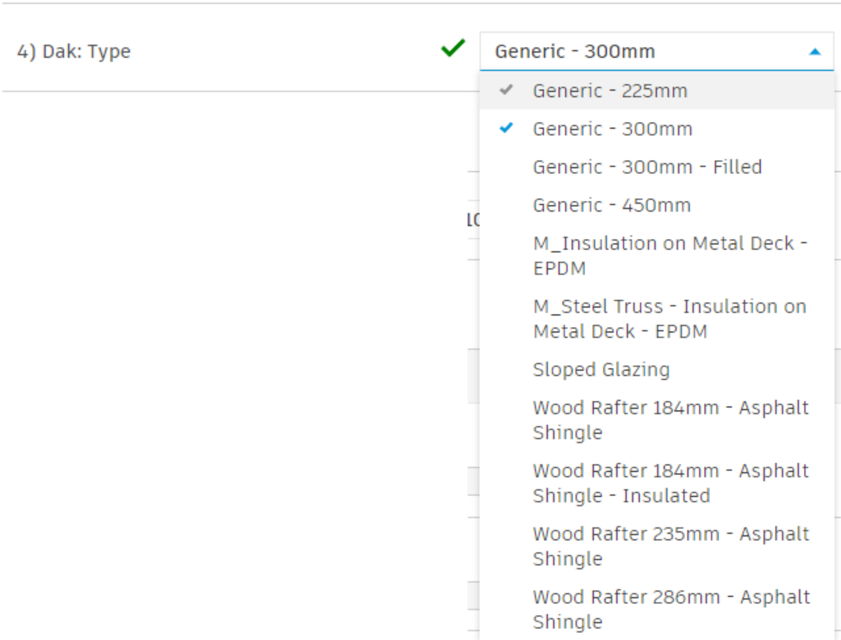


FIGURE 24: Including roof material compositions into the Dynamo script

Step 5: Connect dynamo script to dynamo player

Again, this step is similar for *scenario 2(a)* and *(b)*. Figure 56 under Appendix D reveals the Dynamo script that is created to generate roof models for *scenario 2(a)*. In this script, input and output nodes are tagged, which is necessary to reveal them in the Dynamo player. The Dynamo player can eventually be opened in any new Revit project, allowing the users to exploit the script without seeing the entire background process.

If all input parameters are defined, the cost estimator can press run and the model is generated, which can be viewed in cross-sectional elevations or in 3D. Furthermore, the cost estimator can examine dimensions of each element such as a specific area of a roof element, the slope of the roof or the length of knee walls. Figure 25 and Figure 26 highlight two examples of generated roof models. The first example considers a steep roof for 3 houses, where the middle house is relative smaller than the other two, without considering knee walls. The second example contains a roof that is more flat, for 5 houses, where the houses on the edge vary in size, including knee walls. Moreover, a different roof type has been selected for both test projects.

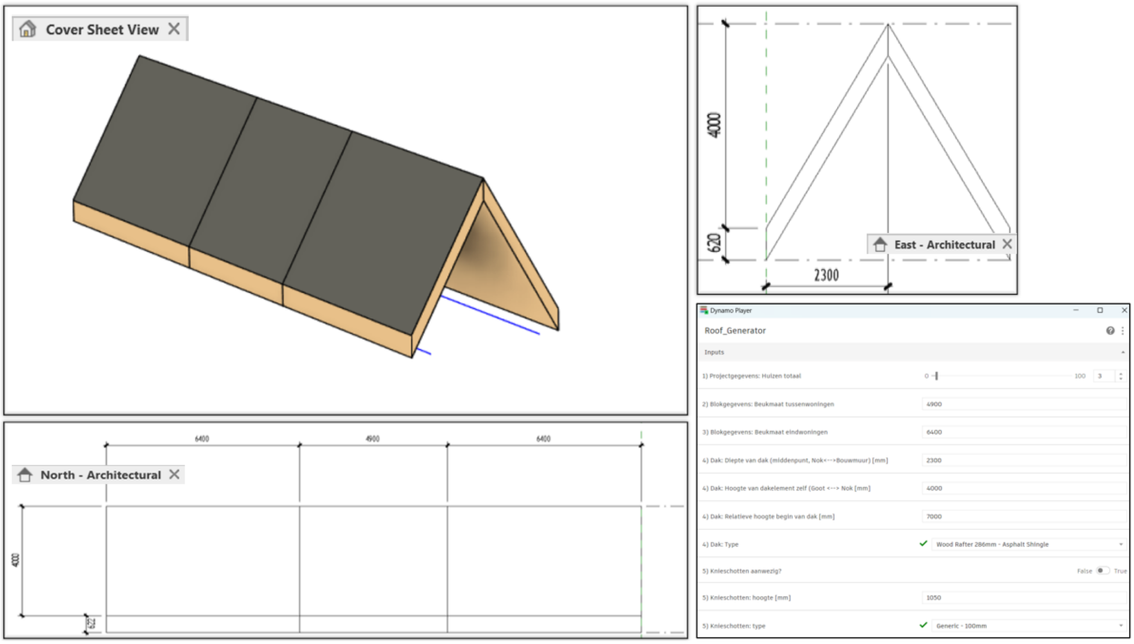


FIGURE 25: Generating a BIM model, example 1

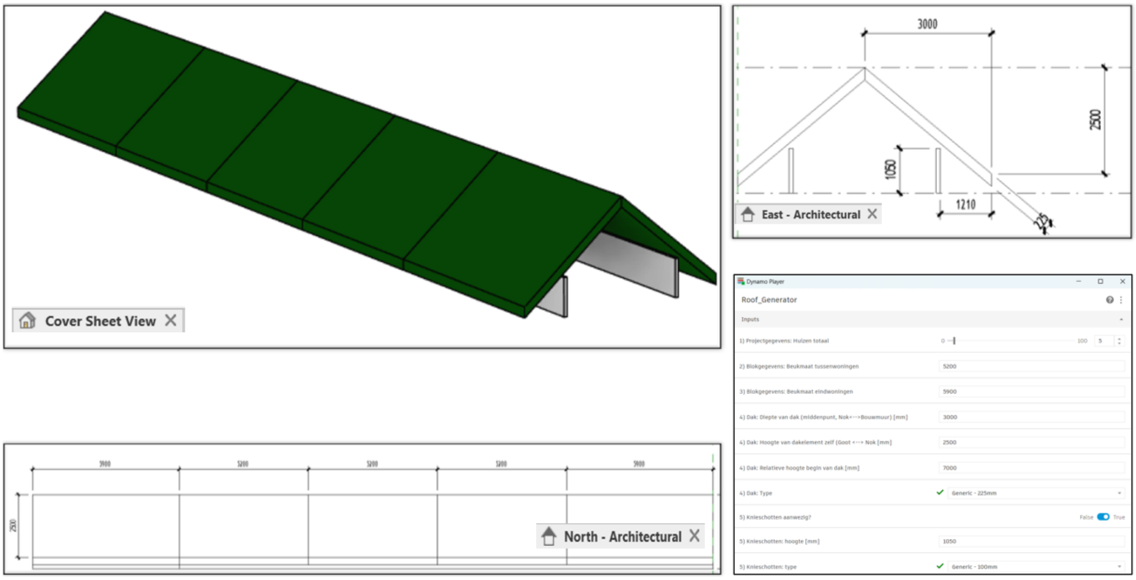


FIGURE 26: Generating a BIM model, example 2

Step 6: Utilise model by extracting data

Simultaneously, this step is equal for both sub-scenarios, which is to translate the model into data. The cost estimator can extract data out of the generated model. In fact, utilising similar methods from **(6) PreFab Scenario 1: BIM Quantity TakeOff**, explained in section 6.1, the translation from BIM model to cost estimations can be done automatically. Corresponding elements are grouped and dimensions are automatically extracted out of the 3D model. In this case, there is no need to define filters or check the quality model as the model is created on behalf of Emergo, specifically for cost estimation purposes. Therefore, BIM use **(6) Quantity Exports** is sufficient, providing a quantity bill containing all elements, their geometric values and their quantities. Extracting data can also be done within the environment of Revit, which also supports the Dynamo script, making the additional usage of software and system exchanges minimal.

Step 7: Automate data imports in cost estimation systems

The final step is similar for both scenarios, which translated the raw data into cost estimation terms of Emergo. The raw data is processed and translated into itemst that are used in the cost estimation systems of Emergo, Excel and/ or ERP. Figure 6.1.1 reveals such a transmission and is similar for this scenario. The processing scheme is similar, however, the type of elements are different. Figure 27 reveals an example of data from the generated roof that can be exported from Revit into cost estimation systems. Data can be processed via a similar method as shown in Figure 20.

<Roof Schedule>

A	B	C	D
Family and Type	Thickness	Area	Count
Basic Roof: Generic - 225mm	225	26 m²	14
Basic Roof: Generic - 225mm	225	30 m²	4

FIGURE 27: Exportable results from the generated roof

6.2.2 Conditions

In order to make exploit the use of parametric modeling, several conditions has to be fulfilled. Since Emergo has more control of deriving the roof model, conditions on input variables are less strict, compared to the first scenario. The conditions differ between the two sub-scenarios, *scenario 2(a)* and *(b)*, especially in terms of information needs. The following category of conditions are identified: *Conditions for information needs, according to (ISO 19650-1)*, *Dynamo script conditions to generate roof models*, *Revit conditions to generate roof elements* and *Conditions for information takeoff's procedures*. On top of that, *Quality conditions for BIM model* is necessary for *scenario 2(b)*. Explicit conditions are derived under the categories below, where all conditions for the scenarios are summarised in Table 7.1.

Scenario a: conditions for information needs, according to (ISO 19650-1)

All the input parameters must be available in the delivered documents by the client. The form of the data is not strictly defined, since the input parameters can be provided in tabular form or the information can be incorporated in the 2D drawings of the project. Hence, this scenario does not require a BIM model. Still, the data must be available in one way or another, leading to the condition: **C2.1: Complete geometric information, C2.2: Complete alphanumerical information** and **C2.3: Presence of all documents in the right format** must be again available for this method.

For the proof of concept, this would mean that data in Figure 6.2.1 must be available. If the scenario is expanded to more complex roof's, including more component's such as frame openings, more data is required. Then, the dimensions of the frame openings are required. In conclusion, in the examined projects, all data is usually delivered and present, meeting the information needs of this scenario.

Scenario b: conditions for information needs, according to (ISO 19650-1) & Quality conditions for BIM model

The second scenario requires a BIM model with a correctly modeled roof component. The crucial characteristic of the BIM models are the geometric development. The roof and the division of elements is based on an overlay of the existing roof in the BIM model, requiring correctly modeled roof elements. Currently, in the checked BIM models, this is already achieved, meaning that the geometric development of the BIM models is sufficient. No technical details are thus necessary, aliging with a BIM model that is developed at at least LOD 300 [3], where the exact geometry is known, as shown in Figure 3. However, not every project included a BIM model. Hence, in order to exploit the benefits of this scenario, each project must contain a BIM model, where the roof element is modeled correctly. This development resulted in the conditions of **C1.2: Correctly modeled BIM**, **C1.3 Complete BIM model** and **C2.1 Complete geometric information**.

Secondly, semantic information is currently insufficient developed within BIM models for this scenario. Yet, it does not have to be incorporated in the BIM model. Semantic information that leads to the roof type can also be included in technical documents, as long it is present. Currently all necessary data is incorporated into technical documents of the project, which is sufficient for this scenario. The roof types are namely modeled in the roof generator, which only requires the geometric shapes of the roof element. Still, information has to be present in other documents to derive a roof type, resulting in the conditions **C2.2: Complete alphanumerical information** and **C2.3: Presence of all documents in the right format**.

Thus, the information has to be present in one of the documents, and not necessarily in the BIM model. **C3.3 Establish an information requirement document, according to LOIN (ISO 19650-1)** should be taken into account as well, ensuring information needs for the roof are present. This specifies the required semantic information, and emphasises the presence of the data.

In conclusion, for *scenario 2(b)* Emergo necessitates a BIM model with correct geometric information for roof elements. Currently, the geometric information of roof elements is sufficient, but the occurrence of a BIM model must be ensured and developed.

Scenario a and b: Dynamo script must be available and working

Obviously, this condition corresponds to the entire working of the parametric modeler. The dynamo script must be complete, working and available for varying approved input parameters. A prototype of such a script is derived for the proof of concept, shown in Figure 56. A complete working of the scenario would require a significant larger and complete script. **C4.1: Dynamo script must result in roof elements** corresponds to the condition that the script must accept varying input and delivers output of high quality. The script is complete if it successfully provides the roof model including the division of elements. Moreover, textbfC4.2: Dynamo script provide an error log should be included as well, resulting in explanation of issues, if issues occur. Furthermore, cost estimator's are now using Revit, requiring minimal revit skills by the cost employee. Hence, **C5.1: Revit skills by cost estimator** is included.

[3] Level of Development (LOD), originally founded by AIA and adopted by BIMForum

Scenario a and b: Revit conditions to generate roof elements

The script must achieve multiple aspects to realise a scenario that is contributing to enhancements of the cost estimation processes. One of these aspects is that the script has access to Emergo's standard material compositions as family type. In this way, the roof components can be modeled according to Emergo's specifications. Therefore, the following condition is taken into account: **C5.2: A Revit family must be accessible, containing Emergo's standard roof types**. Secondly, Emergo contains a high level of expertise when it comes to roof elements. Frequently, Emergo adapts technical details that are initially derived by the client according to their own solutions. Hence, a cost employee must be able to adapt the technical details based on the derived roof elements, resulting in **C5.3 Derive or adapt technical details based on the generated roof model**.

Scenario a and b: Conditions for information takeoff's procedures

The results of the generated roof must be available for automated exchanges between various systems. For example, the results shown in Figure 27 must be able to be imported in Excel or in the ERP via a .xlsx file, which can be automatically read by the cost estimation systems, resulting in **C3.5 Raw data processing algorithms** and **C3.7: Complete cost items in cost estimation models** as a condition for this scenario.

6.2.3 Process changes and value

The process changes resulting from the implementation of the scenarios are outlined in Figure 28. Leveraging a parametric modeler in both scenarios facilitates rapid generation of 3D models and cost estimation data. Furthermore, an **Automatic division of elements** reduces the time required for PreFab's cost estimation process, potentially making it **Potentially faster**. Instead of manually dividing the roof into elements, this task is automated via a dynamo script, making the cost estimation process **Less error-prone**. Consequently, the generation of roof elements within Revit can be exported seamlessly for **Automatic quantification**, streamlining the process. Additionally, early access to the roof model enables its use for **Exploiting other BIM uses (construction analysis)**, expanding the utility of BIM beyond cost estimation. Integration with Timber Modeling Software A further enhances data sharing between departments within Emergo, resulting in **Timber Modeling Software A integration**.

In *scenario 2(b)*, reliance on a BIM model as input eliminates the need for manual measurements, a significant advantage. However, *scenario 2(a)* offers flexibility and independence from BIM models, empowering Emergo. Therefore, while *scenario 2(b)* ensures **No manual measurements are required**, *scenario 2(a)* boasts the benefit of being **Independent of BIM models**.

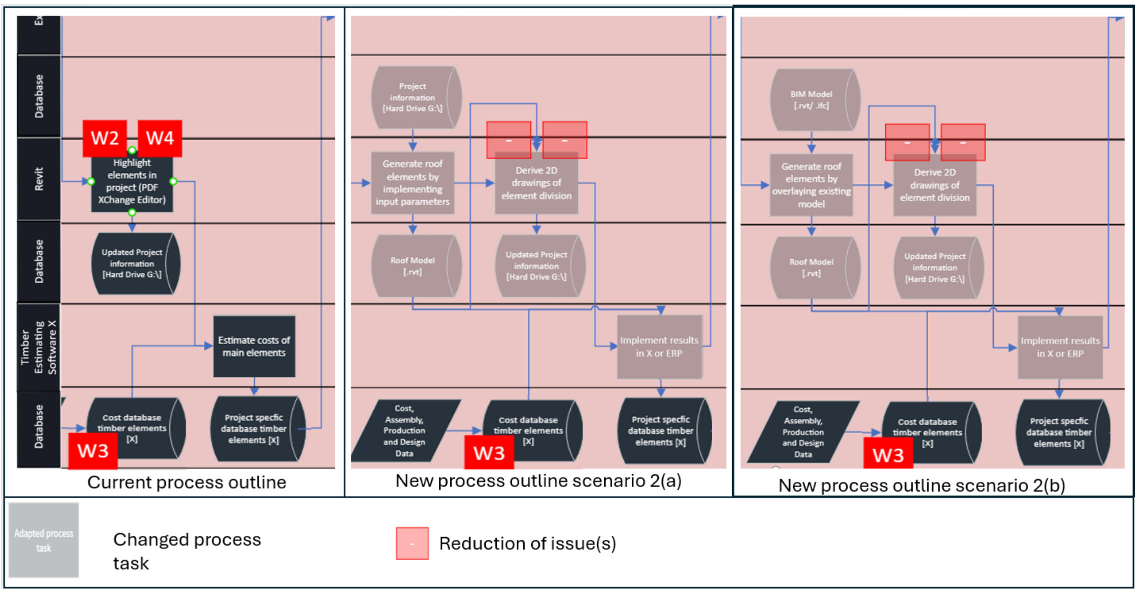


FIGURE 28: Old process outline vs. new process outline, PreFab scenario 2 (a) and (b)

Through both scenarios, roof elements can be generated. This corresponds to generating 18 data entries (see Table 6.7, and Table 6.8) that are necessary for the cost estimation process, centered around the cost estimations of the timber-framed construction elements. In fact, these elements are the core of PreFab's projects, covering the majority of the cost estimations. Moreover, the division of elements is considered to be one of the most time-consuming tasks of Emergo's current cost estimation process. Part of these data entries should be pre-modeled, namely the standard element compositions, which can be stored within a Revit family.

Element Information	Data type	Generated?	Element Width [mm]	*<integer>*	✓
Element ID	*<string>*	✓	Element Length [mm]	*<integer>*	✓
Element Type	*List of 3x <string>*	✓	Element Slope [degrees]	*<float>*	✓
Element Height [mm]	*<integer>*	✓	Element Count	*<integer>*	✓

TABLE 6.7: Generated data during the division of elements

Base Information per element	Data type	Generated?	C.O.C. Size Roof Trusses [mm]	*<integer>*	✓
Element ID	*<string>*	✓	C.O.C. Size Roof Tile Battens [mm]	*<integer>*	✓
Element Count in Block	*<integer>*	✓	C.O.C. Size Roof Lath Battens [mm]	*<integer>*	✓
Element Width [mm]	*<integer>*	✓	Add/Adapt any Additional Article	*<list>*	✗
Element Height [mm]	*<integer>*	✓	Add/Adapt Any Additional Task	*<list>*	✗
Element Compostion	*<list>*	✓	**Additional Cost Information**	***Data type***	**Generated?**
Discount Assembly [%]	*<integer>*	✗	Construction/ Engineering Costs [Euro]	*<integer>*	✓
Discount Machine Hours [%]	*<integer>*	✗	Distance to Project [km]	*<integer>*	✗
Element Area Oblique Elements [%]	*<integer>*	✓	Type of Truck	*List of 2x <string>*	✓
Additional Information Per Element	***Data type***	**Generated?**	Number of Trucks required	*<integer>*	✓

TABLE 6.8: Generated data Timber Estimation Software X

6.2.4 Summary of scenarios

In conclusion, *scenario 2(a)* and *scenario 2(b)* can generate elements based on a dynamo script, the parametric modeler. This task is considered to be one of the most time-consuming and error-prone task of PreFab's cost estimation process. The summary of conditions for both scenarios can be found in Table 6.9 and Table 6.10. *scenario 2(b)* has additional conditions compared to *scenario 2(a)*, yet scenario (b) has additional value due to the fact that no manual measurements are necessary.

Conditions	Value
C2.1: Complete geometric information	**Automatic division of elements**
C2.2: Complete alphanumerical information	**Automatic quantification**
C2.3: Presence of all documents in the right format	**Less error-prone**
C3.5: Raw data processing algorithms	**Potentially faster**
C3.7: Complete cost items in cost estimation models	**Exploit other BIM uses (construction analysis)**
C4.1: Dynamo script must result in roof elements	**Timber Modeling Software A integration**
C4.2: Dynamo script provide an error log	**Independent of BIM models**
C5.1: Revit skills by cost estimator	
C5.2: A Revit family must be accessible, containing Emergo's standard roof types	
C5.3: Derive or adapt technical details based on the generated roof model	

TABLE 6.9: Value and conditions that Scenario 2(a) entails

Conditions	Value
C1.2: Correctly modeled BIM	**Automatic division of elements**
C1.3: Complete BIM model	**Automatic quantification**
C2.1: Complete geometric information	**Less error-prone**
C2.2: Complete alphanumerical information	**Potentially faster**
C2.3: Presence of all documents in the right format	**Exploit other BIM uses (construction analysis)**
C3.3: Establish an information requirement document, according to LOIN (ISO 19650-1	**Timber Modeling Software A integration**
C3.5: Raw data processing algorithms	**No manual measurements required**
C3.7: Complete cost items in cost estimation models	
C4.1: Dynamo script must result in roof elements	
C4.2: Dynamo script provide an error log	
C5.1: Revit skills by cost estimator	
C5.2: A Revit family must be accessible, containing Emergo's standard roof types	
C5.3: Derive or adapt technical details based on the generated roof model	

TABLE 6.10: Value and conditions that Scenario 2(b) entails

6.3 PreModu 1: Information Takeoffs

Initially intended for project-dependent data, this scenario has evolved to encompass complete cost estimations. Consequently, it is divided into *Scenario 1A*, focusing on project-specific quantification, and *Scenario 1B*, which entails comprehensive information takeoffs.

In *Scenario 1A*, information takeoffs are employed for flexible and project-specific data, such as facade finishing and roof tile types, listed under Project-Specific Information in Table 3.6. These data entries are currently manually measured, while other elements in the cost estimation process remain calculated in the traditional manner. *Scenario 1B* goes beyond project-specific information, extracting all necessary data from the BIM model for automated cost estimations. This eliminates the need to manually select options in the cost estimation model for each house, as all data listed in Table 3.6 is derived from the BIM model.

subsection 6.3.1 details the operational workflow within Emergo, subsection 6.3.2 outlines the necessary conditions per scenario, subsection 6.3.3 discusses required process changes and potential values of the scenarios, and subsection 6.3.4 concludes by summarizing the conditions and values and comparing Solibri and Revit

6.3.1 Working in context of Emergo

Figure 29 reveals the scheme of the working of the first scenario of PreModu, which is similar for *Scenario 1A* and *Scenario 1B*, yet on another degree. *Scenario 1B* completely relies on this scheme while *Scenario 1A* focuses on the project-dependent parameters only.

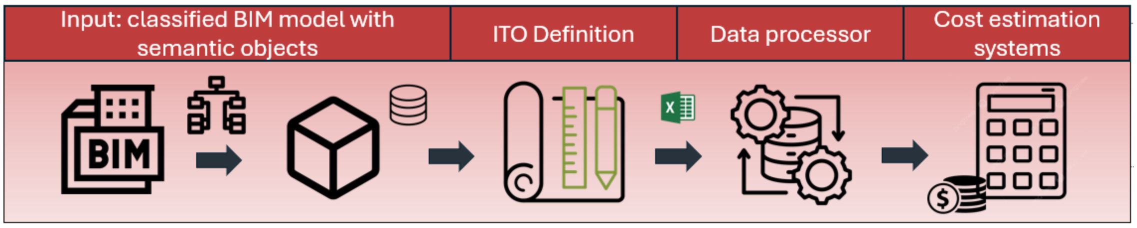


FIGURE 29: Scheme of the working of scenario 1 for PreModu

There are multiple software to conduct quantity takeoff's, among others Solibri and Revit. Both these software are utilised and compared during the test of this scenario, which are tested for one PreModu project. One test project is considered to be sufficient since one can assume that each PreModu project is modeled in a similar way. In contrary, PreFab projects are dealing with different clients, architects and BIM modelers, resulting in different modeling frameworks. The scenario is tested for the project-dependent elements, which can be seen as a proof of concept for an entire working and reliance on ITO's for PreModu

Step 1: opening the BIM model

Cost estimators at Emergo can access both the Revit Model and the IFC model of the project, allowing them to conduct quantity takeoffs within Revit or Solibri. The key distinction between the two is that Solibri automatically assigns bounding boxes when an IFC model is opened, while in Revit, this process requires manual derivation of bounding boxes or the creation of a Dynamo script. Bounding boxes are essential in this context because the roof elements lack element dimensions like length and width, making it impossible to determine or extract the area of each element. By employing bounding boxes, the gross area of each element can be determined, which is crucial for estimating the cost of roof tiles. Consequently, Solibri is preferred for quantity exports, although an example illustrating the process within Revit is provided. Figure 30 presents the project in both environments, with the Revit file displaying the entire project and Solibri revealing only one block.

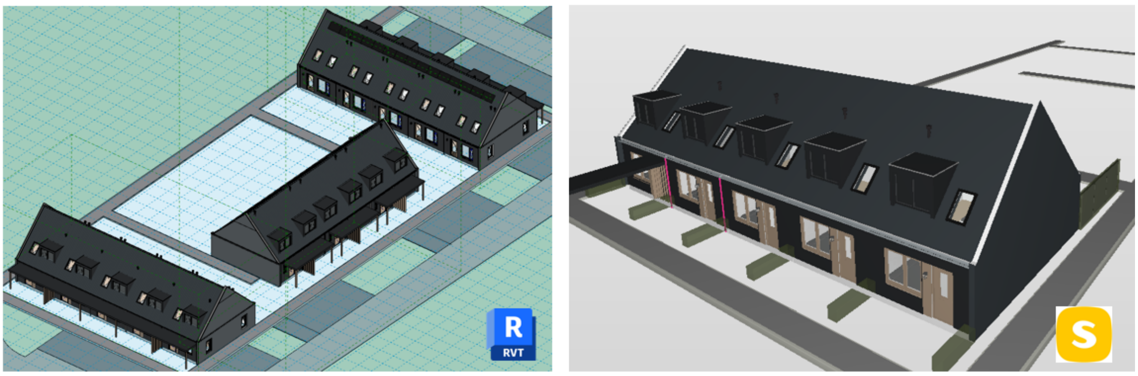


FIGURE 30: IFC Models within Revit and Solibri

Step 2: Filter on project-dependent components

To start, the desired elements need to be filtered out. In Solibri this can be done simultaneously while in Revit each element type needs to be filtered out individually. Both filters can be saved and used across multiple projects. Hence, the filter and specifications needs to be established once as it is project-exceeding. A filter that selects the elements based on element family and type has been chosen (Figure 31), filtering roof and wall elements that are from a specific type, such as *steenstrips*, which is a facade finishing type.

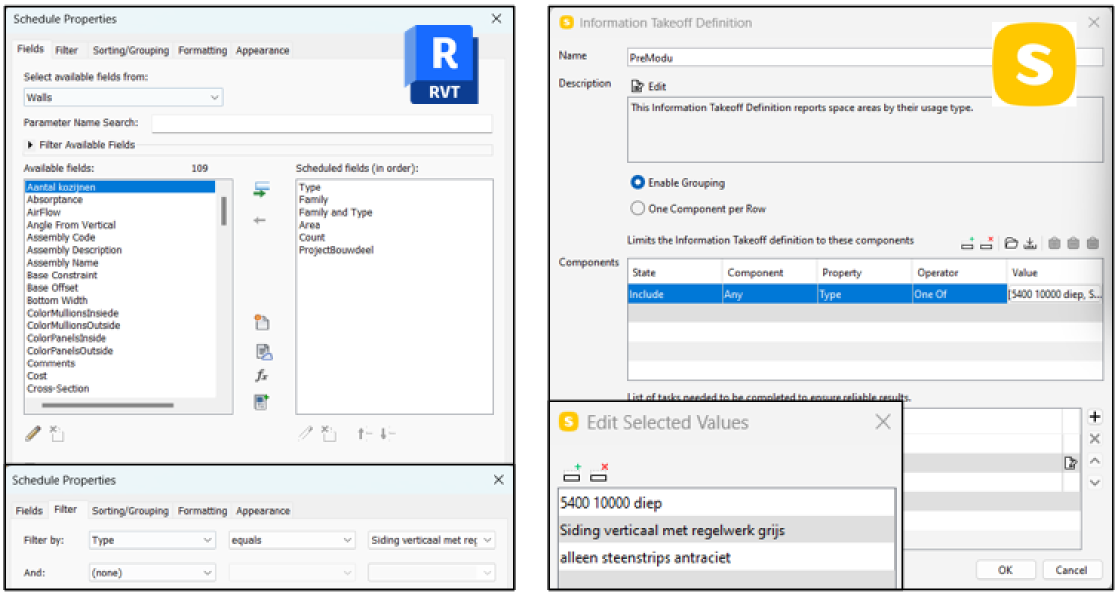


FIGURE 31: Schedule or Takeoff filters within Revit and Solibri, respectively

Step 3: Sort the extracted information

Eventually, all filtered items are either listed in tabular form and in Solibri even highlighted in the IFC model. After the filter has been applied, one can adapt the table to achieve the desired format. For example, the total area of each material can be shown or elements can be grouped based on similar area's, including the frequency of occurrence. Since Emergo's cost estimation model treats every house separately, the result of the takeoff requires separated elements or grouped similar elements, which can be applied in the filter preferences. On the other hand, the total material per block or per project can be established as well, minimising the need to add up all individual values. The results of both takeoffs in the software itself are shown in Figure 32.

Step 4: Import and process data into cost estimation systems

These results can obviously be imported within the Excel cost estimation system through a excel file, utilising BIM use **(18) Linking and Extending**. In Excel, a separate sheet can be crafted that is able to handle and process the results autonomously, where results are automatically are connected to the right cost item. This requires a complete cost model and library, which is then supplemented in order to match the results from the takeoff's, aligned with BIM use **(16) Develop cost library**. On the other side, Solibri's information takeoff provides a high level of visibility and overview, compared to Revit. Therefore, one is also able to select certain elements and immediately see the necessary values, making it possible to quickly provide the values per house.

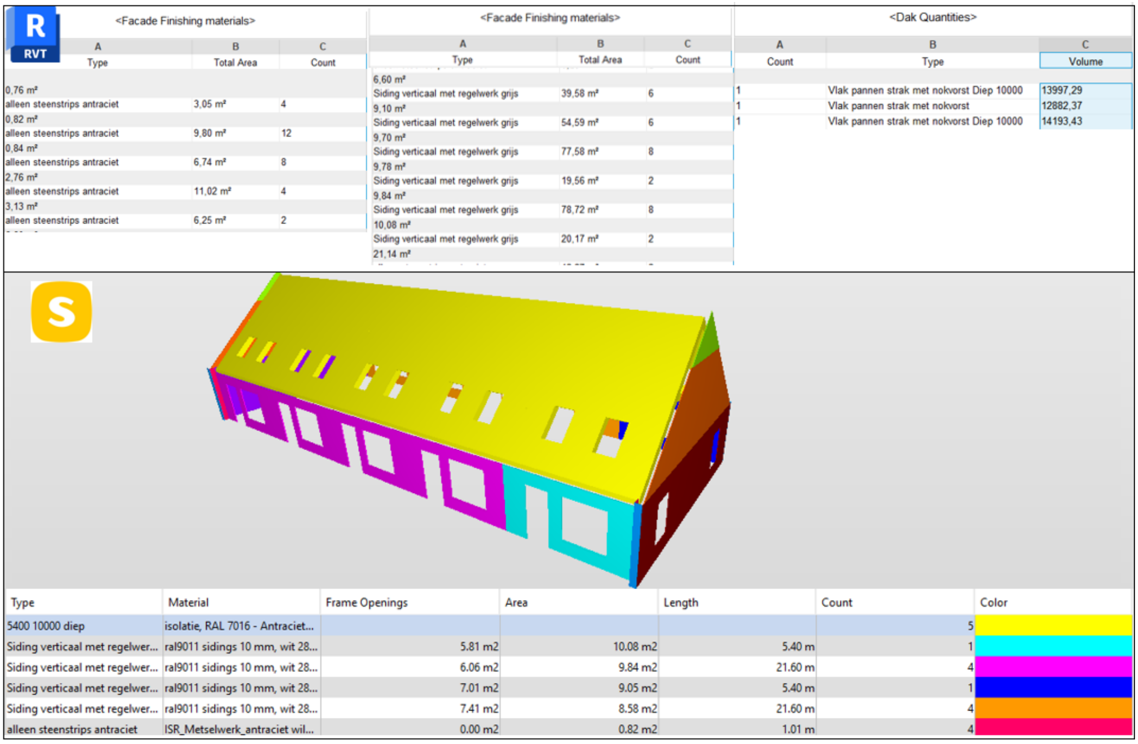


FIGURE 32: Results of the Takeoffs in Revit and Solibri

One element that does not contain an area is the roof element. However, in Solibri each element is given a bounding box, which makes it possible to derive the area. This formula can be implemented in the Excel sheet as well, developing the cost estimation model and library (BIM use **(16) Develop cost library**). The following formula can be utilised to calculate the area of roofing materials per house:

$$Area = 2 * BoundingBoxWidth * \sqrt{(BoundingBoxHeight)^2 + (\frac{1}{2}BoundingBoxLength)^2}$$

So the data that is achieved through the quantity takeoff can be easily manipulated to obtain the desired format. Excel supports all kinds of data manipulation that can be used to gain automatic importable results. An Excel sheet can be designed which is similar as the example showed in Figure 20, to support automatic imports.

6.3.2 Conditions

In this section, the necessary conditions for exploiting quantity takeoffs for PreModu are provided. Since Emergo is in charge of deriving the BIM models for PreModu, Emergo is able to influence how BIM models are developed.

Conditions are scattered around two are three categories. Scenario A necessitates conditions from *Modeling conditions for PreModu* and *Conditions for information takeoff's procedures* while Scenario B utilises similar categories, but on a greater extent. On top of that, conditions from *Standardised cost data and exchanges* are necessary for the Scenario 1B. Explicit conditions are derived under the categories below, where all conditions for the scenarios are summarised in Table 7.1.

Scenario a and b: Conditions for information takeoff's procedures

If the project-specific objects are correctly modeled and potentially linked to a house number, a standardised flow of information is required. This results in additional conditions, similar to the quantity takeoff for PreFab. However, the model does not have to be checked because it is modeled on behalf of Emergo, implying that the model is already approved. A quantity takeoff definition on the other hand, has to be developed, ensuring that only the necessary components and data is extracted out of the model. Also, the raw data has to be readable by cost estimation systems from Emergo, requiring a data processor to translate raw excel data into cost items in terms of PreModu's cost database. **C3.4: Standard ITO definitions**, **C3.5: Raw data processing algorithms in cost estimation software** and **C3.7: Complete cost items in cost estimation models**. These conditions are reused as condition from section 6.1.

Scenario a and b: Modeling conditions for PreModu

In test projects, all project-dependent data could be found back in the test project, shown in Table 6.11. Yet, this has to be a hard condition for all current and future PreModu projects if these are automatically extracted. Therefore, **C2.1: Complete geometric information**, **C2.2: Complete alphanumerical information** per BIM model, are the first two conditions, which has to be achieved within the BIM model, which is aligned with BIM LOD 300[4]

Project-Specific Information	***Data type***	***Revit***	***Solibri***
Additional 'special' costs	*<float>*	✗	✗
Material of Roofing Tiles in House	*<string>*	✓	✓
Quantity of Roofing Tiles per Material	*<float>*	✗✓	✓
Material of Facade Finishing/Cladding in House	*<string>*	✓	✓
Quantity of Facade Finishing/Cladding per Material	*<float>*	✓	✓
Material of Framing Area in House	*<string>*	✓	✓
Quantity of Framing Area per Material	*<float>*	✓	✓

TABLE 6.11: Checked data by for PreModu scenario 1A

Emergo is in charge of the design process, but this process is normally done by an external BIM modeler. Consequently, Emergo can ask the BIM modeler to develop certain information within the BIM. Hence, **C6.1: Establish an information development document, according to LOIN (ISO 19650-1)** information developments. The BIM modeler can develop the model according to Emergo's standard objects, resulting in **C6.2 BIM model must be established out of PreModu's Revit libraries** Currently, the objects that are extracted out of the BIM model are handled simultaneously. For example, the takeoff definition counts the number of facade finishing type A while Emergo estimates their costs specifically per house. If this is desired, **C6.3: Object must be related to a house number of modeling group** is a condition as well. The result will be the same, but the costs could then be structured per house within the project. This condition is considered optional.

Scenario B: Modeling conditions for PreModu

Currently, PreModu relies on a standardisation level of around 85%, meaning that 15% are unique project-dependent components. However, the current component library in Revit is far from this 85% and is thus considered incomplete. This means that not every option in Table 3.6 is predefined and modeled in Revit. These data entries are shown in Table 6.12, which are standardised components, applicable for every house type, but are lacking in a complete Revit family. For example, for house type 1, front facade A and B are modeled and captured in a Revit Family, but front facade

[4]Level of Development (LOD), originally founded by AIA and adopted by BIMForum

C is not available. As seen in Table 6.12, the number of elements can be extracted, but a lack of a complete standardised component library for every house type is lacking. Since these options are predefined, the exact geometries or technical details are not necessary, as modules are counted and connected to predefined calculations. Therefore, only BIM LOD 200[5] is required for the cost estimations of Table 6.12. However, since this scenario is an expansion of scenario 1A, and data in Table 6.11 is also required to realise complete cost estimations, LOD 300 is required.

Standardised Information	Data type	Complete
Corner or inbetween house	*List: 2x <string>*	✗
Option of base configuration	*List: 15x <string>*	✗
Option of front facade	*List: 4x <string>*	✗
Option of back facade	*List: 2x <string>*	✗
Option of head facade (IF corner house)	*List: 4x <string>*	✗
Option of facade finishing	*List: 4x <string>*	✗
Option of roof finishing	*List: 2x <string>*	✗
Option of heating installation type	*List: 3x <string>*	✗
Option of solar panel type	*List: 2x <string>*	✗
Option of solar panel field size	*List: 26x <string>*	✗
Option of kitchen implementation type	*List: 4x <string>*	✗
Option of floor finishing	*List: 3x <string>*	✗
Option of wall finishing	*List: 3x <string>*	✗
Option of sanitary facilities	*List: 3x <string>*	✗
Option of roof window type	*List: 9x <string>*	✗
Number of roof windows	*<integer>*	✗
Number of sun blinds	*<integer>*	✓
Number of ventilation units	*<integer>*	✓
Option of dormer types	*List: 3x <string>*	✗
Number of dormer types	*<integer>*	✓
Option of canopy types	*List: 3x <string>*	✗
Number of canopies	*<integer>*	✓
Option of gutter types	*List: 3x <string>*	✗
Option of sewage type	*List: 3x <string>*	✗
Unique Information	**Data type**	**Complete**
Unique costs for unique components	*<float>*	✗

TABLE 6.12: Checked data by for PreModu scenario 1B

An incomplete Revit Family caused by a lack of resources to develop these libraries for Emergo. Subsequently, Emergo only predefines a family instance if this is incorporated in a project, making it reusable for the next project. As not every option has been modeled in past projects, the component library per house type is incomplete. Thus, only a portion of Emergo's standardised components are included in a component library of Revit, which needs to be developed so that every option, for every house type, is available and incorporated in a Revit Family. Therefore, two conditions are added, namely, **C6.4: Complete Revit Families for PreModu on object level** and **C6.5: Complete Revit modeling families on modular level**. **C6.4** refers to a complete object library such as window type, solar panel type, heat installation type, etc, while **C6.5** refers to complete PreModu concepts such as type of kitchen, type of bathroom, etc. The conditions are specified to develop a Revit Family to at least the 85% which is currently included in the cost estimations systems. However, when 100% standardisation in PreModu's concept is obtained, these conditions has to be evidently fulfilled for the 100% as well.

Scenario B: Standardised cost data and exchanges conditions

In contrary to the component library, cost estimations have been established for the majority of this 85%, where all options per house type have been established in the cost estimation model. However, these standardised cost items have not been established for all options. For example,

[5] Level of Development (LOD), originally founded by AIA and adopted by BIMForum

referring back to Table 6.12, cost estimations have been predefined for front facade A, B and C for house type 5, but not for house type 6. Additionally, for every project, manual cost estimations have to be conducted for the unique or varying components, thus the 15%. Therefore, the cost database and cost estimation model has to be developed as well. Accordingly, the cost database is also considered to be incomplete. to bridge this gap, a synergy between component and cost data is necessary, where standardised components has to be developed, including a standardised cost item to work with. Currently, every project contains new cost estimations, that have not been calculated before. To completely rely on information takeoff's, every component or module must be available in calculation models, meaning that **C7.1: Cost data in ERP must be complete in terms of PreModu** and **C7.2: Standard cost data exchanges from ERP to Excel must be standardised** are required.

Thus, standard cost items have been developed for a great share of PreModu concepts, which are maintained in the ERP system. Still, several details are lacking, making the cost database incomplete, where 15% of the cost database is estimated to be incomplete. Larger modules are encapsulated in the cost database but details and variations are often lacking, such as variations on the concrete floor. These prices are often depenendent on suppliers and have not been used in prior projects. On top of that, the 15% includes unique items per project, based on unique client demands. **C7.1** and **C7.2** refers to developing, or more specifcally, completing the cost database for all the components used in PreModu, which is considered 100%. Unique costs are outside of this development because not all specific wishes of clients can be incorporated.

6.3.3 Process changes and value

Figure 33 reveals the process changes of scenario 1A, where standardised options are still selected in the caulcation model manually. Figure 34 reveals the changed scheme of scenario 1B, which completely relies on the BIM model for the cost estimations, except for the unique calculations.

Instead of manually measuring area's, the element can be extracted out of the BIM model including material and area's, resulting in **Automatic measurements**. Shown in Figure 33 and Figure 35, a new 'lane' is created, referring to the utilisation of a new software, Solibri or Revit. Moreover, a predefined information takeoff structure is necessary to filter the desired elements. These data entries are stored and exported through an excel or .CSV file and imported into the cost estimation system in Excel. As area's are automatically extracted, reducing measuring errors, these scenarios are considered to be **Less error-prone**. Another benefit is the automated nature of the new task, which could improve the task throughput time, making it **Potentially faster**.

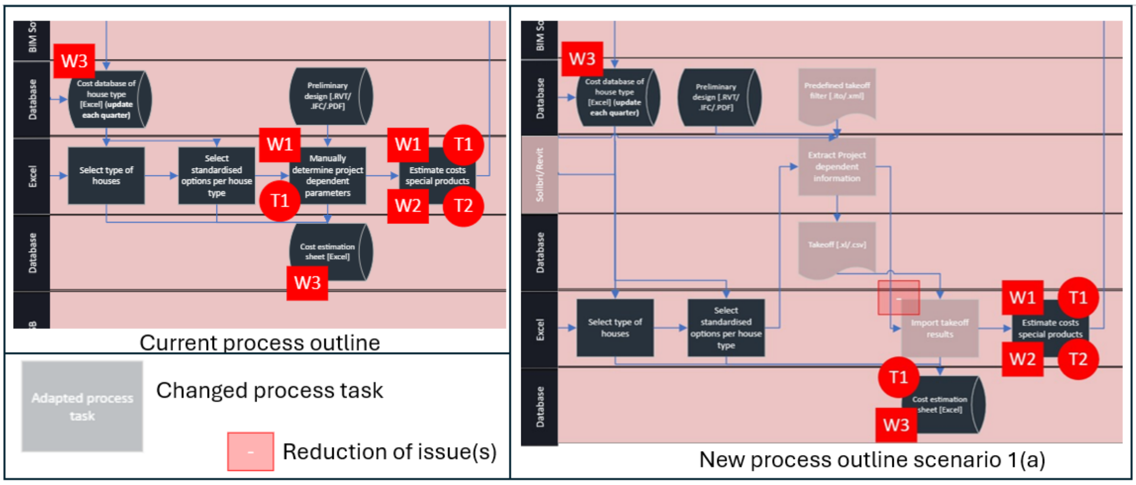


FIGURE 33: Old process outline vs. new process outline, PreModu scenario 1

Scenario 1B has additional value compared to Scenario 1A. While scenario 1A focuses on measurements in terms of squared metres and materials, Scenario 1B evolves to counting the frequency of standardised modules. This adaption refers to the implementation of the correct data, modeling groups per house and relationships between the elements. Consequently, **Automatic quantification** of modules per house is additional value, which can be used for cost estimations. Moreover, besides the unique manual cost estimations, evolving to scenario 1B results in **Complete automatic cost estimations**. The cost estimator implements the information from the BIM model into the cost estimation model, which automatically results in a cost overview. Only the unique clients requirements need to be manually calculated. For example, the delivery of an outside tap.

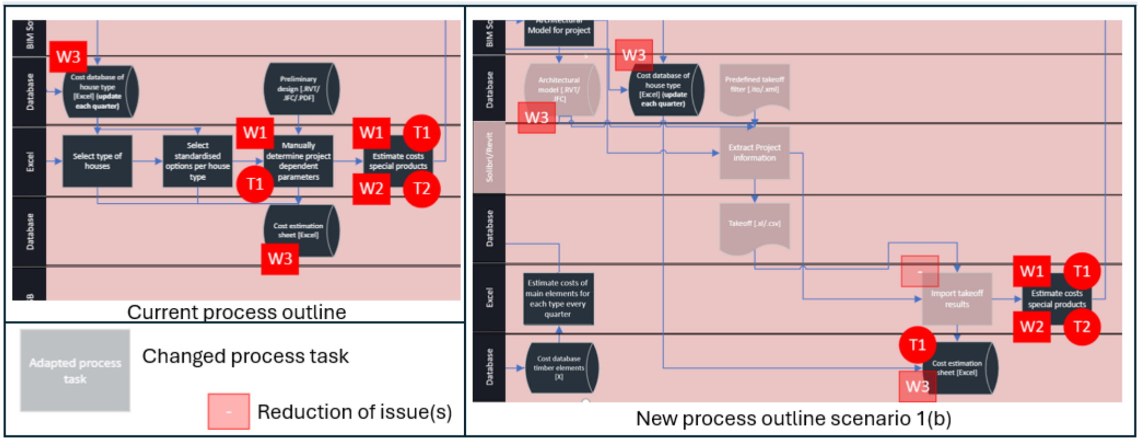


FIGURE 34: Old process outline vs. new process outline, PreModu scenario 1b

6.3.4 Summary of scenarios 1a and 1b

Two variants of this scenario were derived, where scenario 1a was meant for the project-dependent data while the second scenario is similar refers to complete cost estimations based on ITO's. This requires additional conditions but also comes with extended value. Table 6.9 and Table 6.10 reveal the conditions and value for *scenario 1(a)* and *scenario 1(b)*, respectively. For both scenarios **C12** is considered optional, based on the preference of the problem owner, Emergo.

Conditions	Value
C1.2: Correctly modeled BIM	Automatic measurements
C1.3: Complete BIM model	Less error-prone
C2.1: Complete geometric information	Potentially faster
C2.2: Complete alphanumerical information	
C2.3: Presence of all documents in the right format	
C3.4: Standard ITO definitions	
C3.5: Raw data processing algorithms	
C3.7: Complete cost items in cost estimation models	
C6.1: Establish an information development document, according to LOIN (ISO 19650-1)	
C6.2: BIM model must be established out of PreModu's Revit libraries	
(C6.3: Object must be related to a house number of modeling group)	

TABLE 6.13: Value and conditions that Scenario 1(a) entails

Conditions	Value
C1.2: Correctly modeled BIM	Automatic measurements
C1.3: Complete BIM model	Automatic quantification
C2.1: Complete geometric information	Less error-prone
C2.2: Complete alphanumerical information	Potentially faster
C2.3: Presence of all documents in the right format	Complete automatic cost estimations
C3.4: Standard ITO definitions	
C3.5: Raw data processing algorithms	
C6.1: Establish an information development document, according to LOIN (ISO 19650-1)	
C6.2: BIM model must be established out of PreModu's Revit libraries	
(C6.3: Object must be related to a house number of modeling group)	
C6.4: Complete Revit Families for PreModu on object level	
C6.5: Complete Revit modeling families on modular level	
C7.1: Cost data in ERP must be complete in terms of PreModu	
C7.2: Standard cost data exchanges from ERP to Excel must be standardised	

TABLE 6.14: Value and conditions that Scenario 1(b) entails

Solibri and Revit comparison

Two scenarios have been derived for PreModu when it comes to information takeoffs, which are tested in Solibri and Revit. The project-dependent data was successfully extracted out of the BIM models. Moreover, roof dimensions can be derived out of the extracted information from Solibri, namely the bounding boxes. In Revit, this could be achieved, yet a dynamo script has to be established to create the bounding boxes for roof elements, which is possible[6]. Besides the bounding boxes, there were more differences between both software while testing the concept of Takeoff's. First of all, Solibri is able to filter across multiple categories, enabling simultaneous extraction of the facade walls and roof elements. In Revit, the roof's were falling under generic models and necessitated an individual filter. Secondly, Solibri colors and visualised the extracted elements in 3D, making it very clear which information belonged to which element. Revit did not visualised any element, resulting in manual checks. Moreover, Solibri directly showed the area of frame openings per element while Revit did not have this feature. In conclusion, Solibri seems to be more intelligent than Revit while extracting but more importantly, while processing the information.

6.4 PreModu 2: Automated cost estimations

This scenario addresses the possibility to connect cost databases, where Revit components are linked to corresponding cost items, which are originated from the ERP system.

[6] Tutorial: Dynamo Script for Bounding Boxes

subsection 6.4.1 details the operational workflow within Emergo, subsection 6.4.2 outlines the necessary conditions for this scenario, subsection 6.4.3 discusses required process changes and potential values of the scenario, and subsection 6.4.4 concludes by summarising the conditions and values.

6.4.1 Working in context of Emergo

Figure 35 reveals the scheme of the scenario, using these standardised data as input. The script is the main tool, extracting information from different databases and connecting them, visualised in the interface of dynamo player.

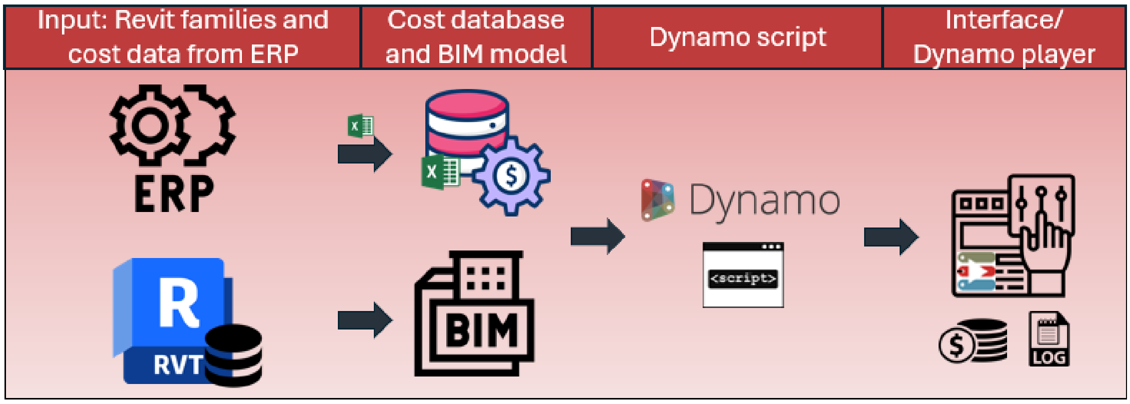
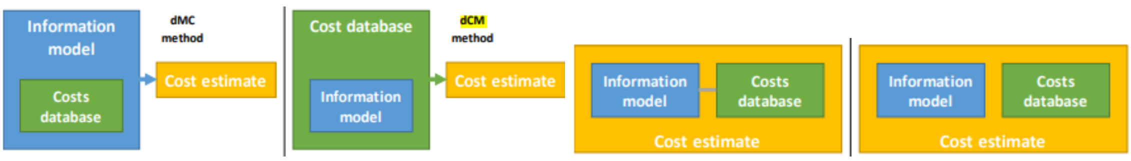


FIGURE 35: Scheme of the working of scenario 2 for PreModu

This scenario is derived in a practical manner for several components. Roof dormers and gutter types are the selected components, which are automatically calculated in Revit for one test project of PreModu. This practical examination of the scenario is considered as an example, proofing the concept of automated cost estimations.

Step 1: Determining an appropriate method for Emergo

There are multiple routes to achieve 5D BIM, highlighted in a variety of research addressing automated cost estimations. Matejka et al. (2018) compared multiple methods from literature and categorised them into 4 categories, where 2 of them are falling under 5D BIM, shown in Figure 36.



(A) Dependent method schematic

(B) Integrated method schematics

FIGURE 36: 5D cost estimation methods, according to Matejka et al. (2018)

First of all, there are dependent methods (Figure 36a), where one database is dependent on the other database. In this case, there is one 'master' database that incorporates data from the other database. Emergo can implement their cost data within their information models. This can be translated to the process of implementing the cost data from their Excel model or Microsoft Access database in ERP within the environment of Revit. Each Revit family type has a cost parameter, which can be manually provided and adjusted. However, this would that Emergo must maintain their cost data in ERP as well as in Revit, resulting in duplicate and time-consuming tasks.

Secondly, there are integrated methods (Figure 36b), which are the most sophisticated methods. These integrated methods are namely based on a full integrated environment of cost estimations, which allows the user to work with the information model and the cost database. These databases could be dependent on each other, which explains the linkage in the first method of Figure 36b. For Emergo, this means that the cost estimation system is able to connect the information models (.rvt or .ifc) with the cost database from ERP, resulting in automated cost estimations through a dynamic environment. This means that cost estimations can be conducted in iterations or provides a price that is live and up-to-date. This flow of data can be achieved through Dynamo[7]. Dynamo is namely able to import .xlsx or .csv data, which is the datatype that could be exported from ERP. In this example, two PreModu concepts, gutters and roof dormers are chosen to be automatically calculated within Revit.

For Emergo, an integrated method is more appropriate, as this method is more aligned with the requirements of the treatment, avoiding manual and time-consuming tasks. An integrated method can achieve 5D BIM in the most efficient manner for Emergo.

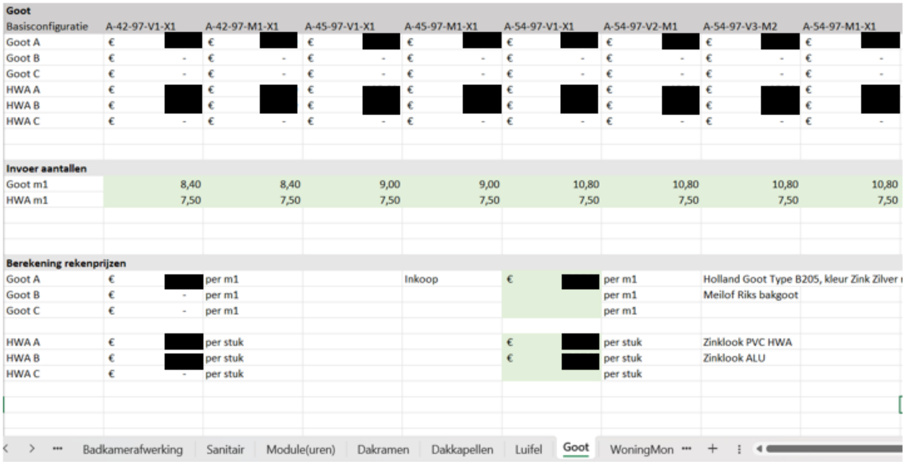
Step 2: Obtain an excel cost database

The first step is to achieve an excel database that includes cost data for PreModu's components. In this example, the current cost estimation system of Emergo is used, which contains cost data, originated from ERP. Cost data considering roof gutters and roof dormers are stored in specific excel data sheets, which are shown in Figure 37. Cost data itself are not shown due to privacy reasons for Emergo.

[7]Dynamo BIM

Dakkapellen						
Dakkapel type	Prijs	lev kozijn	lev dakk excl. kozijn	sparing	montage	aftimmeren
Type A	€ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Type B	€ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Type C	€ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Indekken	€ [redacted]	p/dakkapel				
(indekken ook meerekenen)						

(A) Roof dormer cost data per roof dormer type



Goot								
Basisconfiguratie	A-42-97-V1-X1	A-42-97-M1-X1	A-45-97-V1-X1	A-45-97-M1-X1	A-54-97-V1-X1	A-54-97-V2-M1	A-54-97-V3-M2	A-54-97-M1-X1
Goot A	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]
Goot B	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Goot C	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
HWA A	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]	€ [redacted]
HWA B	€	€	€	€	€	€	€	€
HWA C	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Invoer aantallen								
Goot m1	8,40	8,40	9,00	9,00	10,80	10,80	10,80	10,80
HWA m1	7,50	7,50	7,50	7,50	7,50	7,50	7,50	7,50
Berekening rekenprijzen								
Goot A	€ [redacted]	per m1		Inkoop	€ [redacted]	per m1	Holland Goot Type B205, kleur Zink Zilver	
Goot B	€ -	per m1				per m1	Meilof Riks bakgoot	
Goot C	€ -	per m1				per m1		
HWA A	€ [redacted]	per stuk			€ [redacted]	per stuk	Zinklook PVC HWA	
HWA B	€ [redacted]	per stuk			€ [redacted]	per stuk	Zinklook ALU	
HWA C	€ -	per stuk				per stuk		

(B) Gutter cost data per gutter type

FIGURE 37: Excel sheet containing cost data for a specific PreModu component

Step 3: Import cost data in Dynamo

Secondly, a dynamo script has to be developed that is able to extract the right data from the excel database. Several dynamo nodes are used to import the excel file, the excel data sheet and to filter and adapt all the data entries. Figure 57 reveals the complete dynamo script, where groups: *Import Gutter Data, Import Roof Dormer data, Get Cost data of Gutter type A, Get Cost data of Roof Dormer type A* reveal all the nodes that is necessary to filter the necessary cost items.

Step 4: Import Revit components in Dynamo

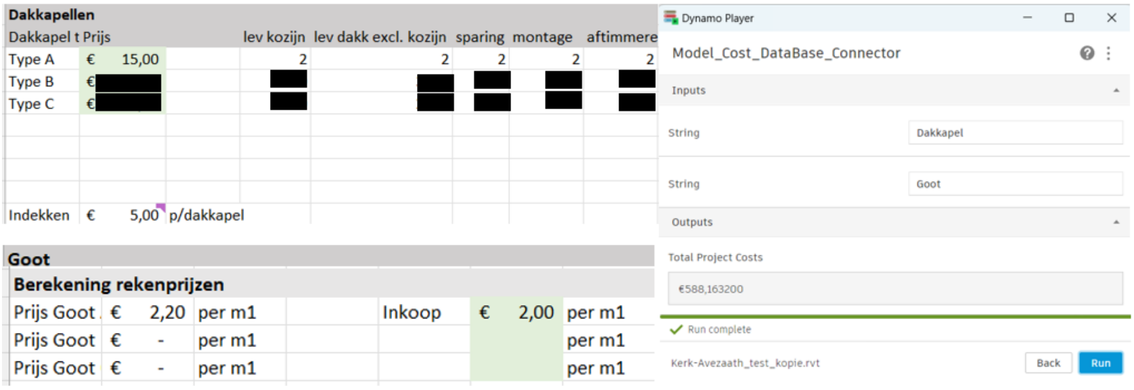
besides the cost items, the Revit components from the preliminary design need to be imported as well. Within Dynamo, there are nodes to import preferred elements from the Revit project based on certain filters. In this case, Elements from a specific parent family and/ or family type are received from the BIM model. There are multiple gutter family types, related to the different object types (A,B, and C) that are shown in Figure 37. These elements can all be received separately due to the fact that they are filtered according to family type in Revit.

Step 5: Connect Revit components with cost items

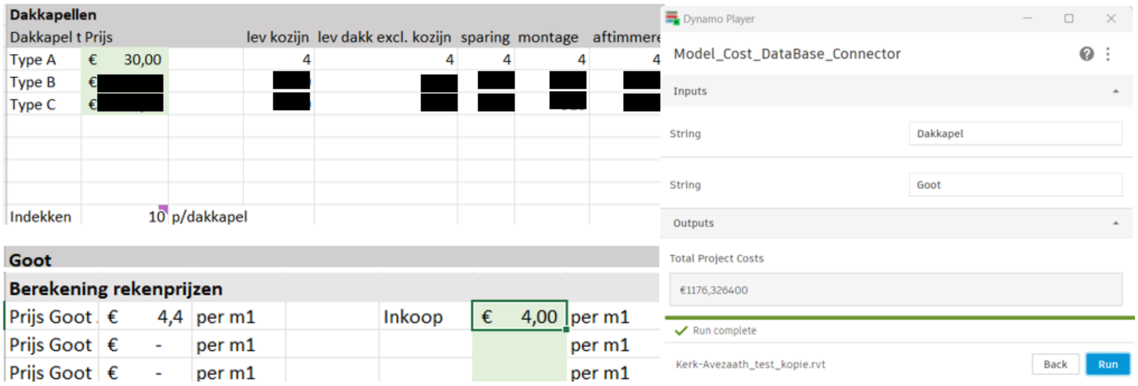
Now that the cost data and Revit components are imported in Dynamo, they need to be connected in an appropriate way. For example, gutter cost estimations are initially based on length, necessitating dynamo nodes to establish the value for length parameter per gutter element. These values are already stored within the elements during the modeling phase of the BIM model. Roof dormers are estimated per roof dormer type, meaning that they not need to be filtered in this case. The dormers are namely standardised and cannot vary in size, opening the opportunity to calculate them per item instead of dimensions. In Table 6.12, the dynamo groups*Extract all gutter elements, Extract all Roof Dormers of Type '...'* and *Total length of each gutter type* reassures the necessary element data. Lastly, once the right information per object is obtained, the simple connection with the cost price reveals the total price and total price per component.

Step 6: Prepare the dynamo player

Finally, the dynamo script can be saved and opened via the dynamo player for any Revit project. In fact, every time the player is being ran, the script reiterates and elements and cost data are extracted again. Hence, if one changes the design and/ or the excel cost database, an iteration of the dynamo player reveals the latest price. An example of integrated cost estimations is provided in Figure 38



(A) Automated cost estimation with initial cost items



(B) Automated cost estimations under increased cost items

FIGURE 38: Example of integrated cost estimations through Dynamo

The dynamo script is able to work while Revit and Excel are opened simultaneously. However, when Excel data is adapted, the file need to be saved before the changes could be visible within Dynamo. This dynamo script is able to provide the costs of gutter and dormer elements immediately, even after prices has been changed or the design has been adapted. A test on changes of Revit elements could not have been performed due to insufficient rights to adapt the design.

6.4.2 Conditions

Emergo is in control of the BIM model, resulting in a high level of control and power to realise certain conditions. On the other side, a complete working of this scenario requires multiple conditions, falling under the following categories: *PreModu conditions for information needs, according to (ISO 19650-1) , standardised cost data and exchanges conditions, quality conditions for BIM models* and *Dynamo scripts conditions for automated cost estimations*. Explicit conditions are derived under the categories below, where all conditions for the scenarios are summarised in Table 7.1.

PreModu conditions for information needs, according to (ISO 19650-1)

Obviously, this scenario only works if preliminary BIM designs are conducted under the concept of PreModu. Hence, **C6.2: BIM model must be established out of PreModu's Revit libraries** is a condition. The design process is outsourced, but conducted on behalf of Emergo. This includes a level of control for Emergo, yet they must apply strict rules for the development of the BIM model. Thus, **C6.1: Establish an information development document, according to LOIN (ISO 19650-1)** is also required

Similar to the scenario of **PreModu 1B**, there has to be some developments in terms of a component library. Currently, the 85% of the components are standardised under the concept of PreModu. These are incorporated in concepts of PreModu, but are lacking in a Revit Family. In fact, the Revit Families are not near the 85% at all. For example, for house type 4, roof tile type 1, and 2 are included in a Revit but roof tile type 3 and 4 are not pre-modeled in a Revit Family. Similar to scenario 1B, data that is incomplete for every house type is shown in Table 6.12, which refers to modules from PreModu, aligned with LOD 200[8] However, data within Table 6.11 is also utilised for this scenario, which includes exact quantities and materials. Therefore, LOD 300[9] is required. The following conditions are thus required: **C6.4: Complete Revit Families for PreModu on object level** and **C6.5: Complete Revit modeling families on modular level**. If this is not met, the dynamo script is not able to detect the necessary component through a standardised manner. Namely, if a similar object is modeled differently between projects, a standardised dynamo script cannot extract the component for every project. Therefore, standardisation and component development is considered key. Also, if Emergo succeeds to develop their standardisation level beyond 85%, conditions **C6.4** and **C6.5** expands along this development. In conclusion, necessary component data is available for some of the standardised components of PreModu's concept, yet this has to be developed in terms of completion for all possible combinations.

Standardised cost data and exchanges conditions

Similar to the component development, the cost database is considered incomplete. Currently, Emergo cost database is developed for the majority of the standardised components (85%) that are included in PreModu's concept. However, not all options have been precalculated. For example, again referring to Table 6.12, heat installation type D and type C are calculated for house type 2 but for house type 5, these calculations are blank. This means that these cost estimations still need to be conducted on conceptual level, making it usable for projects. Also, the remaining components of 15% are considered to be unique, which results in manual and varying cost estimations, which are time-consuming and less accurate. Thus, the cost database has to be developed as well, requiring **C7.1 Cost data in ERP must be complete in terms of PreModu**. Additionally, exports

[8]Level of Development (LOD), originally founded by AIA and adopted by BIMForum
[9]Level of Development (LOD), originally founded by AIA and adopted by BIMForum

from ERP need to be conducted to create a cost environment that is accessible by external applications, such as the cost estimation model in Excel. Currently, Emergo's cost estimation model is evaluated every quarter to check if prices are still correct. This task is done manually. However, if the ERP cost database is complete in terms of PreModu, one is able to make an export at any given time. This could be done in a standardised method, making it possible to update the Excel cost database at any time. Hence, **C7.2: Cost data exchanges from ERP to Excel must be standardised** is necessary to create standardised flows of information. In this way, the excel cost database is similar for every price update and the structure never changes

Quality conditions for BIM models & Conditions for information needs, according to (ISO 19650-1)

Also, if the Revit component library is further developed, as explained by previous conditions, the specific BIM designs need to be established according to this Revit library, resulting in in reusing the following conditions, **C1.2: Correctly modeled BIM** and **C1.3: Complete BIM model**. The information within a BIM model must thus be complete, resulting in **C2.1: Complete geometric information**, **C2.2: Complete alphanumerical information**, **C2.3: Presence of all documents in the right format** of the BIM model and additional documents.

Dynamo scripts conditions for automated cost estimations

If concept and cost data are both available and up-to-date, the dynamo script should be able to connect them. This is in fact the main tool of this scenario, which need several conditions. The script should be able to extract all cost data at any time, resulting in **C8.1: Dynamo must be able to extract all cost data at any time**. Similar to this cost data, a condition is necesarry for component data, namely **C8.2: Dynamo must be able to read BIM models, components and parameters**. Moreover, the right pieces of data need to be connected to each other, realising **C8.3:Dynamo must connect object data to the corresponding cost data**. Finally, due to the fact that there are still unique and special products, a check should be incorporated in the dynamo script. This check can also be useful for trouble-shooting, such as an adaption of a component. A check could be for example a table that provides all the components that have not been calculated, resulting in the unique products, as well as the potentially changed components. **C8.4: Automated checks should be incorporated in the dynamo script to evaluate results**.

A cost estimator is not particularly interested in the background processes, requiring a dynamo player that provides the results. **C8.5: The total costs and a log report should be the output of the Dynamo player** should be taken into account to provide proper results. A cost estimator should establish the total project costs, and a log report if error's are located, such as not calculated components.

6.4.3 Process changes and value

Following the scenario implementation, significant changes occur in the cost estimation process itself, as depicted in Figure 39. The most notable alteration is the elimination of manual cost estimation steps within Excel, replaced by automated processes through the dynamo player. This shift ensures **Complete automatic cost estimations**, avoiding manual tasks, which could be **Potentially faster**.

Furthermore, integration and connectivity between different databases are enhanced. The Excel database is fed with cost data from the ERP database. Subsequently, the Excel database is integrated seamlessly with Revit information models via the dynamo player, resulting in **Connected databases**. In fact, the dynamo player is arranged in a manner that it connects the latest data. In other words, if a change is made in the cost database or in the design, one click on the button results in the latest cost calculation. Therefore, **Dynamic cost estimations** is considered as potential value as well. All measurements in Revit are executed by computers, accuracy is improved by eliminating manual measurement errors, resulting in **Accurate measurements**

This scenario relies on standardised data that is maintained in a standard format, which applies to the cost database in ERP and for the component database in Revit. While resistance to standardisation is partly mitigated through these standardised libraries, unique and specialised projects may still pose challenges due to their unpredictable nature. Despite this, the tool reinforces positive aspects, notably by accelerating the process and enhancing standardisation. Thus, this scenario facilitates **Enhanced standardisation**.

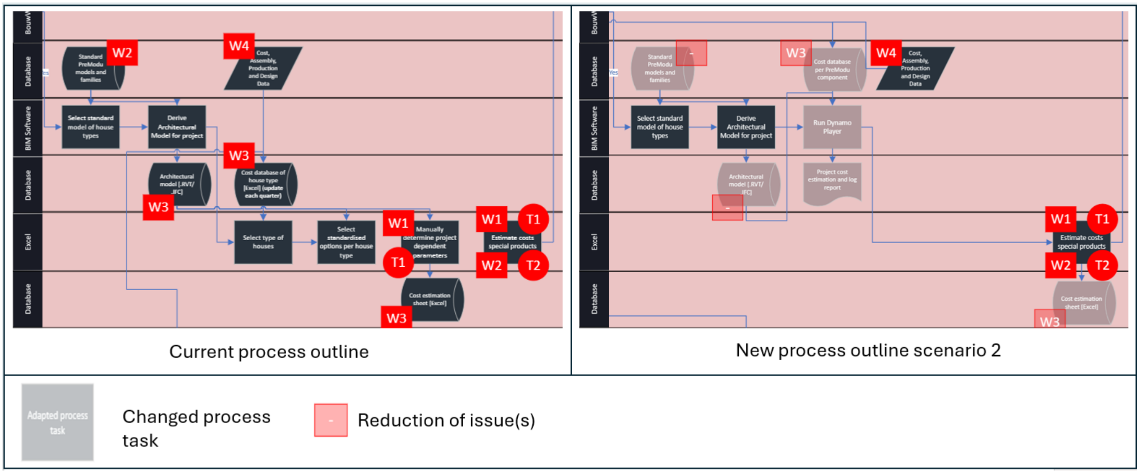


FIGURE 39: Old process outline vs. new process outline, PreModu scenario 2

6.4.4 Summary of scenario

In summary, the value this scenario potentially has seems to be promising, relying on connected databases for automatic cost estimations. Yet, the potential this scenario has is currently locked as Emergo is not meeting the derived conditions. Standardisation is key in this scenario, including complete object and cost databases, which could be exploited by an automatic script. Table 6.15 highlights the value and conditions for this scenario.

6.5 PreModu 3: Integrated cost estimations

The final scenario of PreModu overlaps the **PreModu Scenario 2: Automated calculations** in it's tool and working method. Both utilise Dynamo to calculate costs. However, this scenario estimates the cost at a different moment of the process, namely the initial cost estimation, while scenario 2 estimates the cost of a preliminary project design. Due to a different timing of the application, another level of cost estimations is required, namely on concept level. Therefore, the calculation method is overlapping, yet, the organisation of the scenario needs to be different.

subsection 6.5.1 details the operational workflow within Emergo, subsection 6.5.2 outlines the necessary conditions for this scenario, subsection 6.5.3 discusses required process changes and

Conditions	Value
C1.2: Correctly modeled BIM	**Complete automatic cost estimations**
C1.3: Complete BIM model	**Connected databases**
C2.1: Complete geometric information	**Dynamic cost estimations**
C2.2: Complete alphanumerical information	**Accurate measurements**
C2.3: Presence of all documents in the right format	**Potentially faster**
C6.1: Establish an information development document, according to LOIN (ISO 19650-1)	**Enhanced standardisation**
C6.2: BIM model must be established out of PreModu's Revit libraries	
(C6.3: Object must be related to a house number of modeling group)	
C6.4: Complete Revit Families for PreModu on object level	
C6.5: Complete Revit modeling families on modular level	
C7.1 Cost data in ERP must be complete in terms of PreModu	
C7.2: Cost data exchanges from ERP to Excel must be standardised	
C8.1: Dynamo must be able to extract all cost data at any time	
C8.2: Dynamo must be able to read BIM models, components and parameters	
C8.3:Dynamo must connect object data to the corresponding cost data	
C8.4: Automated checks should be incorporated in the dynamo script to evaluate results	
C8.5: The total costs and a log report should be the output of the Dynamo player	

TABLE 6.15: Value and conditions that Scenario 2 entails

potential values of the scenario, and subsection 6.5.4 concludes by summarising the conditions and values.

6.5.1 Working in context of Emergo

A design configurator is applicable for the modular house branche of Emergo, since this sector revolves around standard house types, modules and module variations. In fact, Emergo already made their interest in such a configurator platform noticeable through previous research[10], showed in the BIM uses of Table 5.1. However, this is considered to be a long-term development, necessitating developments of PreModu's concept on multiple aspects. As explained, this scenario is derived in a theoretical manner, where practical elaborations are unrealistic at this point. Emergo aims for a configurator that is used during the project start up phase, enabling clients to get a first look of what their project will look like. Consequently, the configurator is projected to be derived on conceptual level, rather than providing technical details.

Once a design configurator is available for PreModu, cost data can be achieved through connecting the internal cost database and the kit-of-parts via a Dynamo script. A cost database containing conceptual costs is derived, which is the input for conceptual cost estimations in the design configurator. In this way, a client can already examine the projected costs for their projected design preferences. Figure 40 highlights the working of integrated cost estimations with the conceptual design phase

[10] *BIM uses in Modular Construction*

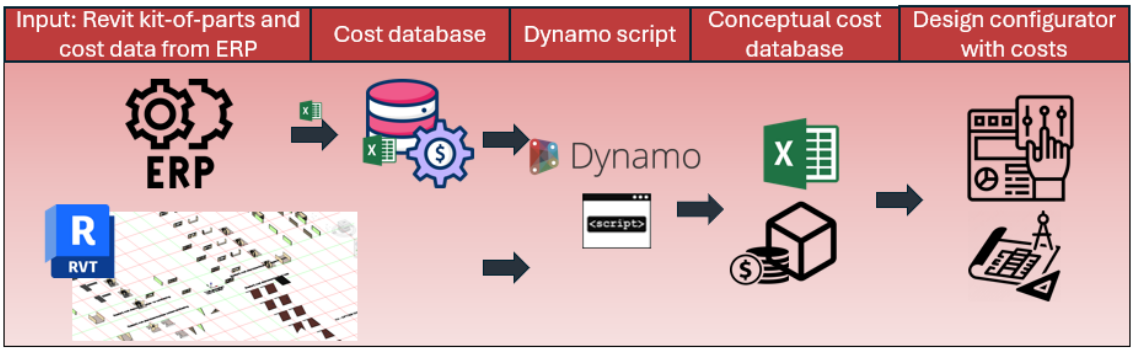


FIGURE 40: Scheme of the working of scenario 3 for PreModu

Step 1: Establish a design platform

Evidently, before cost estimations can be integrated with the design phase, a design platform needs to be established by Emergo. Figure 41 reveals a simplified version of the working of such a configurator platform. User inputs are converted to a customised product via configuration rules, using standard components from the kit-of-parts.

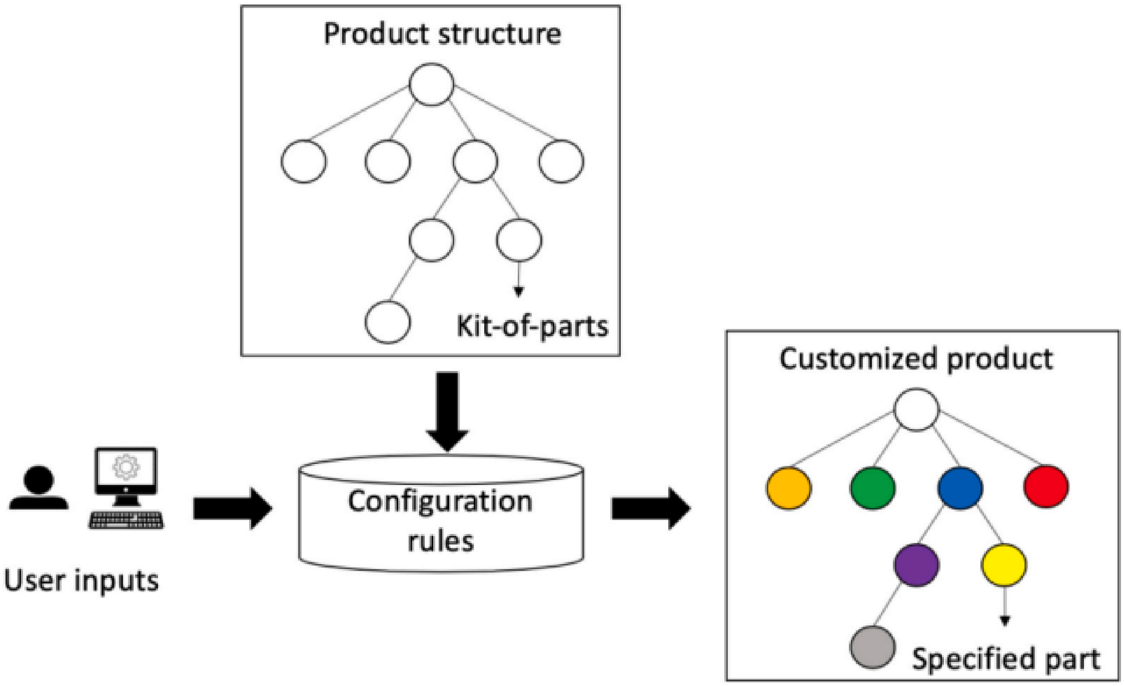


FIGURE 41: Structure of product configurators, derived by Cao et al. (2021)

The kit-of-parts structure is a database with a series of reusable building instances, such as linear components (e.g. beams), planar components (e.g. panels) and even volumetric components (e.g. modules). The last one, the modules, are the one that is most applicable for Emergo since this design configurator will be on conceptual level, reducing the need for detailed drawings. A library of 3D models in Revit, supported by 2D drawings in Autocad and technical documents could be used to maintain and manage the kit-of-parts (Cao et al., 2021).

The configurator rules can be divided into four categories, according to Cao et al. (2021). The following rules need to be developed:

- **Composition rules:** Determine which parts are mandatory and which are optional. In terms of Emergo, a house could not be built without a house type, roof type, front type, back type and side type. These aspects could be at least mandatory
- **Compatibility rules:** Rules that adress which components cannot be modeled simultaneously. For example, if facade finishing type A is selected, consequences could influence the finishing types for the rest of the house.
- **Dependency rules:** Automatically selects mated parts, if an initial part is selected. This could apply for the type of bathroom, where a luxury bathroom automatically is connected to the set of luxurious bathroom components.
- **Cardinality rules:** Obtains the required or limited number of parts under the project environment. A number need to be assigned to define the quantity of a product with a cardinality rule, for example the number of house type A.

Besides the 3D models that are maintained in an design software, such as Revit, more applications are necessary. The system architecture of Cao et al. (2021) is based on a three-tier architecture. First of all, a web framework is necessary as a graphical user interface (GUI). This is where the user can select their preferences and the resulting models are shown. Subsequently, the application tier translates the user inputs to the model, executing the core functionality of the configurator. Data is established out of the data tier, where raw files and the objects are stored.

Step 2: Establish a conceptual cost database

The method of cost estimations is similar to the method explained in section 6.4. Yet, the database can vary depending on the level of detail that is incorporated within the resulted models of the design configurator. Presumably, the configurator will provide initial conceptual outlines to the ideas of the client, meaning that not all technical details are included within the design. Consequently, a fully automatic dynamo script that is used for automatic project cost estimations is too extensive and potentially unusable for the design configurator.

Instead, a conceptual cost database has to be established for every module or component that is located in the kit-of-parts. A modified dynamo script can accomplish the costs of each component. There are modules that have a fixed price, independent on which type of house is selected, such as type of bathroom and type of roof window. However, there are also prices for modules that are dependent on the house type due to variable dimensions. In this case, it is necessary to obtain a cost price per dimensions, such as squared metre. An conceptual example is given in Figure 42.

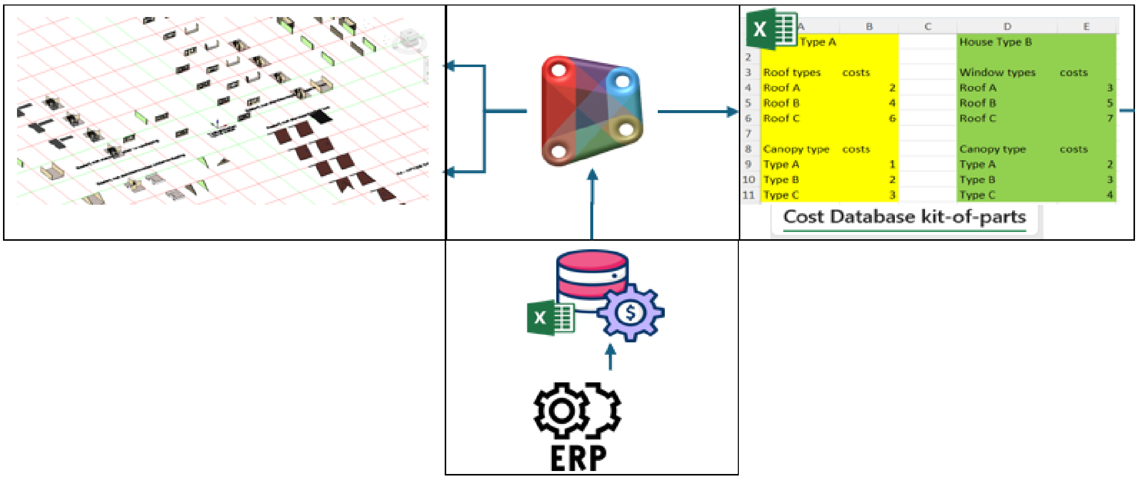


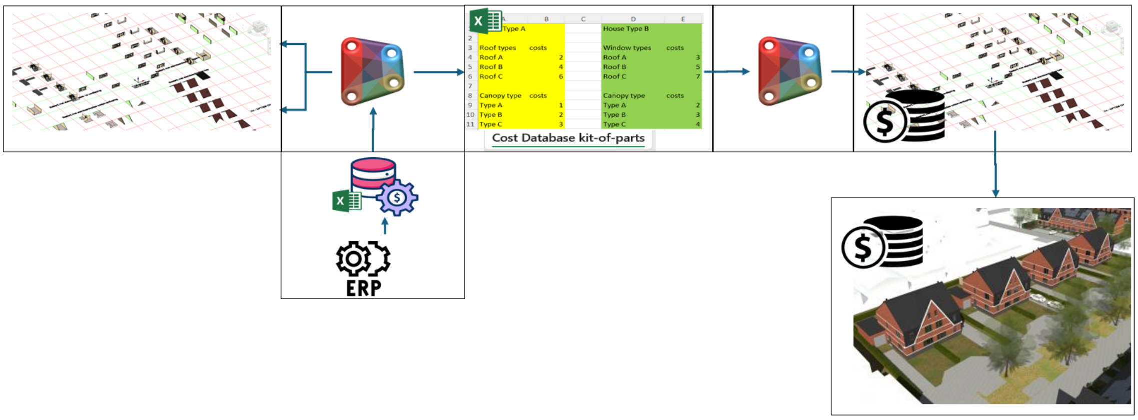
FIGURE 42: Scheme of deriving a cost database for the kit-of-parts

Step 3: Determine initial costs in the design configurator

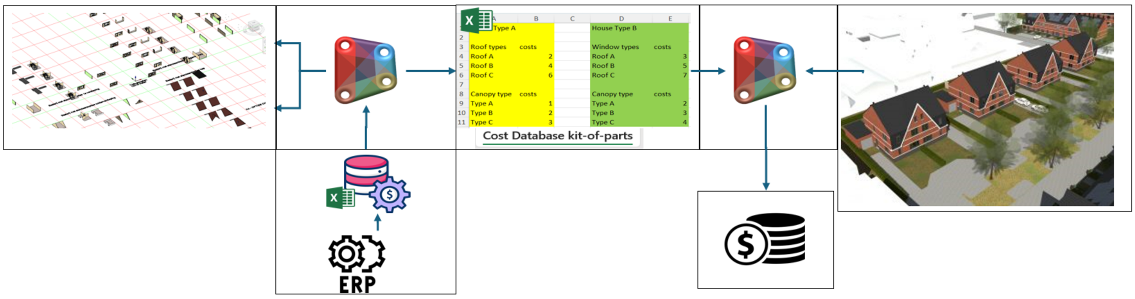
The conceptual cost database ensures that the costs are known. These data entries can be handled in multiple methods, for example by already incorporating the costs in the modules In fact, the cost data can already be implemented within Revit if desired with the use of the same of a new Dynamo script. Other add-ins such as DiRoots[11] can also realise parameter adaptions by linking Revit to Excel. Figure 43a shows the initial scheme, supplemented with the structure to implement cost data in the modules

Another way is to link the conceptual design, that has been formed by the user preferences, to the cost database at the end. Thus, extracting the modules out of the design and connect them to the correct cost item. This methods is more similar to the tools that are explained in section 6.3, namely extracting information and connect them to the cost data. Figure 43b shows the initial structure, added with the scheme that connects the design parameters with the cost items after the design has been made.

[11] DiRoots



(A) Option 1: Implement cost data in the modules



(B) Option 2: Connect conceptual design to cost database

FIGURE 43: Two examples of cost and design configurator integration

6.5.2 Conditions

For this scenario, the most conditions can be derived as multiple concepts have to be developed. The design configurator can be unravelled into a large number of conditions itself, as it is a tool to be developed completely. In these cases, the condition is limited to the presence of the tool itself.

The conditions for the third scenario of PreModu are falling under the following categories: *Modeling conditions for PreModu, Standardised cost data and exchanges conditions, Conditions for information needs, according to (ISO 19650-1)* and *Design configurator conditions*. Explicit conditions are derived under the categories below, where all conditions for the scenarios are summarised in Table 7.1.

Modeling conditions for PreModu

Similar to previous scenarios, the level of information needs have to be determined, according to LOIN (ISO 19650-1), reusing **C6.1: Establish an information development document, according to LOIN (ISO 19650-1)**. Currently, PreModu contains a standardised component level of 85%, which means that there are still variable components left. There are Revit Families developed for the current 85%, but this is incomplete. For example, gutter type A and B are included as an instance within a Revit Family, but gutter type C is not. A complete Revit Family has to be developed for the initial 85%. Therefore, the requirements **C6.4: Complete Revit Families for PreModu on object level** and **C6.5: Complete Revit modeling families on modular level**. In contrary to scenarios 1 and 2, The design configurator requires a standardisation level on modular and concept level, meaning that not every detail has to be modeled. In fact, for the design configurator, the necessary developed objects are dependent on the desires of which modules are implemeted in the configurator. All the modules that are desired in the configruator, have to be included in a as a modeled family instance in the kit-of-parts.

Standardised cost data and exchanges conditions

Similar to the component library, not all fixed cost estimations are predefined for the standardised 85% of PreModu. Referring back to Table 6.12, predefined cost estimations for bathroom type A is defined for house 6, but predefined cost estimations for bathroom type B is lacking for house 6. The cost estimations must be predefined and complete for these options, resulting in **C7.1 Cost data in ERP must be complete in terms of PreModu**. For the design configurator, the standardised component level need to be further expanded to the full 100%, if standardised components are developed. Also, for the complete conceptual component library, data exchanges have to be standardised, requiring **C7.2: Cost data exchanges from ERP to Excel must be standardised**.

Conditions for information needs, according to (ISO 19650-1)

In this case, data need to be generated per module on conceptual level. The conditions **C2.1 Complete geometric information**, **C2.2: Complete alphanumerical information** and **C2.3: Presence of all documents in the right format** are re-used while it does not refer to a project BIM model but it refers to the kit-of-parts for every component/ module. For every module in the kit-of-parts, the necessary information to determine its cost is required. This could differ per conceptual module. For example, if all the different front facade types are encapsulated as modules in the design configurator and thus the kit-of-parts, necessary cost information has to be modeled. For front facade types, this could be the material of wall finishing, the frame opening material, the squared metres per wall finishing material. This should thus be developed and available per module in the kit-of-parts. Again, this is dependent on which modules and preferences are desired in the design configurator. Since customers are deriving their own conceptual design, which leads to corresponding predefined conceptual costs, LOD 100[12] is already sufficient. Note that if the client is satisfied with this conceptual design, the design process will start and LOD 300 is necessary for the actual design and cost estimation process, as explained in Scenario 1B and 2 from PreModu.

Design configurator conditions

Additionaly, new conditions arise through implementation of the design configurator. **C9.1: Model every instance of a family type in a kit-of-parts**. Clearly, the design of the design configurator can unravel itself in a significant number of conditions. However, the outline of the design configurator is out of the scope for this research, resulting in limited conditions. The conditions are limited to **C9.2: Establish a web-based design configurator platform** and **C9.3: Utilise and connect Revit and Excel databases as the Data tier**

There are two levels of cost data that needs to be established. First of all, the conceptual cost database, which derives a cost item for every instance in the kit-of-parts. Dynamo seems to be the easiest way to do this, and is already proved in section 6.4. A similar, yet Dynamo adapted script can be utilised to establish a cost database for the modules in the kit-of-parts. **C9.4: Dynamo script that derives conceptual cost items**.

On the other hand, the conceptual cost items must be translatable into conceptual project parameters, defined by the user of the design configurator. This can be achieved in various manners,

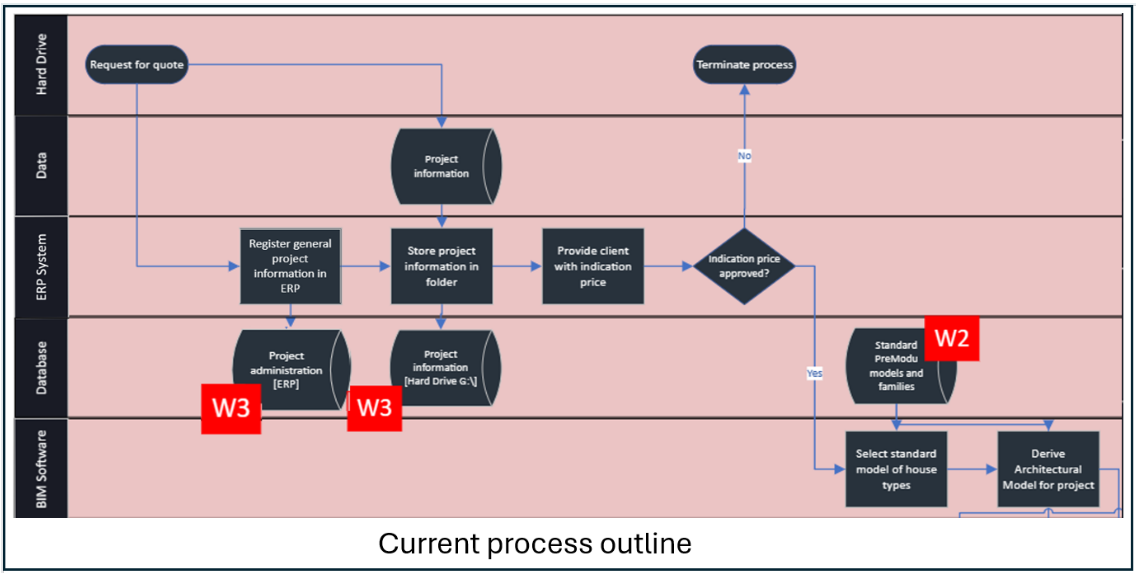
[12] Level of Development (LOD), originally founded by AIA and adopted by BIMForum

such as Dynamo to implement cost data in the modules or connect the resulted design to the conceptual cost database. In Cao et al. (2021), Application Programming Interfaces (API) are utilised, such as MongoDB. In conclusion, the condition is limited to **C9.5: Link project specifications to the conceptual cost items** and leaves the method unspecified.

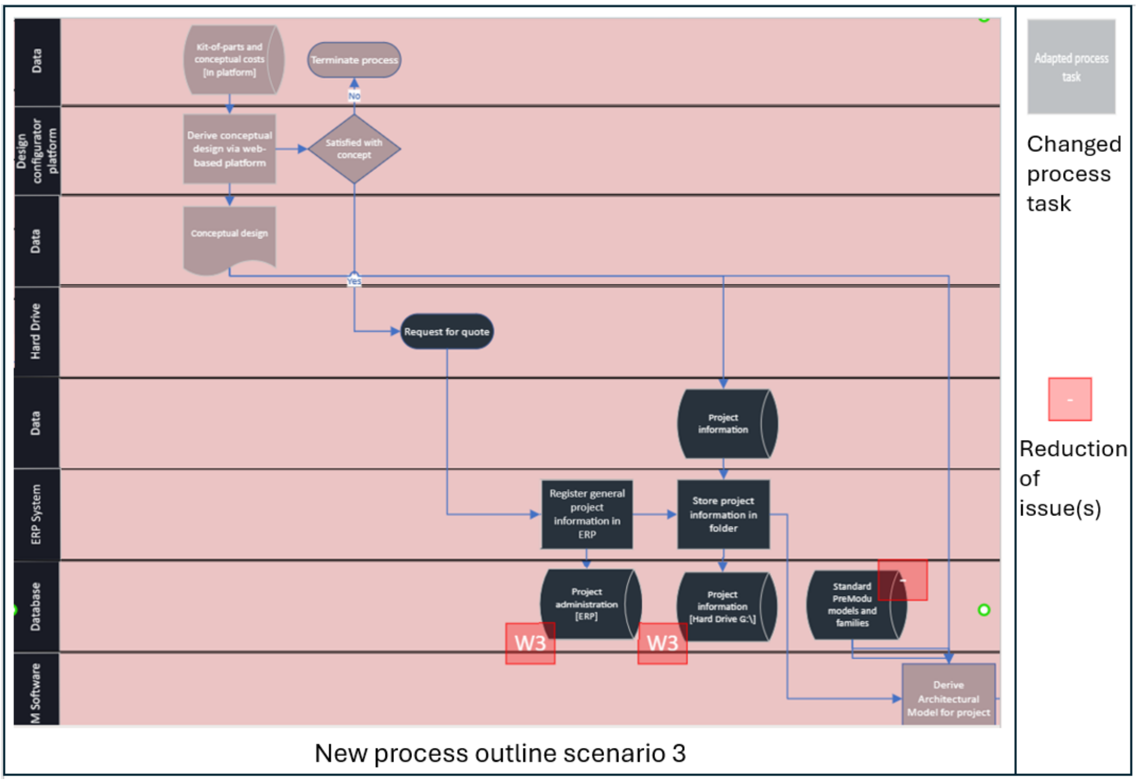
6.5.3 Process changes and value

Potentially, this scenario can have the most changes. Actually, for this scenario specifically, the cost estimation process must be extended. Revealed in Figure 44b, a web-based design platform is supplemented to the current process structure, which is fed from PreModu's databases.

The client can explore PreModu's potential through an independent online platform or with guidance from an Emergo representative. This allows for gathering and analyzing multiple designs to select the most suitable one. **Dynamic cost estimations** ensure that design or cost database changes reflect the latest prices per component and for the overall design. Upon approval of the design and conceptual price, clients can request a quote for further development, benefiting from **Automatic indication prices**. An online platform can potentially expand Emergo's client base, increasing **Reach of clients**. Moreover, **Automatic client interaction** reduces effort for both parties, enhancing overall satisfaction. Visualizing conceptual designs can also improve **Client satisfaction** by providing a clearer project vision. Additionally, data obtained through the platform can inform strategic decisions, leveraging **Data analytics**.



(A) Old process outlinte



(B) New process outline (PreModu scenario 3)

FIGURE 44: Old process outline vs. new process outline, PreModu scenario 3

On the technical front, the linkage between conceptual components in Revit's kit-of-parts library and corresponding cost items enables **Complete automatic cost estimations** at a conceptual level. Database transitions are automated through **Connected databases**, reducing manual intervention. Depending on the design's detail level, it can be reused at various stages, automatically registering project information in ERP or deriving preliminary designs in Revit. Future plans include web-based platforms capable of importing, designing, and exporting Revit databases, streamlining integration with Timber Modeling System A and potentially automating parts of the supply chain. This integration offers the **Possibility to integrate with the supply chain**, fostering **Enhanced standardisation** and efficiency across the product lifecycle.

6.5.4 Summary of scenario

This scenario is plainly the one that requires the most developments and implementations. Meanwhile, the scenario is reaching a high-level of automatisation across PreModu's cost estimation process and the entire concept. This high level of automatisation touches the characteristics of industry 4.0 in the construction sector. Table 6.16 shows the conditions and value of the scenario.

Conditions	Value
C2.1: Complete geometric information	**Complete automatic cost estimations**
C2.2: Complete alphanumerical information	**Connected databases**
C2.3: Presence of all documents in the right format	**Dynamic cost estimations**
C6.1: Establish an information development document, according to LOIN (ISO 19650-1)	**Accurate measurements**
C6.4: Complete Revit Families for PreModu on object level	**Potentially faster**
C6.5: Complete Revit modeling families on modular level	**Enhanced standardisation**
C7.1: Cost data in ERP must be complete in terms of PreModu	**Automatic indication prices**
C7.2: Cost data exchanges from ERP to Excel must be standardised	**Automatic client interaction**
C9.1: Model every instance of a family type in a kit-of-parts	**Client satisfaction**
C9.2: Establish a web-based design configurator platform	**Reach of clients**
C9.3: Utilise and connect Revit and Excel databases as the Data tier	**Data analytics**
C9.4: Dynamo script that derives conceptual cost items	**Possibility to integrate with supply chain**
C9.5: Link project specifications to the conceptual cost items	

TABLE 6.16: Value and conditions that Scenario 3 entails

6.6 Conclusion

In this chapter, the design of scenarios is conducted, which constitutes the culmination of our investigation into the research question *(3) Which BIM-based scenarios can be employed and tailored to meet specific requirements?* In total, five scenarios have been devised, encompassing three for PreModu and three for PreFab. The PreFab scenarios center on information takeoffs and parametric modeling for generating roof elements. Conversely, the PreModu scenarios also incorporate information takeoffs, alongside automated cost estimations facilitated either through Dynamo or via a configurator.

Each scenario is accompanied by a set of conditions, detailed individually and consolidated in Table 7.1. Similarly, the value proposition of the BIM solutions is delineated for each scenario and summarized in Table 7.2. Furthermore, the validation and verification of these scenarios have been undertaken through requirements checks and focus group sessions.

Chapter 7

Roadmap design

In this chapter, the derived BIM scenarios are evaluated and placed within a roadmap, outlining the various pathways that Emergo can pursue to enhance cost estimations through the adoption of BIM methodologies. Addressing the following research questions:

4. What are useful criteria for assessing the BIM scenarios and how are these translated to a roadmap for Emergo?
    (a) How can the scenarios be assessed to evaluate the feasibility, benefits, and potential challenges of the derived scenarios in the context of PreModu and PreFab projects?
    (b) How can a strategic roadmap be designed to guide Emergo in the successful implementation of BIM scenarios to enhance the efficiency and integration of the calculation processes for both PreModu and PreFab projects?

Initially, the derived scenarios undergo assessment for their feasibility, benefits and challenges. scenarios are evaluated in consultation with stakeholder from Emergo where the working, conditions and value as main topic of the discussion. Finally, the scenarios are assessed, based on these meetings and findings.

Subsequently, a roadmap is developed following the design cycle outlined by Wieringa (2014). By aligning stakeholder goals with literature-derived roadmap guidelines, necessary design requirements are established. These requirements, along with the scenario assessments, serve as the foundation for designing the roadmaps. Finally, the validity of these roadmaps is verified in collaboration with the client and through a requirement's check.

7.1 Scenario Assessment

Given the conceptual state of each scenario, quantitative assessment is impractical, lacking metrics such as accuracy enhancement, time reduction, or precise costs. Therefore, a qualitative approach is adopted. Each scenario is examined in its potential application at Emergo, including the necessary conditions and eventual value it offers. These aspects form the basis of the scenario evaluation conducted with Emergo stakeholders, guiding the assessment process.

Feasibility is contingent upon meeting the conditions required for scenario implementation. By addressing these conditions, the feasibility of each scenario can be determined, identifying necessary actions. Benefits stem directly from the value proposition of each scenario. Conversely, potential challenges are assessed based on the complexity of meeting conditions and inherent risks associated with each scenario.

7.1.1 Feasibility

The conditions tend to be crucial to assess the feasibility of each scenario, as they provide the resources that enable a scenario. All conditions are detailed in Table 7.1, accompanied by an occurrence check for each scenario. This analysis reveals the frequency of each condition and facilitates comparison between scenarios. Additionally, conditions for PreFab can be categorised into those directly controlled by Emergo and those influenced by external factors. Consequently, Table 7.1 segregates conditions into internal and external categories, with internal conditions being more manageable. Conversely, for PreModu, all conditions are deemed within Emergo's reach.

Conditions	Int.	PF:Ext.	PF1	PF2.a	PPF2.b	PM1.a	PM1.b	PM2	PM3
C1: Quality conditions for BIM models									
C1.1: Correctly classified BIM Models		✓	✓						
C1.2: Correctly modeled BIM		✓	✓		✓	✓	✓	✓	
C1.3: Complete BIM model		✓	✓			✓	✓	✓	
C2: Conditions for information needs, according to (ISO 19650-1)									
C2.1: Complete geometric information		✓	✓	✓	✓	✓	✓	✓	✓
C2.2: Complete alphanumerical information		✓	✓	✓	✓	✓	✓	✓	✓
C2.3: Presence of all documents in the right format		✓	✓	✓	✓	✓	✓	✓	✓
C3: Conditions for information takeoff's procedures									
C3.1: A check for classification issues	✓		✓						
C3.2: A check for quality of the BIM	✓		✓						
C3.3: Establish an information requirement document, according to LOIN (ISO 19650-1)	✓		✓	✓	✓				
C3.4: Standard ITO definitions	✓		✓			✓	✓		
C3.5: Raw data processing algorithms in cost estimation software	✓		✓	✓	✓	✓	✓		
C3.6: Standardised and complete component library in cost estimation model	✓		✓	✓	✓				
C3.7: Complete cost items in cost estimation models	✓		✓	✓	✓	✓	✓		
C4: Dynamo script conditions to generate roof models									
C4.1: Dynamo script must result in roof elements	✓			✓	✓				
C4.2: Dynamo script provide an error log	✓			✓	✓				
C5: Revit conditions to generate roof elements									
C5.1: Revit skills by cost estimator	✓			✓	✓				
C5.2: A Revit family must be accessible, containing Emergo's standard roof types	✓			✓	✓				
C5.3: Derive or adapt technical details based on the generated roof model	✓			✓	✓				
C6: Modeling conditions for PreModu									
C6.1: Establish an information development document, according to LOIN (ISO 19650-1)	✓					✓	✓	✓	✓
C6.2: BIM model must be established out of PreModu's Revit libraries	✓					✓	✓	✓	
(C6.3: Object must be related to a house number of modeling group)	✓					✓	✓	✓	
C6.4: Complete Revit Families for PreModu on object level	✓						✓	✓	✓
C6.5: Complete Revit modeling families on modular level	✓						✓	✓	✓
C7: Standardised cost data and exchanges conditions									
C7.1: Cost data in ERP must be complete in terms of PreModu	✓						✓	✓	✓
C7.2: Cost data exchanges from ERP to Excel must be standardised	✓						✓	✓	✓
C8: Dynamo scripts conditions for automated cost estimations									
C8.1: Dynamo must be able to extract all cost data at any time	✓							✓	
C8.2: Dynamo must be able to read BIM models, components and parameters	✓							✓	
C8.3: Dynamo must connect object data to the corresponding cost data	✓							✓	
C8.4: Automated checks should be incorporated in the dynamo script to evaluate results	✓							✓	
C8.5: The total costs and a log report should be the output of the Dynamo player	✓							✓	
C9: Design configurator conditions									
C9.1: Model every instance of a family type in a kit-of-parts	✓								✓
C9.2: Establish a web-based design configurator platform	✓								✓
C9.3: Utilise and connect Revit and Excel databases as the Data tier	✓								✓
C9.4: Dynamo script that derives conceptual cost items	✓								✓
C9.5: Link project specifications to the conceptual cost items	✓								✓
Number of Internal/External conditions	-	-	7/6	9/3	9/4	11/0	15/0	17/0	13/0

TABLE 7.1: All conditions divided among internal and external conditions, and listed on appearance per scenario

For PreFab, **Scenario 2A** requires one condition less (12) than the other two scenarios (13), as it does not necessarily demands a BIM model. **Scenario 2B**, on the other hand, necessitates the presence of a correct BIM model, including accurate roof geometries. Both **Scenario 2A** and **2B** share overlapping conditions for the remaining aspects. In contrast, **Scenario 1** entails a similar number of conditions as **2B** (13), but the composition of conditions differs, particularly in the division between internal and external factors. For **Scenario 1**, Emergo is heavily reliant on external factors such as BIM model classification and data quality, resulting in fewer internal conditions compared to the roof generator scenarios. Based on the condition evaluation, the feasibility ranking from most to least feasible is as follows:

1. **PreFab Scenario 2A**

2. **PreFab Scenario 2B**
3. **PreFab Scenario 1**

For PreModu, all conditions are considered internal, as Emergo oversees the entire process and BIM models are developed on its behalf. **Scenario 1** is associated with the fewest number of conditions (11). Surprisingly, **Scenario 3** only requires 13 conditions. However, the abstract nature of some conditions (e.g., **C9: Establish a web-based configurator platform**) means that they entail additional research and thus additional conditions for these specific developments. Therefore, in reality, the design of this scenario entail significantly more requirements than the stated 13. **Scenario 1B** is an extension of **1A**, adding four additional conditions focused on complete data libraries. **Scenario 2** shares an equal number of conditions with **1B**, concerning BIM model and data library developments. However, the technical approach results in a different number of conditions, with more conditions associated with Dynamo script development compared to information takeoffs.

1. **PreModu Scenario 1A**
2. **PreModu Scenario 1B & 2**
3. **PreModu Scenario 3**

7.1.2 Benefits

The values of each scenario can be compared to evaluate their benefits. Since these values are not linked to quantitative data such as time reduction or accuracy improvement, a qualitative approach is necessary. Table 7.2 presents the various values contributed by each scenario, categorised into benefits for PreFab and PreModu.

Values for PreFab	PF1	PF2.a	PPF2.b	–	–	–	–
Accuracy	✓	✓	✓				
Potentially faster	✓	✓	✓				
Automatic measurements	✓		✓				
Automatic quantification	✓	✓	✓				
Automatic division of roof elements		✓	✓				
Timber Modeling System A-integration		✓	✓				
Exploit other BIM-uses (construction analysis)		✓	✓				
Values for PreModu	–	–	–	**PM1.a**	**PM1.b**	**PM2**	**PM3**
Accuracy				✓	✓	✓	✓
Potentially faster				✓	✓	✓	✓
Automatic measurements				✓	✓	✓	✓
Automatic quantification				✓	✓	✓	✓
Complete automatic cost estimations					✓	✓	✓
Dynamic automatic cost estimations						✓	✓
Connected databases						✓	✓
Client interaction, satisfaction and reach							✓
Data analytics							✓
Supply chain integration							✓

TABLE 7.2: All values listed on appearance per scenario

In terms of PreFab, **Scenario 1** offers value similar to **2A** and **2B**, yet at a different level. While **Scenarios 2A** and **2B** focus on roof elements, **Scenario 1** targets other components like windows. Comparing these values directly proves challenging due to the varying nature of the components. Nevertheless, since the roof is a pivotal component in PreFab projects and its division is a time-intensive task in cost estimation, **Scenarios 2A** and **2B** tend to provide more value. Moreover,

Scenario 2B surpasses **2A** as it eliminates the need for manual roof measurements. Consequently, the order of value within PreFab is as follows:

1. **PreFab Scenario 2B**
2. **PreFab Scenario 2A**
3. **PreFab Scenario 1**

For PreModu, comparing values is more straightforward as all scenarios contribute to similar tasks. **Scenario 1B** introduces one additional value compared to **1A**, which significantly enhances the cost estimation process by transitioning to complete automated calculations. Moving forward, **Scenario 2** offers more value than **1B** by avoiding manual data exchanges through integrated databases. Finally, **Scenario 3** yields the highest value, not only automating the cost estimation process but also integrating prior and subsequent processes, extending the benefits beyond mere cost estimations. Based on this evaluation, the order of benefits within PreModu is determined as follows:

1. **PreModu Scenario 3**
2. **PreModu Scenario 2**
3. **PreModu Scenario 1B**
4. **PreModu Scenario 1A**

7.1.3 Challenges and costs

Challenges

The scenario assessment concludes with an examination of the potential challenges associated with each scenario, which have been identified through scenario evaluations involving multiple stakeholders at Emergo. These challenges may arise even if all conditions are met, representing inherent risks to the implementation of each scenario. The identified challenges for each scenario are as follows:

- **PreFab Scenario 1**
  - Missing elements in the BIM model are undetected by quality checks and remain excluded from information takeoffs, leading to the fact that they are not taken into account.
  - Maintaining the current level of detail in Emergo's cost estimation model may be challenging with the implementation of Scenario 1, necessitating potential revisions to the cost estimation process, such as relying more on square meter prices rather than object prices.
  - There is a risk of losing Emergo's expertise if the cost estimation process becomes more automated, potentially resulting in missed opportunities for enhanced solutions or design changes.
- **PreFab Scenario 2A**
  - Standardising design flexibility poses a significant challenge, as PreFab designs can vary widely, requiring numerous input variables to generate a roof. Manual adjustments of the generated roof model are likely to be necessary, which may be time-consuming, potentially offsetting any time reductions.

- Cost estimators may need to make manual adjustments, supplementing modeling tasks in the cost estimation process and requiring a solid knowledge of Revit. Resistance to such drastic changes in the roles of cost estimator employees may arise.

- **PreFab Scenario 2B**
  - Similarly, as seen in scenario 2A, cost estimators will need a base level of Revit experience, and their roles will change, potentially facing resistance from the cost estimation department.
- **PreModu Scenario 1A**
  - No significant risks or challenges have been identified for this scenario.
- **PreModu Scenario 1B**
  - Maintaining the background processes poses a challenge, including the maintenance of standard ITO's, manual data exchanges and data processing formulas. These background procedures may introduce errors that are difficult to detect, particularly after concept changes in PreModu.
- **PreModu Scenario 2**
  - The main risk with this scenario lies in the background processes. The dynamo script required for all PreModu components can be complex and error-prone, requiring adequate and careful maintenance to ensure its accuracy.
- **PreModu Scenario 3**
  - Determining the appropriate level of complexity within the designs offered by the configurator poses a challenge, as it must align with client expectations while accommodating unique solutions within the PreModu process. Some clients may prefer personalised interaction over a configurator.
  - Sharing information with competitors is a risk, as initial cost data will be made public, allowing competitors to adjust their strategies and prices accordingly.

Costs

While this research does not delve into estimating the absolute costs per scenario, it allows for relative comparisons between them. This section presents assumptions regarding costs, with a recommendation for further research to obtain precise figures.

For PreFab, scenarios 2A and 2B focus on internal developments, whereas scenario 1 also involves external BIM model developments. Consequently, scenarios 2A and 2B are expected to incur higher expenses due to the development of parametric roof modelers in Revit.

In the case of PreModu, scenario 1 appears to have lower costs, primarily requiring the development of standard ITO and cost estimation procedures. Conversely, scenarios 1B, 2, and 3 necessitate the development and completion of libraries, which can be costly. However, these expenses are common to all PreModu scenarios. Scenario 3, however, involves additional developments such as the kit-of-parts and the house configurator, making it potentially significantly more expensive than the other PreModu scenarios.

7.1.4 Conclusion of assessment

In conclusion, the scenarios could not be evaluated in a quantitative manner due to the lack of quantitative data. On the other hand, qualitative assessment is accomplished for feasibility, benefits and challenges via scenario evaluations with stakeholders including working, conditions and value as main theme. These insights turned out to be very useful in prioritising the scenarios and gave input for the sequence and interpretation of the roadmap. The sequel in the roadmaps is thus supported by this assessment, which is further explained in section 7.3 per branche, PreFab and PreModu

7.2 Roadmap template

Per concept, PreFab and PreModu, the evaluated and assessed scenarios have to be placed in a strategic outline, a roadmap. To derive these roadmaps, another iteration of the design cycle (Wieringa, 2014) has been applied. In this section, the roadmap requirements are derived, resulting in a roadmap template. The requirements are derived via stakeholder needs, which are supplemented with general requirements for roadmapping located in literature.

7.2.1 Stakeholder needs

At the outset, this research aimed to identify BIM-based scenarios to enhance cost estimation processes for both PreFab and PreModu. Moreover, it sought to assess and compare these scenarios using a roadmap framework. For Emergo, such a roadmap is indispensable for making strategic decisions, offering a clear timeline of scenarios along with their associated costs and benefits. The problem analysis in section 1.4 highlighted a lack of strategic direction in implementing BIM for improved cost estimation processes at Emergo. Furthermore, the detailed process analyses of the cost estimation processes for PreFab and PreModu in 3.2 underscored the specific issues that the BIM scenarios are intended to address.

These specific BIM scenarios need to be integrated back into the broader strategic perspective, zooming out to return the research focus to a strategic level. These identified problem statements, combined with insights from stakeholder interviews, have led to the following needs for Emergo:

- Need for a strategic overview for each concept, PreFab, and PreModu, mapping the current state to the desired state of the cost estimation process.
- Need to include various strategic routes and optional pathways that can be pursued to achieve the desired state.
- Need to divide these strategic routes into multiple actionable steps, delineating the necessary actions to realise the scenarios.
- Need for a development of an estimated timeline indicating when the scenarios and the desired state of the cost estimation process can be achieved.
- Need for an identification of the direct conditions that must be fulfilled to unlock the implementation of each strategic step or scenario
- Need for a provision of an overview of the benefits associated with each scenario, encompassing both immediate process-level benefits and broader conceptual or market-level advantages that can be attained

7.2.2 Roadmap characteristics from literature

Definition

Originally rooted in industrial engineering, roadmapping has evolved into an effective method for aligning investments in technologies. It has found application across various systems, from processes to organisational and sectoral levels, and even at an international scale. Today, roadmapping is widely adopted by diverse domains and sectors to tackle challenges or drive initiatives (Kerr and Phaal, 2021).

A roadmap serves as a planning and alignment tool for organisations. It outlines future goals in a timeline and ensures coordination across different aspects and perspectives to achieve these objectives. Roadmaps provide valuable input for decision-makers and support strategic communication (Kerr and Phaal, 2021). The following definition for a roadmap has been defined by Kerr and Phaal (2021), which is unravelled into characteristics in the next section:

- *A roadmap is a a structured visual chronology of strategic intent*

Characteristics

The characteristics of a roadmap, as defined by Kerr and Phaal (2021), along with additional insights from connected literature, are outlined below.

1. **Structured visual**: A roadmap is primarily visual, aiding in knowledge construction and communication. Its graphical representation facilitates information transfer and enhances understanding (Phaal and Muller, 2007; Phaal et al., 2008; Phaal and Muller, 2009)). Behind the visual elements lies an organised information structure detailing the current state of the process and the conditions required for progression towards the desired state. Additionally, the inclusion of a time variable makes the roadmap dynamic (Kerr and Phaal, 2021).

2. **Strategic Intent**: The roadmap embodies a strategic intent, representing a vision or direction for the future. It articulates a unique perspective on competitive innovation and flexibility, increasing the likelihood of achieving strategic objectives by coordinating different aspects of the plan (Kerr and Phaal, 2021).

3. **Chronological Order**: A roadmap follows a chronological order, narrating the logical connections between information elements. Each layer of the roadmap represents a chapter or checkpoint, contributing to a cohesive narrative. Chronological sequencing accommodates dynamic changes and future possibilities (Kerr, 2021).

4. **Layered Structure**: Phaal and Muller (2009) emphasize the importance of a multi-layered approach in roadmapping. This structure allows for different levels of detail regarding strategic intentions. The top layers addresses the *Why?*, elaborating the developments on concept and organisational level, as well as the broad developments such as: market, social, technical, environmental, economical, and political. The middle layer focuses on the *What?*, which is the direct product or service to be developed. Lastly, the bottom layer encompasses the *How?* resources like technology, skills, and finance necessary for implementation (Phaal and Muller, 2009).

7.2.3 Roadmap requirements and template

In this section, the treatment requirements for the roadmap can be established. The stakeholder needs for the roadmap and general roadmap characteristics from literature can be combined to

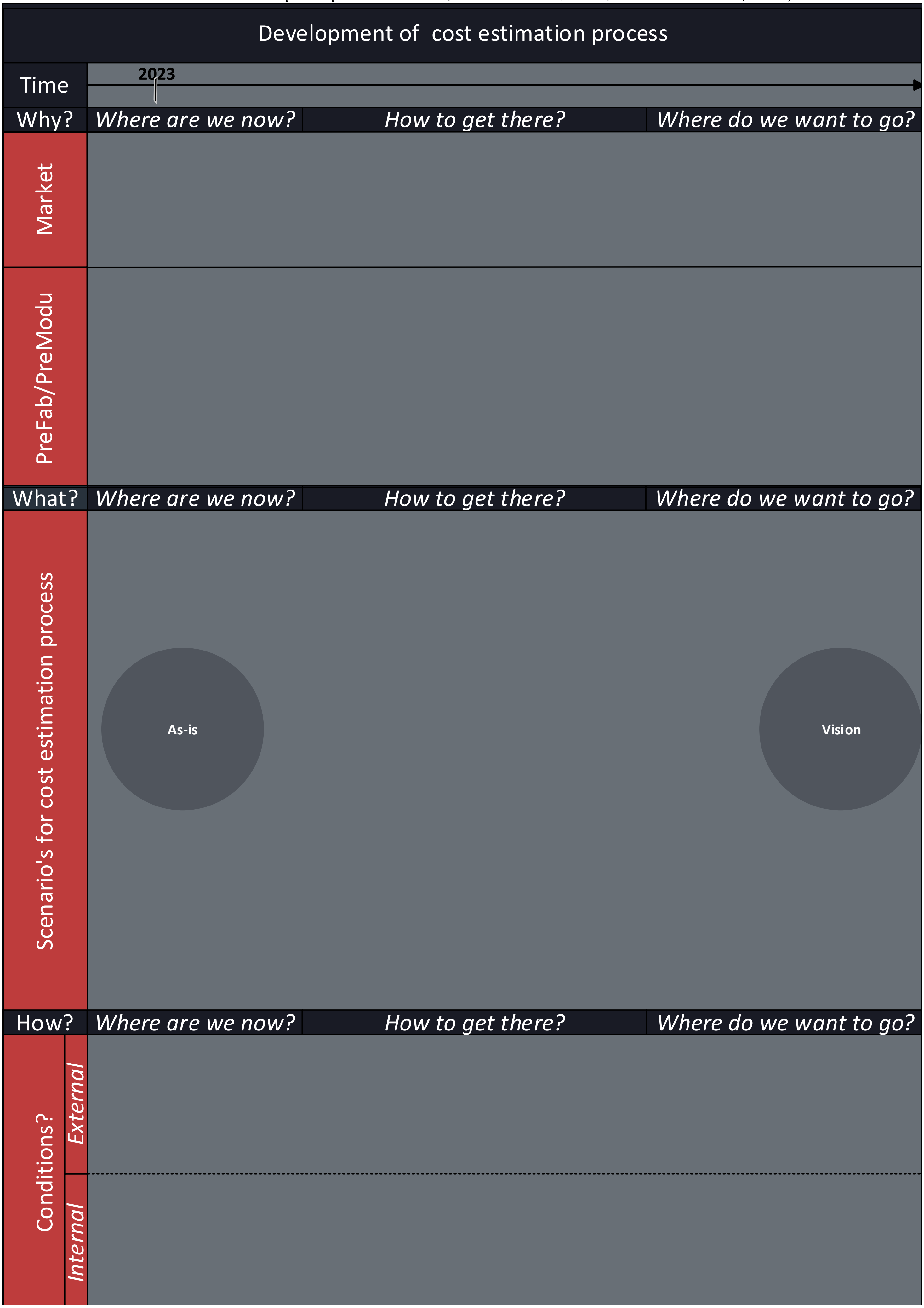
Stakeholder needs	Characteristics	Treatment requirement
Need for a strategic overview for each concept, PreFab, and PreModu, mapping the current state to the desired state of the cost estimation process	Strategic Intent Structured visual	**R1.1 Roadmap must start from as-is scenario** **R1.2 Roadmap must end at the desired state of the cost estimation process** **R1.3 The desired state of the cost estimation process must include a vision** **R1.3 Roadmap must entail one strategic route for one concept (PreFab/PreModu)** **R1.4 Roadmap must be represented in one visual**
Need to include various strategic routes and optional pathways that can be pursued to achieve the desired state		**R2.1 Roadmap must include all possible routes that Emergo can take to reach the desired state** **R2.2 Roadmap must reveal optional pathways**
Need for to divide these strategic routes into multiple actionable steps, delineating the necessary actions to realise the scenarios.		**R3.1 Roadmap must include crucial steps that unlock the scenarios**
Need for a development of an estimated timeline indicating when the scenarios and the desired state of the cost estimation process can be achieved	Chronological Order	**R4.1 Roadmap must contain a timeline** **R4.2 The scenarios must be placed in the estimated point of time**
Need for an identification of the direct conditions that must be fulfilled to unlock the implementation of each strategic step or scenario		**R5.1 Each scenario must be connected to the necessary conditions** **R5.2 The conditions must be placed in order of development sequence**
Need for a provision of an overview of the benefits associated with each scenario, encompassing both immediate process-level benefits and broader conceptual or market-level advantages that can be attained		**R6.1 Value for cost estimation processes must be revealed per scenario** **R6.2 Value on broader (organisational/market) level must be revealed per scenario** **R6.3 Value must be placed in order of achievement sequence**
	Layered Structure	**R7.1 The bottom layer must contain the conditions (the how?)** **R7.2 The bottom layers must distinguish internal and external conditions** **R7.3 The middle layer must contain the scenarios (the what?)** **R7.4 The top layer must contain the values (the what?)**

TABLE 7.3: Treatment requirements for the Roadmap

derive the treatment requirements. Subsequently, a template can be established in which the scenarios can be placed.

A roadmap template, depicted in Figure 45, is derived following the characteristics and framework outlined by Kerr and Phaal (2021); Phaal and Muller (2009). This generic template is applicable to both PreFab and PreModu. The top layer is regarded as the "why?" layer, addressing general market and process-related aspects of PreModu or PreFab separately. The middle layer focuses on the cost estimation scenarios, considered as the "what's", whose functioning contributes value to the top layers. The bottom layer introduces the conditions that ensure the functioning of the scenarios, thus the "how's". All layers have a timeline for the current and desired states of each layer, where Emergo's vision for cost estimation's is included in the middle layer.

FIGURE 45: Roadmap Template, based on (Kerr and Phaal, 2021; Phaal and Muller, 2009)



7.3 Final Roadmaps

In section 7.1 and in section 7.2, the scenarios have been evaluated and the roadmap requirements have been established and translated into a roadmap template. Combining these two aspects, can result in the final roadmaps, where the evaluation of the scenarios is the input while the template is the framework in which the evaluation becomes visible.

7.3.1 PreFab's Roadmap

In the evaluation conducted in section 7.1, it became evident that **PreFab Scenario 1** exhibited the least feasibility and offered fewer potential benefits compared to **PreFab Scenarios 2A** and **2B**. As a result, this scenario has been positioned last in the timeline. When assessing **PreFab Scenarios 2A** and **2B**, they were found to be relatively equal. However, **Scenario 2B** presents additional advantages by eliminating the need for manual measurements and adjustments, as it involves copying the outline of existing roof components. Conversely, **Scenario 2A** is more feasible as it doesn't necessitate existing BIM models. The challenges associated with both scenarios are also quite similar. Therefore, they have been included as options within the roadmap, which is logical considering the likelihood of implementing both scenarios is lower. This sequence has also been validated through consultation with Emergo.

The roadmap of PreFab is visible in Figure 46 and commences with the creation of an information exchange document, conforming to LOIN (ISO 1965-1), which serves as an internal prerequisite for all PreFab scenarios. This document enables Emergo to influence the development of BIM models provided by clients, offering potential incentives such as discounts while respecting client preferences to mitigate the risk of losing clients. Additionally, Emergo can establish agreements with regular clients regarding required information, providing a level of influence over external conditions (C1.1 - C2.3). Thus, Emergo is not in control of these external conditions, yet not powerless.

Subsequently, the initial focus is on generating roof models, necessitating a choice between creating them from scratch (Scenario 1A) or overlaying existing BIM models (Scenario 1B). While the latter option offers added value, it depends on the external quality of the BIM models. These scenarios are prioritised due to Emergo's significant control over them, where conditions are mainly internal. Standardised flows of data have to be developed and maintained to unleash all the benefits, such as automatic element division and further integration with Emergo's engineering software, which is called Timber Modeling System A. This leads to a faster and more accurate process

Ultimately, Emergo aims to increase reliance on BIM information takeoffs from client-delivered designs, with the goal of full deployment of scenario 1 and scenario 2A or 2B by 2026-2028, contingent on the overall standardisation level of BIM models provided by clients. In the interim, Emergo can begin generating core PreFab elements, such as roof components (scenario 2A or B). Upon deployment of both scenarios, automated quantification, measurements, and cost estimations become feasible, provided that standardised information takeoffs, quality checks, and data processing routines are established beforehand.

From a market perspective, the transition to holistic data management contrasts with the initial fragmented industry landscape, where data loss was prevalent. With these developments, coordinated data management facilitates faster and more accurate processes.

7.3.2 PreModu's Roadmap

Based on the assessment detailed in section 7.1, the sequence of scenarios within the roadmap has been established. **Scenario 1A** emerges as the most feasible option. Remarkably, this scenario is already ripe for implementation, positioning it logically as the initial step despite offering fewer benefits. Conversely, **Scenario 3** ranks highest in terms of potential benefits but lowest in feasibility assessment. This disparity arises from its reliance on the functionality of automated cost estimations, thus necessitating the completion of **Scenario 1B** or **Scenario 2** beforehand. Moreover, **Scenario 3** presents the most formidable challenges. Meanwhile, **Scenario 2** exhibits comparable feasibility scores to **Scenario 1A** but outperforms it in benefits due to reduced manual data exchanges. Specifically, **Scenario 2** facilitates cost estimation via interconnected databases, automatically linked through a Dynamo script. Consequently, **Scenario 2** claims the foremost position in the roadmap. Nonetheless, the roadmap incorporates an option, allowing Emergo to select between these scenarios, as they serve the same purpose. Thus, the choice between **Scenario 2** and **Scenario 1A** hinges on Emergo's preference.

The roadmap for PreModu, depicted in Figure 46, shares similarities with PreFab's initial focus on developing information development documents (LOIN, ISO 1965-1). However, Emergo's role differs, as it determines modeling guidelines instead of information exchange requirements. This utilises Emergo greater control over which information is developed in BIM models, enhancing its influence over external conditions (C1.1-C2.3). Emergo outsources the BIM modeler, which enables Emergo to demand these conditions.

Subsequently, Emergo can swiftly implement standard Information Takeoff (ITO) routines and Scenario 1A. This scenario allows for the extraction of project-dependent data from BIM models, resulting in additional value compared to the current cost estimation process, although the gained value is considered low.

The pivotal step in PreModu's roadmap is the acquisition of standard complete Revit families and corresponding cost items, projected for completion by the end of 2025. Once these data libraries are established, Emergo can leverage their significant value through various BIM-based methods, such as information takeoffs, automatic cost estimations in Revit, or even integrated cost estimations via a web-based design configurator. Subsequent scenario development and implementation rely on these crucial conditions.

Ultimately, the endpoint for PreModu is integrated cost estimations by 2026, extending beyond cost estimations to encompass the entire supply chain. Clients can initiate an online conceptual design, which transitions into a preliminary BIM model in Revit. Timber-framed construction elements can be converted to production drawings through Timber Modeling System A-integration, while all BIM model elements are automatically calculated and integrated with subsequent departments, including purchasing, production, and construction.

From a market perspective, this integrated workflow aligns with Emergo's vision of producing affordable houses efficiently, optimizing efficiency across the supply chain. This approach addresses current housing industry challenges such as shortages, high costs, and project overruns.

Comparison between the two roadmaps

One can immediately spot the main difference of both roadmaps, which already concludes remarks about the difference of both concepts. The roadmap of PreModu is namely more extensive than the one of PreFab, which concludes several statements.

- First of all, the maturity of PreModu's processes, meaning that they still are under a development curve. This can be seen to the number of scenarios and number of conditions, concluding that there is work to be done.
- On the other hand, the potential value of PreModu reaches more perspectives than PreFab. The number of values that can be unleashed is greater, reaching beyond the cost estimation processes.
- Moreover, the market value's of PreModu are considered to be beneficial while PreFab's market contributions are characterised as problem-solving. PreFab scenarios are focussed on a strategy to deal with unique and varying data while PreModu scenarios are focusing on the benefits of standardised components, modules and cost items
- PreFab's conditions are categorised into internal and external conditions, whereas PreModu's roadmap solely encompasses internal conditions. Despite the preliminary BIM model derivation being outsourced, Emergo retains control over this process, thereby exerting a high degree of power and influence. This underscores the divergent strategies between the two concepts.
- In terms of timeline, the initial implementation of a scenario for both approaches is forecasted for 2024. While PreModu's inaugural scenario is already viable, PreFab's requires further development. Moreover, this scenario is expected to yield more value than PreModu's initial scenario.
- For both aspects, the first utilisation of a scenario is projected to be released in 2024. PreModu's first scenario can already be exploited while PreFab's first scenario needs some developments. This scenario will also unleash more value than PreModu's first scenario.

In conclusion, both processes could result in benefits for Emergo's process outcomes. On top of that, these benefits could be an example for the entire construction process, highlighting the possible benefits of BIM and data integration's.

7.3.3 Validation and verification

A conceptual iteration of the roadmap was initially developed, which underwent refinement and finalization during a collaborative session with Emergo's business developer, who initiated this research. During this session, the placement and timeline of the roadmap were meticulously finetuned, resulting in immediate validation.

Furthermore, a requirements checklist was distributed to multiple stakeholders at Emergo, soliciting their feedback on whether all roadmap requirements for PreFab and PreModu were adequately addressed, and if they concurred with both timelines. All respondents affirmed the accuracy of the roadmaps and expressed agreement with their arrangement. Interestingly, all respondents also noted that the envisioned state of PreModu is achieved earlier than PreFab's desired state, despite the developments that need to be conducted.

7.4 Conclusion

The design methodology outlined by Wieringa (2014) has been utilized once again in this study to develop roadmaps for PreFab and PreModu. Research question *(4) What are the relevant criteria* *for assessing BIM scenarios, and how are these criteria translated into roadmaps for Emergo?* has been addressed. The criteria derived from stakeholder sessions, along with the associated conditions and value for each scenario, were instrumental in evaluating the viability of each scenario.

All scenarios underwent assessment based on their benefits, feasibility, and challenges. In the case of PreFab, Scenario 1 emerged as the least feasible, with minimal benefits. Scenarios 2A and 2B exhibited comparable attributes, with Scenario 2B offering greater benefits but posing feasibility challenges. These scenarios have been presented as optional for Emergo, providing flexibility for their selection. Figure 46 illustrates the finalized roadmap, which was crafted based on these assessments, scenario-specific challenges, and feedback from Emergo. The roadmap underwent validation and verification following its development.

Similarly, the scenarios for PreModu underwent assessment, with Scenario 1A ranking highest in terms of feasibility. Despite offering fewer benefits, it was prioritized as the initial step. Scenarios 1B and 2 were presented as alternate options due to their comparable performance in the assessment. Scenario 3, with its lower feasibility score and higher number of conditions, was positioned last. The final PreModu roadmap, depicted in Figure 47, was crafted based on assessments, scenario-specific challenges, and input from Emergo. Like its PreFab counterpart, this roadmap also underwent validation and verification through stakeholder sessions and a requirements check.

FIGURE 46: Roadmap for PreFab, based on the template of Kerr and Phaal (2021); Phaal and Muller (2009)

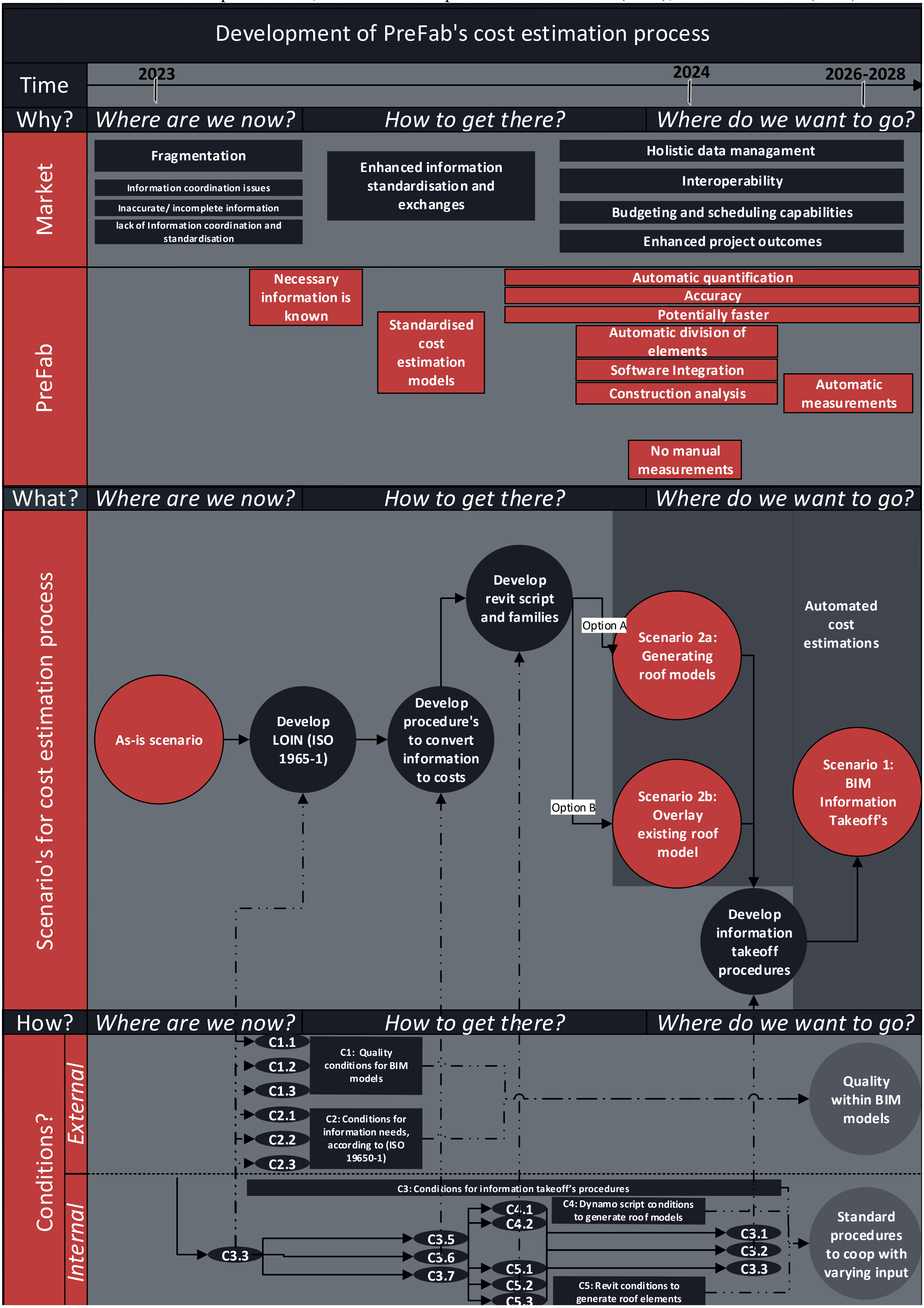
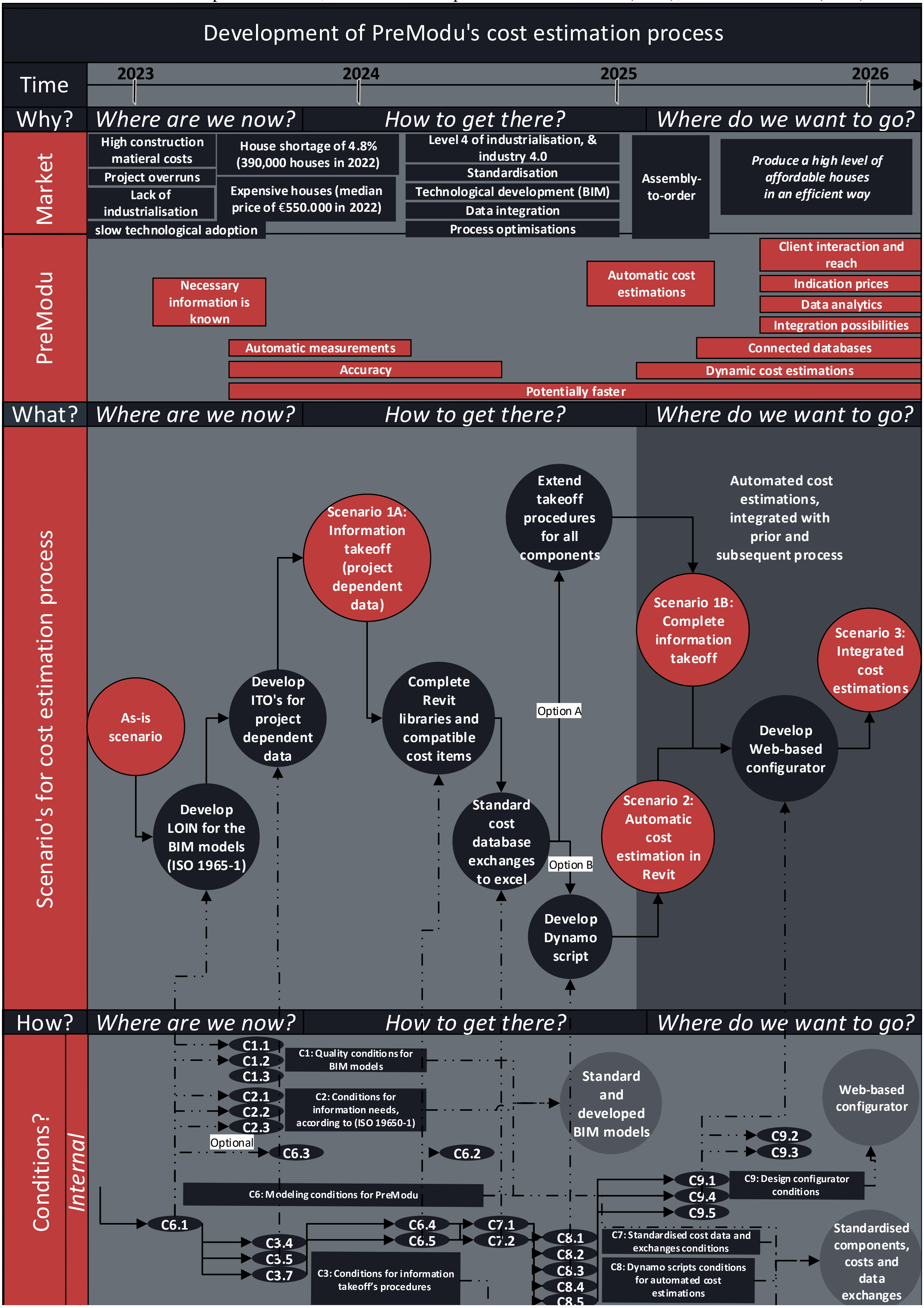


FIGURE 47: Roadmap for PreModu, based on the template of Kerr and Phaal (2021); Phaal and Muller (2009)



Chapter 8

Final Remarks

8.1 Discussion and limitations

In this section, the final results are discussed, including a reflective analysis of the final scenarios and roadmaps. These artifacts serve as the primary outcomes of our study, encapsulating the essence of our design goals. Additionally, we address the inherent limitations of our research. Recognising and acknowledging these limitations is essential, as they underscore areas for potential improvement and avenues for future investigation.

8.1.1 Reflection on Final Results

The findings in this research build upon previous insights outlined in the position paper[1]. Within this paper, the concept of *Author cost estimate* was identified as one of the BIM applications that Emergo was keen on exploring. This study delved into this particular BIM application at a strategic level, providing guidance to Emergo in refining their BIM-based cost estimation process. Moving forward, further research should delve into each scenario meticulously, focusing on the realisation of the desired scenarios.

The final outcomes encompass the scenarios and corresponding roadmaps, synthesised into a coherent timeline. Derived and validated through consultations with multiple Emergo stakeholders, these results align with the company's long-term strategies. The roadmap strategically positions scenarios and is valuable for Emergo to aid them in their decision-making processes concerning the enhancement of cost estimation strategies. Emergo recognised that this research can aid them in their strategic decision-making, where the working, conditions and value per scenario is introduced. A logical timeline can guide Emergo towards their final destination, including crucial steps to adopt each scenario.

However, The research's extensive scope led to predominantly conceptual elaboration of each scenario. Absent critical conditions, like a comprehensive Revit component library or complete cost database, hindered full scenario implementation. Time constraints also limited depth, resulting in proof of concept rather than full realisation, exemplified by conceptual exploration of PreFab scenario 2B. Thus, scenario detail remains brief, serving as an introduction to concepts. As a consequence of the incomplete realisation of each scenario, solutions were verified conceptually, impeding assessment of accuracy and speed until scenarios are fully operational. Thus, requirements were verified potentially, suggesting the scenarios can achieve defined objectives. Consequently, the conceptual nature of each scenario and the uncertainty surrounding their final

[1] *BIM Uses in Modular Construction and at Emergo (working paper)* (Ketabi, 2023)

value and conditions, the roadmap may be deemed incomplete. Full establishment of each scenario could alter the roadmap's structure, introducing some level of uncertainty. During the validation phase, Emergo agreed on the sequel of the roadmaps, and the criteria on how they are evaluated that led towards this sequel.

Nonetheless, proof of concepts demonstrated the potential way of working and benefits, like automated cost estimations in PreModu scenario 2 for roof dormers and gutter elements. Thereby, each scenario has been practically examined as well, which makes the results tangible. The results are thus moving beyond the theory from literature research, and are demonstrated practically. The scenarios have been tested practically in the context of Emergo, resulting in tangible and specific conditions that Emergo need to bridge, rather than general conditions and values. Thus, despite the conceptual states, each scenario has been deriving specifically according to Emergo's desires and characteristics, making it significantly valuable for Emergo.

On top of that, the research results can be be useful for the broader construction industry. In this case, the significance lies in the comprehensive overview provided within the roadmap rather than intricate scenario details. The research highlights differences between unique and standardised designs and identifies potential BIM-based tools applicable to both methods, emphasising the potential caused by standardisation. Additionally, the outcomes offer insights into the value, conditions, and necessary steps for each scenario, extending beyond Emergo's context. While not detailed enough for a comprehensive implementation plan, the results are valuable for comparative analysis and strategic decision-making across scenarios.

In conclusion, the results are in line with the projections and purpose of this research. Despite the fact that scenarios and roadmap are conceptual and far from implementable, strategic directions and potential BIM-based enhancements for cost estimations are discoverd. The roadmaps acknowledge their value in potential directions for PreFab and PreModu, outlining necessary steps for each scenario. The research offers insights into BIM-based concepts applicable beyond Emergo, introducing methods to enhance cost estimations across various contexts. Additionally, it highlights the potential of standardisation within designs.

8.1.2 Limitations

Addressing potential limitations of the research is crucial, encompassing general research limitations and validity concerns as outlined by Wieringa (2014). Validity encompasses both internal and external aspects, where internal validity assesses result plausibility, and external validity considers generalisability within the research context (Wieringa, 2014).

General limitations of the results

Several limitations within the results and research framework may impact result reliability and suggest avenues for further exploration.

Firstly, due to the research's broad scope and time constraints, BIM-based scenarios were introduced rather than fully developed in detail. Consequently, some conditions, values, risks, or constraints might have been overlooked. Delving deeper into each scenario in future research could provide new insights. For example, while discussing PreFab scenario 1, Emergo expressed interest in assessing the quality of BIM models from key clients, an area only lightly explored in this research.

Secondly, all scenarios assumed a final and fixed design for cost estimations. In reality, multiple changes to the design often occur after the cost estimation process, which may not be captured in subsequent BIM models but are discussed and decided among stakeholders. These design changes represent a risk for every scenario, necessitating further research to explore how to address these potential challenges within each scenario. However, the purpose of BIM is to serve as central information warehouse across all project phases. The higher the integration and coordination capabilities are, the higher the accuracy of BIM models at any point, and the less likely this problem will occur.

Additionally, not all risks or challenges were included during the elaboration of the BIM scenarios. Each scenario primarily addressed its working, potential value, and necessary conditions, but did not thoroughly explore all associated risks. For instance, despite that Revit skills was a condition for one of the scenarios, cost estimators could be unable or unwilling to work with Revit could, hindering the implementation of PreFab Scenario 2. Crucial conditions are taken into account but implementation risks were less discussed in this research. Also, risks were not explicitly incorporated into the roadmap framework derived from Kerr and Phaal (2021); Phaal and Muller (2009). Future research could focus on examining and mitigating risks within individual scenarios, enhancing understanding of potential challenges.

Lastly, resource constraints limited examination of certain scenarios. For instance, PreModu scenarios 1B, 2, and 3 couldn't be fully tested due to incomplete data libraries. Consequently, some scenarios were derived in an abstract manner, assuming the availability of critical components in the future. Thus, during scenario demonstrations, assumptions about component availability were made.

Interal Validity

Internal validity, as delineated by Wieringa (2014), encompasses causal inference, architectural inference, and rational inference.

Causal inference, crucial for ensuring the replicability and reliability of study findings, encounters challenges due to subjective decisions in artifact design and qualitative data interpretation. Designing artifacts, especially in establishing BIM scenarios based on qualitative insights, involves subjective judgments, posing a risk of bias. To address this, the research employs a standardised process for scenario selection, including rigorous examination of potential BIM applications, compatibility checks and requirements checks. Additionally, variations in scenario derivation methods, such as software and formulas, pose threats to causal inference. Thus, the initial general exploration of each scenario emphasises its general workings to ensure alignment with a standardised approach

Architectural inference involves obtaining sufficient and relevant data to support research findings (Wieringa, 2014). However, due to the incomplete realisation of each scenario, there are challenges in validating results. The scenarios are based on potential rather than complete workings, hindering data acquisition for validation. To address this, the research employs the triangulation method, utilising multiple data collection methods. For instance, during validation, results are continuously verified with at least 3 stakeholders, which has been done during this entire research. Similarly, the process investigation phase utilises hands-on experience, interviews, and document analyses to gain insights into the processes via multiple ways.

Lastly, rational inference involves understanding stakeholders' rational motivations. However, a potential threat in this research is the establishment of research requirements without analysing stakeholder goals. To address this, the method proposed by Wieringa (2014), which aligns research requirements with stakeholder desires, is utilised. Additionally, conducting interviews with multiple stakeholders helps uncover their rational motivations, enhancing the reliability of the research.

External validity

External validity is further divided among object of study, sampling of study and treatment of the study.

The object of this study encompasses the designed artifacts and their potential applicability to different environments, such as other firms. However, the cost estimation processes of PreModu and PreFab are customised for Emergo, utilizing unique software, tools, and procedures. Consequently, the scenarios are specifically tailored and tested within Emergo's context, limiting their generalisability. Despite this specificity, the findings offer potential for generalisation to other contexts regarding the inherent conditions and values per scenario. For example, the concept of standardisation within BIM model classification extends beyond Emergo to the broader construction industry. Similarly, the need for a standardised component library is universal in modular construction. Thus, while the scenarios and roadmaps are crafted for Emergo, their underlying principles can be adapted to other contexts while maintaining consistent value and conditions. However, this must be supported and concluded in further research.

Regarding sampling, it concerns the number of cases tested with the treatment. In this study, scenarios are developed as proof of concept with varying sample sizes. For instance, PreModu scenario 1A is tested with minimal cases, often just one project, while PreModu scenario 3 remains practically untested due to the absence of critical components. On the other side, PreModu projects are assumed to adhere to standard design outlines across different projects, thus necessitating fewer samples. Still, despite assuming standard design outlines across different PreModu projects, the lack of practical cases poses a challenge to external validity. Moving forward, as PreModu undergoes further development, exploring scenarios in more detail could enhance the external validity of sampling sizes in subsequent research.

Finally, the treatment refers to the implementation phase of the artifacts, which remains unexplored in this study. While the scenarios' outlines and conditions are designed, their full implementation has not yet been realised. Consequently, any results or findings regarding the implementation of these tools are inevitably compromised by the absence of actual implementation. Nonetheless, many scenarios have been tested both theoretically and practically, such as the specifically developed Dynamo scripts, contributing to enhancing the external validity of the results

8.2 Conclusion and recommendations

This section marks the culmination of this research, offering final conclusions and recommendations for Emergo, the problem owner. The conclusions are referring back to each research question, where the main research questions are included in each section of the conclusion. The recommendations stem from both overarching insights and potential avenues for further investigation.

8.2.1 Conclusions

1. **What are Emergo's current cost estimation processes and challenges for PreFab and PreModu?**
   (a) How do the current calculation processes for Emergo's PreModu and PreFab projects operate, including the sequence of activities, input sources, needs and desired output?
   (b) What are the primary challenges, bottlenecks, and areas of improvement within the calculation processes of both PreModu and Prefab projects?
   (c) What are the key differences and similarities between the calculation processes of PreModu and PreFab projects?

Emergo's current cost estimation processes follow a standardised sequence of activities that have been well-established, yielding detailed estimations. Particularly in PreFab, cost estimations are conducted meticulously, considering every single component. These estimations necessitate a significant amount of data, as outlined from Table 3.1 until Table 3.5.PreModu's cost estimation processes primarily rely on predefined and calculated components supplemented with project-specific data, detailed in Table 3.6. In both processes, a cost estimation model automatically converts information into total prices, with calculations performed in the background. Cost data is manually updated in these models quarterly. Quotes are then derived manually based on the model results, with PreFab's quotes supplemented by highlighted technical drawings in 2D. Process overviews for PreFab and PreModu are provided in Figure 6 and Figure 7, respectively. Notably, despite the presence of BIM models in every PreModu project and some PreFab projects, current input through these models is nonexistent

PreFab's current cost estimation process is perceived as both time-consuming and error-prone, primarily due to manual tasks and disjointed databases. Lack of automated and standardised solutions exacerbates inefficiencies, particularly concerning the unique designs characteristic of PreFab projects. This manual approach may become outdated in an era where the construction industry is rapidly digitising and prioritising efficiency.

PreModu's cost estimation process is still in development, evolving alongside the concept itself. Challenges arise from incomplete object libraries and the continued use of unique components, hindering efforts to standardise estimations. Manual processes and inaccuracies persist due to these incomplete libraries, while varying client preferences further complicate standardisation. Additionally, disconnected databases impede potential automation and standardisation of the cost estimation process.

The cost estimation processes share common characteristics, utilising systems such as ERP, Excel, and Timber Estimation Software X. They employ similar approaches, including partly automated models that convert input variables into cost prices. Moreover, there is overlap in PreFab components, as similar timber-framed elements are employed within the PreModu framework.

However, the differences between the projects are more pronounced than the similarities. PreFab adopts a pull strategy, relying on Engineer-to-Order (ETO) tactics that necessitate adaptation to unique client demands. In contrast, PreModu embraces an Assemble-to-Order/Make-to-Order (ATO/MTO) approach, standardising components throughout the design and supply chain. While PreModu's cost estimation processes extend across projects, enabling faster calculations due to pre-calculated modules and house types, the concept is still under development, lacking a standardised component library, thus resulting in less accurate estimations. On the other hand, PreFab's project-specific estimations require detailed information for every component, potentially making the process more time-consuming compared to PreModu's estimations. Nevertheless, the complete and standardised material compositions used in PreFab enhance repeatability and accuracy.

2. **What are the needs and treatment requirements of potential scenario's for both cost estimation processes?**

    (a) What are the anticipated requirements and expectations for the desired calculation processes of PreModu and PreFab projects?

    (b) How can the data generated within the calculation processes be effectively utilised in other phases of the project life-cycle, contributing to an overall improved efficiency and decision- making?

Emergo aims to enhance both cost estimation processes through the integration of BIM-based methods, prioritising accuracy, speed, and efficiency through automation. Table 4.2 and Table 4.3 refers to the treatment requirements for both cost estimation processes, derived via the stakeholder goals

For PreFab, treatment requirements focus on translating unique data inputs into standardised solutions. This necessitates access to accurate datasets for cost estimation models to accelerate the process and minimise errors. Automation and BIM solutions are key in achieving these goals.

Conversely, PreModu's cost estimation process requires comprehensive data libraries to leverage its standardised nature effectively. This entails a complete component library encompassing all PreModu variations, alongside a cost database capable of estimating costs for each component. Integration of these libraries is essential for seamless and automatic cost estimations. BIM tools must be implemented to efficiently connect these data sources and enhance the cost estimation process.

Data obtained from the cost estimation process serves as the foundation for subsequent departmental activities, including production, assembly, and construction. Accurate estimations of material usage and component quantities are critical for these activities, emphasising the importance of a detailed and precise cost estimation process. Improved integration of data with other departments can further optimise workflow efficiency.

3. Which BIM-based scenarios can be used and adapted to achieve desired requirements?

    (a) Which BIM uses can be be harnessed to address the challenges and improve the efficiency of the calculation processes within both PreModu and PreFab project

    (b) What are the necessary conditions and challenges to facilitate BIM and which value come with the successful implementation of these solutions?

    (c) To what extent do the proposed scenario's align with the identified design requirements and effectively mitigate challenges in cost estimation processes for both Premodu and Prefab projects?

Table 5.2 reveals all the potential BIM uses that are considered within this research. A combinations of the most appriorate ones are selected and developed as BIM scenarios. Compatibility and requirement checks led to a minimum selection of BIM uses that were necessary to realise the stakeholder goals. These have been clustered, which resulted in 2 scenarios for PreFab and 3 scenarios for PreModu.

The first scenario of PreFab included ITO tools to facilitate data extraction from BIM models that are delivered by the client. Information can be extracted and calculated in an automatic manner, increasing the reliance of computer-based and automatic cost estimations. This could benefit the cost estimations process in terms of time and accuracy by avoiding mistakes. However, current BIM models were considered incomplete, and must be developed in terms of information per component. Table 6.7 until Table 6.5 reveal which data was found in 5 test projects, and which were currently unavailable and must be developed in the future.

The second scenario addressed parametric modeling to generate a roof including a division of elements. This scenario is divided in two sub-scenarios where one creates a roof from scratch while the other overlays current roof geometries. This scenario could benefit the most time-consuming task of PreFab's cost estimation process, which is the division of roof elements. Also, generated elements in Revit are beneficial for subsequent procedures, such as Timber Modeling System A-integration. Starting from scratch requires less conditions, where information of current 2D drawings is sufficient. Overlaying current roof models require a BIM model where the roof element is complete and accurate in terms of geometries. BIM models are often lacking in current projects.

The first scenario of PreModu utilises ITO tools to automate data measurement, enabling project-dependent cost estimations based on BIM information takeoffs. The value per project is considered little, as a large part of PreModu is fixed while a small part is flexible for aesthetics. The first part of this scenario can be employed immediately and is tested with one PreModu project. However, expanding this scenario for a wider range of components, highlighted in a sub-scenario, requires developments. To completely rely on information takeoff's, Revit instances per family must be completed. There are some components incorporated in a Revit familiy, usable between multiple projects. However, the Revit libraries are considered incomplete, as not all concepts of PreModu are developed for every PreModu house type. This must be developed in order to expand the information takeoff's, utilising similar takeoff procedures. Then, each design in Revit can be read through the ITO procedures and imported in the cost estimation model of Excel. This would drastically enhance PreModu's cost estimation process in terms of accuracy and speed.

PreModu's second scenario connects the data in a dynamic way. Compared to the first scenario, less manual interventions are required as the cost estimations are conducted on the background. A dynamo script calls out data from an Excal database and connects this to the components from the Revit model. A major benefit is that cost data or the design can be changed, which automatically results in a new calculation of costs. The databases are more or less integrated, instead of manually connected. Besides the development of Revit libraries in terms of completion, this scenario necessitates developments in the cost database as well. Namely, a fixed manner of exporting cost data to excel must be maintained, including a complete cost database. Currently, the cost database is incomplete due to variations in components, a lack of previous experience and dependency on suppliers. Thus, for every concept of PreModu, a price item in Excel must be present.

The final scenario of PreModu refers to initial cost estimations, which could be achieved through a house configurator. Clients are able to select a combination of PreModu concepts as their design, which automatically provides some initial costs. Besides the arrangement of this entire platform, which is under development for Emergo, several conditions are necessary. These type of cost estimations are conceptual, meaning that a conceptual cost database must be derived, which can be obtained through similar cost estimation methods as Scenario 2. A kit-of-parts in Revit should be developed, meaning that every combination that is desired to be included in the configurator, must be modeled in advance. Consequently, the conceptual cost database and this kit-of-parts must be connected in order to derive conceptual costs. This scenario includes a wide range of value. Initial client interaction is automated and online, enabling a high level of reaching clients and a higher level of client satisfaction. Also, this scenario is aligned with a high level of integration across the supply chain. The design platform that is under development at Emergo enables integration with Revit, Timber Estimation Software X and Timber Modeling System A. Thus, data coordination between departments across the supply chain is significant.

Finally, all scenarios have been validated and verified in consultation with the client.

4. What are useful criteria for assessing the BIM scenarios and how are these translated to a roadmap for Emergo?
   (a) How can the scenarios be assessed to evaluate the feasibility, benefits, and potential challenges of the derived scenarios in the context of PreModu and PreFab projects?
   (b) How can a strategic roadmap be designed to guide Emergo in the successful implementation of BIM scenarios to enhance the efficiency and integration of the calculation processes for both PreModu and PreFab projects?

The roadmap for Emergo's cost estimation processes integrates all potential scenarios into a template derived from Kerr and Phaal (2021) and Phaal and Muller (2009). Each scenario, along with its operational details, is central to the roadmap, while additional layers represent necessary conditions and the value each scenario offers to Emergo and the construction industry. This roadmap serves as a guide for Emergo to select directions that enhance their cost estimation processes via BIM, considering the introduced and analysed scenarios. The location of the scenarios are determined by the assessment of the scenarios. The assessment is conducted based on the feasibility, conditions, challenges and the roadmap template. Feasibility is derived through an analysis of the conditions, benefits are derived through analysing the value per scenario and the challenges are described per scenario.

For PreFab, the initial focus lies on developing a roof modeler, offering Emergo greater control. This involves developing information exchange documents (LOIN), standard cost estimation procedures, and Dynamo scripts. Emergo can choose to create roof elements from scratch or overlay existing models. Targeting exploitation by 2024, the subsequent step involves standardising information takeoff procedures as the construction industry's overall standardisation progresses. Depending on BIM model quality, Emergo aims to fully exploit information takeoffs and automated cost estimation models between 2026 and 2028.

In the PreModu roadmap, the first scenario is information takeoffs, where Emergo has control over the design phase. Initially, project-dependent quantities are extracted, requiring an information development plan and standard ITO procedures. This scenario can be immediately exploited. Subsequently, through completing Revit families, cost databases, and cost data integration, Emergo can achieve automatic cost estimations by 2025. Emergo can decide to expand information takeoffs to extract information from a BIM model into the cost estimation system or integrate cost data within the Revit environment using a dynamo script, which offers more integration between the design and cost items. By 2026, the end goal is integration not only for the cost estimation process but the entire supply chain. Data utilisation across departments enables conceptual cost provision via a design platform, expanding client reach. Integration from conceptual design to construction should be realised by 2026.

Due to Emergo's control and standardisation, PreModu's development holds more potential and may reach completion sooner compared to the final scenario for PreFab. If this development curve remains constant, PreModu has the potential to surpass PreFab as the core business in the near future. Additionally, the standardisation that lies within the future of PreModu offers more value in the future, paving the way to an integrated workflow. Client dependency remains a challenge for PreFab, highlighted by the delayed initiation of the first scenario, information takeoffs. Despite the relatively straightforward nature of this scenario, Emergo's progress is contingent upon broader construction industry developments, such as the adoption of standardised modeling languages

8.2.2 Recommendations

Emergo can utilise the roadmap and associated scenarios strategically to advance their cost estimation processes. While the scenarios offer valuable insights, it's advisable to conduct thorough analyses for each scenario before implementation. This ensures a comprehensive understanding and utilisation of each scenario, potentially revealing additional requirements and enhancing their effectiveness. The roadmap offers a broad vision to guide Emergo's short-term decision-making, with detailed examinations of each scenario contributing to their long-term objectives.

Secondly, it is recommended that Emergo promptly completes information requirement documents, following LOIN (ISO 19650-1) standards, for both the PreFab and PreModu concepts. These documents serve as comprehensive guides outlining the necessary data requirements for effective information exchanges. By formalising these requirements, Emergo can ensure clarity and consistency in data management practices. For PreFab, such documents can streamline client communication and guide data development efforts. Similarly, for PreModu, adhering to LOIN standards can optimise BIM model development for efficient cost estimations, providing clarity for Emergo and assisting in understanding the cost estimation process and required input.

Additionally, Emergo should prioritise the development of comprehensive libraries for PreModu to fully leverage the potential of standardised modular construction. Establishing comprehensive Revit families with all necessary instances and corresponding cost items in ERP is essential for advancing current systems. The advanced scenarios (scenario 1B, 2, and 3) particularly rely on complete libraries, emphasising their significance. Therefore, investing in complete libraries is crucial for enhancing Emergo's cost estimation process outcome.

To expedite the realisation of complete libraries, Emergo should allocate additional resources to PreModu in the short term. Currently, Emergo is focusing on expanding the concept of PreModu with additional house types and variations. While the current focus on expanding the number of concepts of PreModu is valuable, equal attention should be directed towards enhancing existing concepts in quality. Allocating additional resources to these improvements is essential to overcome existing resource constraints that impede PreModu's progress.

Lastly, for PreFab's cost estimation process, it is recommended to review and adjust the current cost estimation procedures. Implementing one of the PreFab scenarios will necessitate restructuring the cost estimation process. Cost estimators are then required to conduct new tasks such as information extraction, roof modeling, and acquiring general knowledge in BIM models. Emergo should factor in these additional efforts, as implementing these scenarios entails more than just the technical implementation itself.

Bibliography

A. Aapaoja and H. Haapasalo. The challenges of standardization of products and processes in construction. In *Proceedings of the 22nd Annual Conference of the International Group for Lean*, pages 983–993. Citeseer, 2014.

ABF Research. Primos-prognose 2023, Jul 2023. URL http://www.abfresearch.nl/.

A. Adriaanse. Bruggen bouwen met ict. *Oratieboekje*, Oct 2014. doi: 10.1007/s12428-015-0022-2.

A. M. Al-Ashwal, H. Abdul-Rahman, and A. M. Beksin. Knowledge sharing in a fragmented construction industry: on the hindsight. *Scientific Research and Essays*, 6(7):1530–1536, Apr 2011. URL http://www.academicjournals.org/SRE.

W. S. Alaloul, M. S. Liew, N. A. W. A. Zawawi, and B. S. Mohammed. Industry revolution ir 4.0: future opportunities and challenges in construction industry. In *MATEC web of conferences*, volume 203, page 02010. EDP Sciences, 2018.

N. Bertram, S. Fuchs, J. Mischke, R. Palter, G. Strube, and J. Woetzel. Modular construction: From projects to products, Jun 2019. URL https://www.mckinsey.com/capabilities/operations/our-insights/modular-construction-from-projects-to-products.

M. Bew and J. Underwood. Delivering bim to the uk market. In *Handbook of research on building information modeling and construction informatics: Concepts and technologies*, pages 30–64. IGI Global, 2010.

M. Bilal, L. O. Oyedele, J. Qadir, K. Munir, O. O. Akinade, S. O. Ajayi, H. A. Alaka, and H. A. Owolabi. Analysis of critical features and evaluation of bim software: towards a plug-in for construction waste minimization using big data. *International Journal of Sustainable Building Technology and Urban Development*, 6(4):211–228, 2015.

A. Björnfot and L. Stehn. Industrialization of construction: a lean modular approach. In *Annual Conference of the International Group for Lean Construction: 03/08/2004-05/08/2004*, 2004.

Building Societies Association, 2017. URL https://www.bsa.org.uk/information/publications/research-and-reports/laying-the-foundations-for-modern-methods-of-const.

J. Cao, D. F. Bucher, D. M. Hall, and J. Lessing. Cross-phase product configurator for modular buildings using kit-of-parts. *Automation in construction*, 123:103437, 2021.

Y. Chen, G. E. Okudan, and D. R. Riley. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in construction*, 19(2):235–244, 2010.

M.-Y. Cheng, H.-C. Tsai, and E. Sudjono. Conceptual cost estimates using evolutionary fuzzy hybrid neural network for projects in construction industry. *Expert Systems with Applications*, 37(6):4224–4231, 2010.

M. Claypool. Disrupting the digital: An architecture of parts. 2018.

Constructing Excellence, 2015. URL https://constructingexcellence.org.uk/wp-content/uploads/2015/03/preassembly.pdf.

B. Dave and L. Koskela. Collaborative knowledge management—a construction case study. *Automation in Construction*, 18(7):894–902, 2009. doi: 10.1016/j.autcon.2009.03.015.

H. De Jonge. Abf rapportages primos en plancapaciteit en betekenis voor de bouwopgave, Jul 2023.

M. Deng, Y. Tan, J. Singh, A. Joneja, and J. C. Cheng. A bim-based framework for automated generation of fabrication drawings for façade panels. *Computers in Industry*, 126:103395, 2021.

A. Dubois and L.-E. Gadde. Supply strategy and network effects — purchasing behaviour in the construction industry. *European Journal of Purchasing & Supply Management*, 6(3–4): 207–215, 2000. doi: 10.1016/s0969-7012(00)00016-2.

A. O. Elfaki, S. Alatawi, and E. Abushandi. Using intelligent techniques in construction project cost estimation: 10-year survey. *Advances in Civil Engineering*, 2014:1–11, Dec 2014. doi: 10.1155/2014/107926.

H. H. Elmousalami. Artificial intelligence and parametric construction cost estimate modeling: State-of-the-art review. *Journal of Construction Engineering and Management*, 146(1): 03119008, 2020.

V. Ezcan, U. Isikdag, and J. S. Goulding. Bim and off-site manufacturing: recent research and opportunities. In *19th CIB World Building Congress Brisbane, Australia*, 2013.

E. R. Farr, P. A. Piroozfar, and D. Robinson. Bim as a generic configurator for facilitation of customisation in the aec industry. *Automation in Construction*, 45:119–125, 2014.

C. Fu, G. Aouad, A. Ponting, A. Lee, and S. Wu. Ifc implementation in lifecycle costing. *Journal of Harbin Institute of Technology(New Series)*, 11(4):437–441, 2004.

E. Goh and M. Loosemore. The impacts of industrialization on construction subcontractors: a resource based view. *Construction management and economics*, 35(5):288–304, 2017.

J. S. Goulding, F. Pour-rahimian, M. Arif, and M. Sharp. Offsite construction: strategic priorities for shaping the future research agenda. *Journal of Architectoni. ca*, 1(1):62–73, 2012.

A. Grilo and R. Jardim-Goncalves. Value proposition on interoperability of bim and collaborative working environments. *Automation in Construction*, 19(5):522–530, 2010. doi: 10.1016/j.autcon.2009.11.003.

T. Hartmann, H. van Meerveld, N. Vossebeld, and A. Adriaanse. Aligning building information model tools and construction management methods. *Automation in Construction*, 22:605–613, Mar 2012. doi: 10.1016/j.autcon.2011.12.011.

A. N. Hasan and S. M. Rasheed. The benefits of and challenges to implement 5d bim in construction industry. *Civil Engineering Journal*, 5(2):412, 2019.

R. He, M. Li, V. J. Gan, and J. Ma. Bim-enabled computerized design and digital fabrication of industrialized buildings: A case study. *Journal of Cleaner Production*, 278:123505, 2021.

J. Hong, G. Q. Shen, Z. Li, B. Zhang, and W. Zhang. Barriers to promoting prefabricated construction in china: A cost–benefit analysis. *Journal of cleaner production*, 172:649–660, 2018.

M. A. Hossain and A. Nadeem. Towards digitizing the construction industry: State of the art of construction 4.0. *Proceedings of International Structural Engineering and Construction*, 6(1), 2019. doi: 10.14455/isec.res.2019.184.

X. Jiang. Developments in cost estimating and scheduling in bim technology. Aug 2011. doi: 10.17760/d20002392.

J. Jiao, T. W. Simpson, and Z. Siddique. Product family design and platform-based product development: a state-of-the-art review. *Journal of intelligent Manufacturing*, 18:5–29, 2007.

C. Kerr and R. Phaal. Roadmapping and roadmaps: Definition and underpinning concepts. *IEEE Transactions on Engineering Management*, 69(1):6–16, 2021.

A. Ketabi. Bim uses in modular construction and at emergo (working paper). 2023.

N. Kordestani Ghalenoei, M. Babaeian Jelodar, D. Paes, and M. Sutrisna. Challenges of offsite construction and bim implementation: providing a framework for integration in new zealand. *Smart and Sustainable Built Environment*, 2022.

KPMG, Apr 2016. URL https://assets.kpmg.com/content/dam/kpmg/pdf/2016/04/smart-construction-report-2016.pdf.

M. Lawrence, R. Pottinger, S. Staub-French, and M. P. Nepal. Creating flexible mappings between building information models and cost information. *Automation in Construction*, 45:107–118, 2014.

M. Lawson, R. Ogden, and C. Goodier. *Design in modular construction*. CRC Press, 2014.

J. Lee, H. Yang, J. Lim, T. Hong, J. Kim, and K. Jeong. Bim-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase. *Journal of Asian Architecture and Building Engineering*, 19(4):384–399, 2020.

S.-K. Lee, K.-R. Kim, and J.-H. Yu. Bim and ontology-based approach for building cost estimation. *Automation in construction*, 41:96–105, 2014.

N. Lu and T. Korman. Implementation of building information modeling (bim) in modular construction: Benefits and challenges. In *Construction Research Congress 2010: Innovation for reshaping construction practice*, pages 1136–1145, 2010.

W. Ma, X. Wang, J. Wang, X. Xiang, and J. Sun. Generative design in building information modelling (bim): approaches and requirements. *Sensors*, 21(16):5439, 2021.

R. Maskuriy, A. Selamat, P. Maresova, O. Krejcar, and O. O. David. Industry 4.0 for the construction industry: Review of management perspective. *Economies*, 7(3):68, 2019.

P. Matejka, S. Vitasek, et al. Comparison of different cost estimation methods with use of building information modelling (bim). In *17 th International Scientific Conference Engineering for Rural Development*, pages 843–849, 2018.

M. N. Mohd Nawi, N. Baluch, and A. Y. Bahauddin. Impact of fragmentation issue in construction industry: An overview. *MATEC Web of Conferences*, 15:01009, 2014. doi: 10.1051/matecconf/20141501009.

A. Monteiro and J. Poças Martins. A survey on modeling guidelines for quantity takeoff-oriented bim-based design. *Automation in Construction*, 35:238–253, May 2013. doi: 10.1016/j.autcon.2013.05.005.

J. Mukkavaara, G. Jansson, A. Holmberg, and M. Sandberg. Approach for automated planning using 5d-bim. In *33rd CIB W78 Conference 2016, Oct. 31st-Nov. 2nd 2016, Brisbane, Australia*, 2016.

A. Nadeem, A. K. Wong, and F. K. Wong. Bill of quantities with 3d views using building information modeling. *Arabian Journal for Science and Engineering*, 40(9):2465–2477, Apr 2015. doi: 10.1007/s13369-015-1657-2.

S. Navaratnam, A. Satheeskumar, G. Zhang, K. Nguyen, S. Venkatesan, and K. Poologanathan. The challenges confronting the growth of sustainable prefabricated building construction in australia: Construction industry views. *Journal of Building Engineering*, 48:103935, 2022.

M. Nawi, A. Lee, M. Azman, and K. Kamar. Fragmentation issues in malaysian industrialised building system (ibs) projects. *Journal of Engineering Science and Technology*, 9(1):97–106, Feb 2014.

NVM. *Analyse woningmarkt 2e kwartaal 2023*. NVM, 2023. URL https://www.nvm.nl/media/fztotvzz/bijlage-1-analyse-woningmarkt-2e-kwartaal-2023.pdf.

J. K. Ofori-Kuragu and R. Osei-Kyei. Mainstreaming pre-manufactured offsite processes in construction–are we nearly there? *Construction Innovation*, 21(4):743–760, 2021.

J. K. Ofori-Kuragu, R. Osei-Kyei, and N. Wanigarathna. Offsite construction methods—what we learned from the uk housing sector. *Infrastructures*, 7(12):164, 2022.

R. Ogden, R. M. Lawson, and C. I. Goodier. *Design in modular construction*. CRC Press, 2014.

D. Olsen and J. M. Taylor. Quantity take-off using building information modeling (bim), and its limiting factors. *Procedia Engineering*, 196:1098–1105, Jun 2017. doi: 10.1016/j.proeng.2017.08.067.

J. Park. Bim-based parametric design methodology for modernized korean traditional buildings. *Journal of Asian Architecture and Building Engineering*, 10(2):327–334, 2011.

M. Parsamehr, U. S. Perera, T. C. Dodanwala, P. Perera, and R. Ruparathna. A review of construction management challenges and bim-based solutions: perspectives from the schedule, cost, quality, and safety management. *Asian Journal of Civil Engineering*, 24(1):353–389, 2023.

R. Phaal and G. Muller. Towards visual strategy: An architectural framework for roadmapping. In *PICMET'07-2007 Portland International Conference on Management of Engineering & Technology*, pages 1584–1592. IEEE, 2007.

R. Phaal and G. Muller. An architectural framework for roadmapping: Towards visual strategy. *Technological forecasting and social change*, 76(1):39–49, 2009.

R. Phaal, L. Simonse, and E. Den Ouden. Next generation roadmapping for innovation planning. *International Journal of Technology Intelligence and Planning*, 4(2):135–152, 2008.

S. Pibal, I. Kovacic, and R. Jakoubek. Digital twins to bim object library a top-down modeling approach. In *Proc. of the Conference CIB W78*, volume 2021, pages 11–15, 2021.

S. Riazi, M. Zainuddin, M. Nawi, and S. Lee. A critical review of fragmentation issues in the construction industry. *Talent Development and Excellence*, 12(2):1510–1521, 2020.

T. Salama, O. Moselhi, and M. Al-Hussein. Modular industry characteristics and barriers to its increased market share. *Modular and Offsite Construction (MOC) Summit Proceedings*, 2018. doi: 10.29173/mocs34.

A. Sattineni and R. H. Bradford. Estimating with bim: A survey of us construction companies. *28th International Symposium on Automation and Robotics in Construction (ISARC 2011)*, Jun 2011. doi: 10.22260/isarc2011/0103.

D. Savitri, A. Pramudya, et al. Clash detection analysis with bim-based software on midrise building construction project. In *IOP Conference Series: Earth and Environmental Science*, volume 426, page 012002. IOP Publishing, 2020.

S. M. Sepasgozar, A. M. Costin, R. Karimi, S. Shirowzhan, E. Abbasian, and J. Li. Bim and digital tools for state-of-the-art construction cost management. *Buildings*, 12(4):396, 2022.

G. Sivard. *A generic information platform for product families*. PhD thesis, KTH, 2001.

P. Smith. Project cost management with 5d bim. *Procedia-Social and Behavioral Sciences*, 226: 193–200, 2016a.

R. E. Smith. Off-site and modular construction explained. *National institute of building sciences*, 2016b.

S. Staub-French, M. Fischer, J. Kunz, and B. Paulson. A generic feature-driven activity-based cost estimation process. *Advanced Engineering Informatics*, 17(1):23–39, 2003.

K. Subramanya, S. Kermanshachi, and B. Rouhanizadeh. Modular construction vs. traditional construction: Advantages and limitations: A comparative study. In *Creative Construction e-Conference 2020*, pages 11–19. Budapest University of Technology and Economics, 2020.

ukbimframework, Sep 2020. URL https://ukbimframework.org/wp-content/uploads/2020/09/Guidance-Part-D_Developing-information-requirements_Edition-1.pdf.

M. Valinejadshoubi, O. Moselhi, I. Iordanova, F. Valdivieso, and A. Bagchi. Automated system for high-accuracy quantity takeoff using bim. *Automation in Construction*, 157:105155, Jan 2024. doi: 10.1016/j.autcon.2023.105155.

W. Wahbeh. Building skins, parametric design tools and bim platforms. In *Conference Proceedings of the 12th Conference of Advanced Building Skins*, pages 1104–1111, 2017.

K.-C. Wang, W.-C. Wang, H.-H. Wang, P.-Y. Hsu, W.-H. Wu, and C.-J. Kung. Applying building information modeling to integrate schedule and cost for establishing construction progress curves. *Automation in construction*, 72:397–410, 2016.

R. J. Wieringa. *Design science methodology for information systems and software engineering*. Springer, 2014.

S. Wu, G. Wood, K. Ginige, and S. W. Jong. A technical review of bim based cost estimating in uk quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19:534–562, 2014.

S.-W. Yang, S.-W. Moon, H. Jang, S. Choo, and S.-A. Kim. Parametric method and building information modeling-based cost estimation model for construction cost prediction in architectural planning. *Applied Sciences*, 12(19):9553, 2022.

A. Zarzycki. Parametric bim as a generative design tool. *Boston, ACSA*, 2012.

L. Zhao, W. Zhang, and W. Wang. Construction cost prediction based on genetic algorithm and bim. *International Journal of Pattern Recognition and Artificial Intelligence*, 34(07):2059026, 2020.

Appendices

Appendix A

Flowcharts of processes

In this appendix, an overview of all the flowcharts describing the Prefab processes is provided. These flowcharts are detailed and include every seperate step of the process, rather than the tasks within the process.

Figure 48: Complete overview of PreFab Process

FIGURE 49: Zoomed-in flowchart of administration

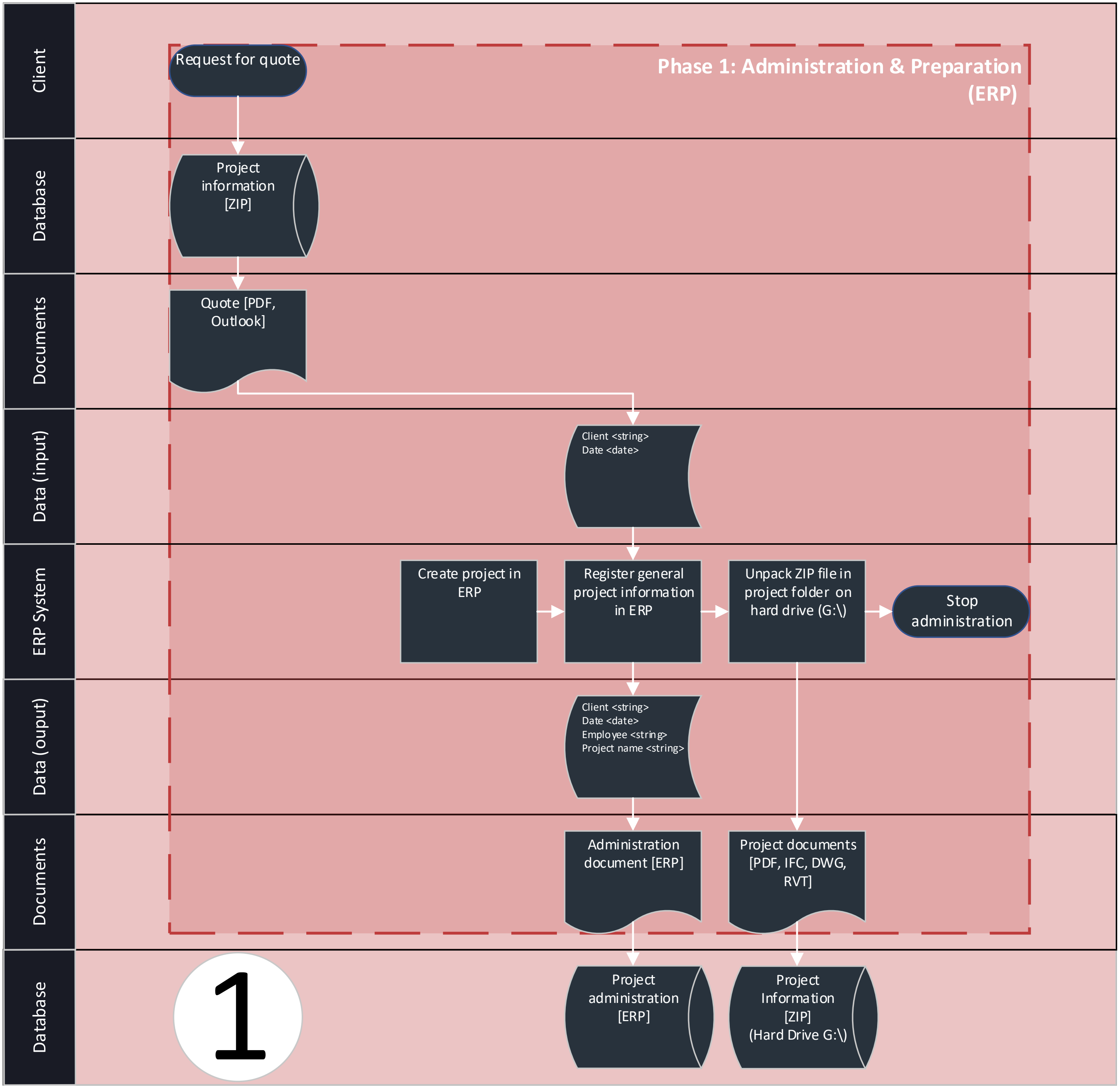


FIGURE 50: Zoomed-in flowchart of counting and measuring

FIGURE 51: Zoomed-in flowchart of cost estimation in Timber Estimation Software X

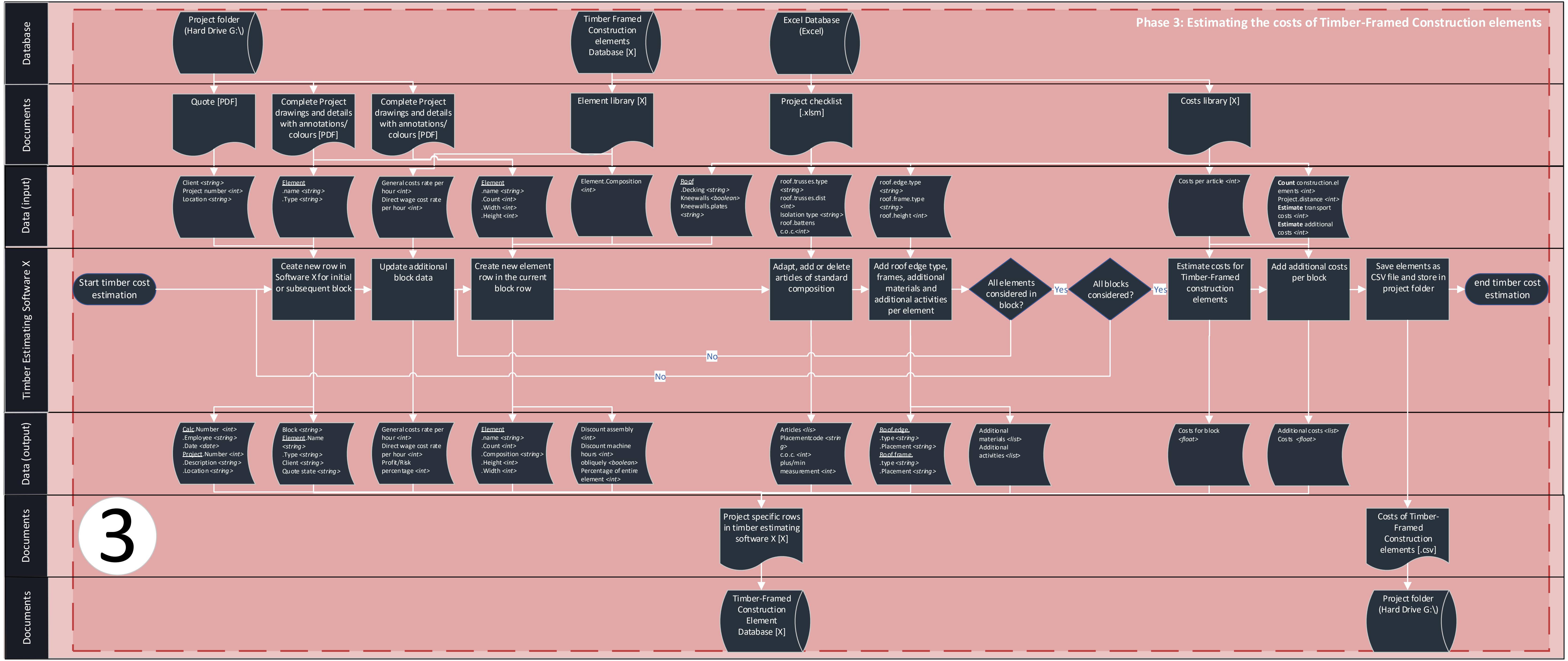


FIGURE 52: Zoomed-in flowchart of cost estimation in excel

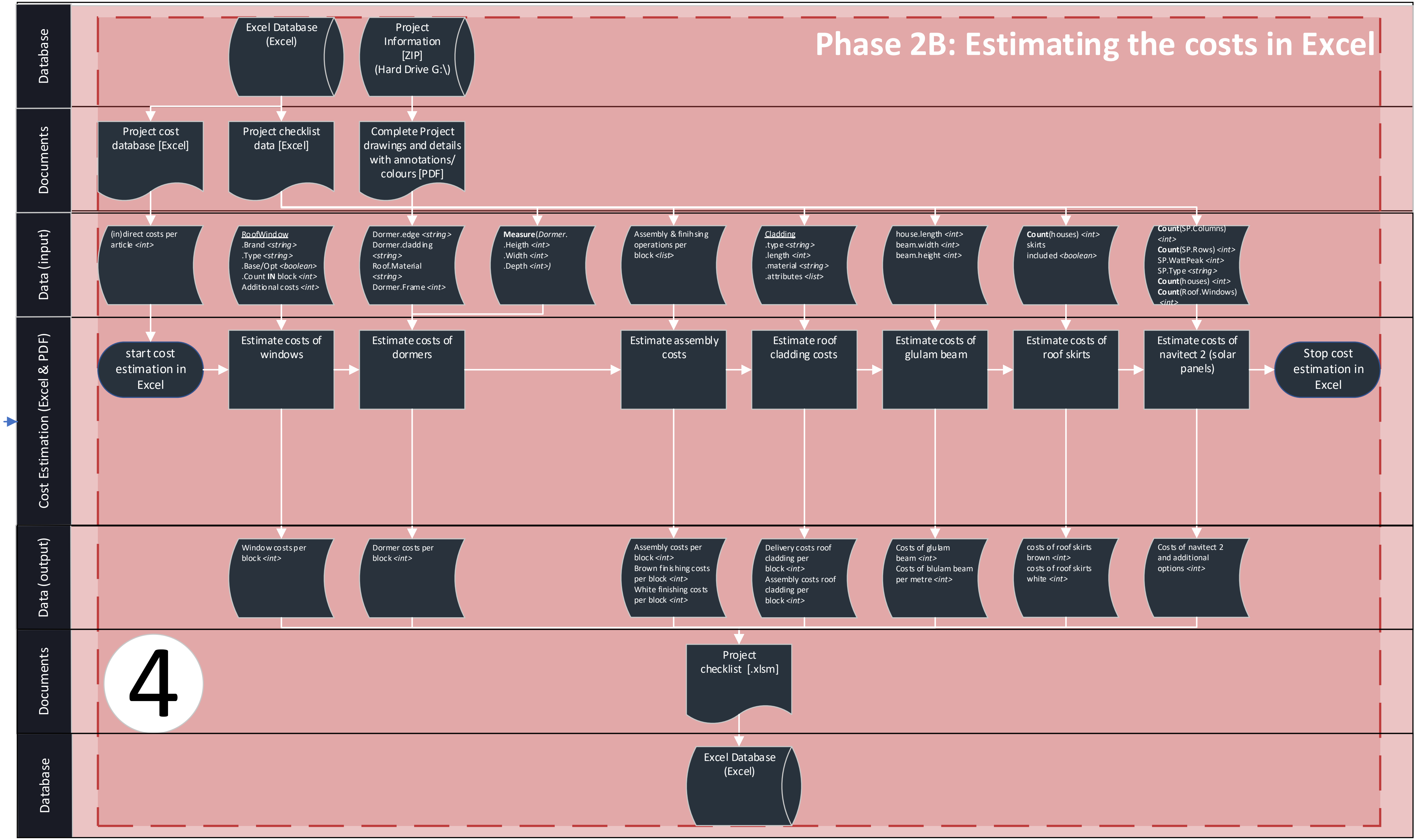
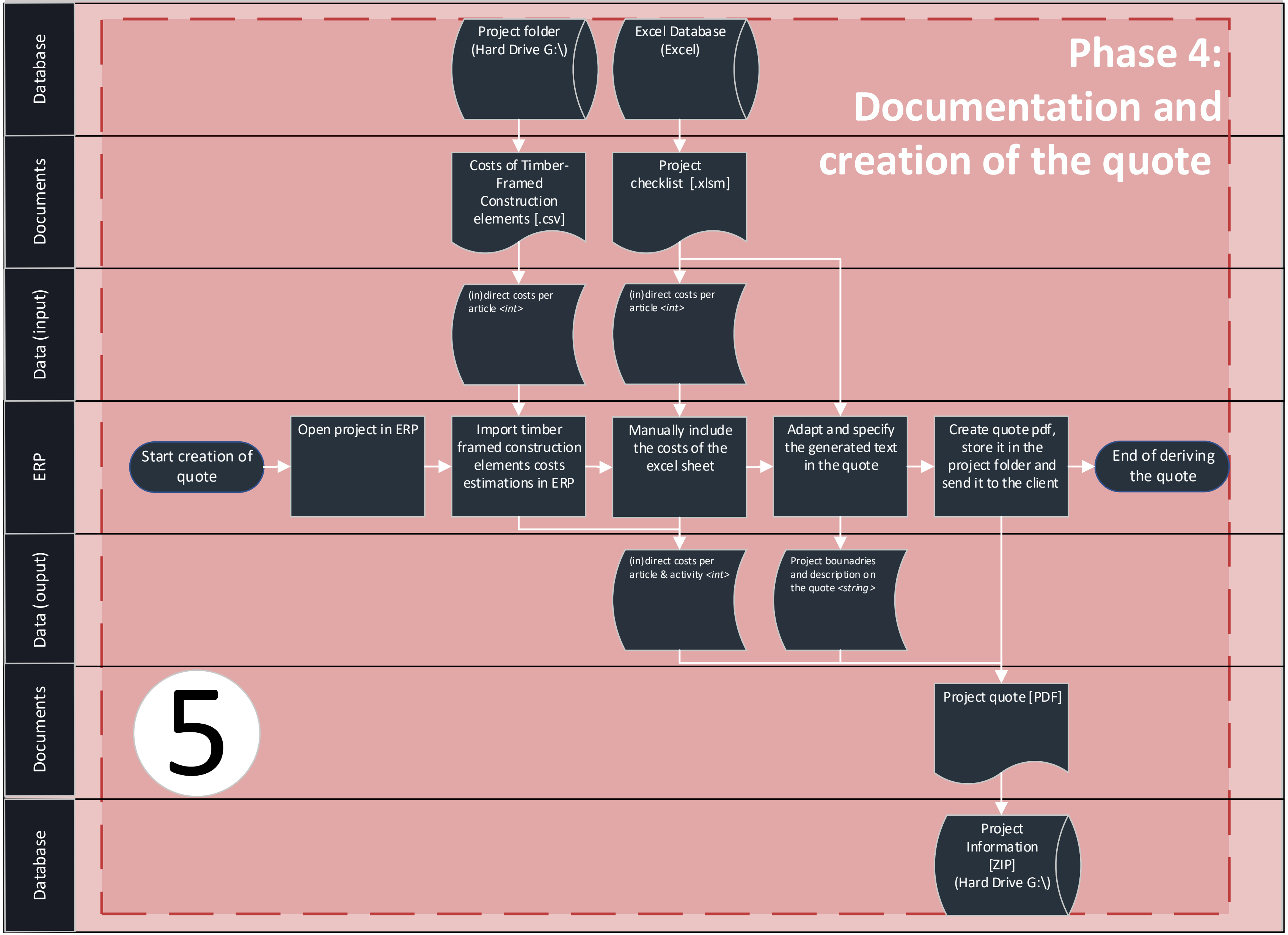


FIGURE 53: Zoomed-in flowchart of quote composition



Appendix B

Literature Search Results

Search Term (Range 2010 - ...)	Results	Found Literature + Secondary literature
BIM cost estimation	17.300	–
Impact BIM on cost estimation	17.300	–
"BIM tools" AND "cost estimation"	2.090	*digital tools for state-of-the-art construction cost management (Sepasgozar et al., 2022):* ***Secondary Literature:*** *- Create flexible mappings beween building information models and cost information (Lawrence et al., 2014)* *- Applying building information modeling to integrate schedule and cost for establishing construction progress curves (Wang et al., 2016)*
"BIM" AND "review" AND "cost estimation"	7.260	*A technical review of BIM based cost estimating in UK quantity surveying practice, standards and tools (Wu et al., 2014)*
"BIM" AND "developments" AND "cost estimation"	2.840	*Developments in cost estimating and scheduling in BIM technology (Jiang, 2011)*
"BIM" AND "cost estimation" AND "industrial construction"	301	–
"BIM" AND "cost estimation" AND "modular construction"	601	–
"BIM" AND "fabrication drawings"	311	*A BIM-based framework for automated generation of fabrication drawings for façade panels (He et al., 2021)*
"BIM AND "generating" AND "fabrication"	6.680	*BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study (Deng et al., 2021)*
"BIM" AND "life cycle cost estimation"	76	*BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase (Lee et al., 2020)*
"BIM" AND "cost prediction"	827	*Construction cost prediction based on genetic algorithm and BIM (Zhao et al., 2020)*
"Parametric cost estimation" AND "BIM"	84	*Artificial intelligence and parametric construction cost estimate modeling: State-of-the-art review (Elmousalami, 2020)*
"BIM" AND "Configurator"	474	*BIM as a generic configurator for facilitation of customisation in the AEC industry (Farr et al., 2014)*
"BIM" AND "Kit-of-parts"	400	*Cross-phase product configurator for modular buildings using kit-of-parts (Cao et al., 2021)* *Disrupting the Digital: An Architecture of Parts (Claypool, 2018)*
"parametric design" AND " generating" AND "BIM"	2.680	*BIM-based parametric design methodology for modernized Korean traditional buildings (Park, 2011)* *Parametric BIM as a generative tool(Zarzycki, 2012)* *Building skins, parametric design tools and BIM platforms (Wahbeh, 2017)*
"Generative design" AND "BIM" AND "Modular"	1.060	*Generative design in building information modelling (BIM): approaches and requirements(Ma et al., 2021)*
""BIM" AND "Model Checker" AND "Industrial construction""	38	*Digital twins to bim object library a top-down modeling approach(Pibal et al., 2021)*
"5D BIM" AND "automated cost estimation"	26	*Approach for automated planning using 5D-BIM(Mukkavaara et al., 2016)*
"BIM" AND "automated cost estimation"	106	*Comparison of different cost estimation methods with use of building information modelling (BIM) (Matejka et al., 2018):* *A review of construction management challenges and BIM-based solutions:* *perspectives from the schedule, cost, quality, and safety management (Parsamehr et al., 2023)*

Appendix C

BIM Scenario's

In this appendix, the compatibility and requirement check for each BIM use is shown to contribute to deriving the BIM scenario's

C.1 Compatibility check

Table C.1 reveals how each BIM use matches the cost estimations processes for PreFab as well as PreModu. For example, parametric estimation models based on algorithms or machine learning to predict costs does not fit to current cost estimation processes, since Emergo is pursuing a high level of accuracy, making costs predictions less relevant. In other words, this BIM use ignores the strengths of process characteristics, such as PreFab's strength and opportunity **S1: Accuracy** and **O2: Use of limited materials**, which holds onto a accurate translation of unique project data into standardised and detailed solutions. For PreModu, it ignores the fact that these designs are standardised (**S1: Standardisation**) and the opportunity modular designs has for cost estimations if all data libraries are complete (**O2: Enhanced process outcomes by finishing object libraries**.

Another example that demonstrate the fact that BIM uses has to fit within the supply chain of a concept is 5D BIM or BIM-based estimating software implementation at PreFab. Clearly, Emergo is not responsible for establishing BIM models at PreFab, which corresponds to a threat of the process, namely **T2: Client dependency**, which leads to the weakness of unique **W1: Unique designs** and unique input data. These aspects make it impossible to steer on the integration of cost and component data that results in 5D BIM. In contradiction to PreModu's conceptual characteristics, where 5D BIM is aligned with the opportunities PreModu has: **O1: Influence**, **O3: BIM integration**, which could finally further address **S1: Standardisation** and **S2: Speed of cost estimation process**.

ID	Name	PreFab	Reason	PreModu	Reason
BIM uses for design, affecting cost estimation					
1	Design Configurator	✗	No, Emergo is not in control of the design	✓	Yes, switch between concepts and corresponding costs
2	Parametric modeller	✓	Emergo could create or adapt models, making them suitable cost estimations	✓	Yes, but more compatible for Emergo's design process
3	Generative design	✗	Emergo is not in control of the design	✓	Yes, but more compatible for Emergo's design process
4	Automate creation of construction documents	✓	Yes, improved prediction of PreFab's production cost	✓	Yes, influencing design possibilities improved prediction of PreModu's production cost
BIM uses for cost estimations					
5	Model viewer	✓	Yes, 3D views instead of 2D views for quantification and measurements	✓	Yes, 3D views for project-specific measurements
6	Quantity Exports	✓	Yes, extract all quantities instead of manual methods	✓	Yes automatic material determination instead of manually
7	Quantity TakeOffs (QTO) Tools	✓	Yes, filter on desired components and extract them instead of manual quantification and measurements	✓	Yes, extract project specific components to determine area and material
8	BIM-based estimating software	✗	No, necessitates standard design components and costs and	✓	Yes, utilise BIM-models for cost estimations
9	5D BIM	✗	No, necessitates standard design components and costs, where designs are varying due to the different clients	✓	Yes, Emergo is in charge of information models and cost database, which could be linked
10	Parametric estimation models	✗	No, cost estimations are detailed and exact	✗	No, cost estimations are detailed and exact
11	BIM-based LCC	✗	No, LCC is beyond delivering roof components	✗	No, currently beyond PreModu's cost estimation
BIM uses affected by cost estimations					
12	BIM design analysis	✗	No, Emergo is not in control of the design	✓	Yes, optimise designs through standardisation
13	Author construction site logistics planning	✓	Yes, improved prediction of PreFab's construction and logistics cost	✓	Yes, influencing design possibilities and improved prediction of PreModu's construction and logistic cost
Supportive BIM uses					
14	Model checking	✓	Yes, check BIM models delivered by third parties	✗	No, checking BIM models falls under design protocols for PreModu. Assume that models are correctly delivered to cost estimation departments
15	Convert 2D drawings to 3D BIM models	✓	Yes, could be used to establish 3D models	✗	No, 3D models always available
16	Develop cost libraries	✓	optimise cost models and standardised cost items	✓	Complete cost library for all current and future components
17	Develop component library	✓	Translate varying input to standard outputs	✓	Finish object libraries for all PreModu types
18	Linking and extending	✓	Yes, integrated or automatic methods instead of manual ones	✓	Yes, integrated or automatic methods instead of manual ones

TABLE C.1: Compatibility check per BIM use

C.2 Requirements check

The BIM uses are also compared to the treatment requirements. In other words, which BIM uses can contribute to which treatment requirement. There are some uses that do not match treatment requirements, such as Automate creation of construction documents and requirements for PreFab. This BIM use does not contribute to any of the treatment requirements and does not influence PreFab's cost estimation process in a direct manner. On the other hand, treatment requirements can be met by multiple BIM uses. For example *R5.4 The cost estimation system must automatically calculate the costs according to the chosen options or modules* could be achieved in multiple manners, through 5D BIM, parametric estimation methods or even the excel worksheet that is currently used.

Treatment requirements / BIM use	1) Design configurator	2) Parametric modeller	3) Generative Design	4) Automate creation of construction documents	5) Model viewer	6) Quantity Exports	7) Quantity TakeOffs (QTO) Tools	8) BIM-based estimating software	9) 5D BIM	10) Parametric estimation models	11) BIM-based LCC	12) BIM design analysis	13) Author construction site logistics planning	14) Model checking	15) Convert 2D drawings to 3D BIM models	16) Develop cost libraries	17) Develop component library	18) Linking and extending
R1.1: The process must have a strategy to receive or generate data input from the unique designs		X			X	X	X								X			
R1.2: The process must have a strategy to coop with varying data input		X								X								
R1.3: BIM-models must be checked on quality and completeness before utilisation					X									X				
R1.4: Cost estimation models or tools must be able to automatically translate unique data input to standard outputs/ solutions																	X	
R2.1: The cost estimation process must have access to cost databases to integrate cost data and cost estimation models																X		X
R2.2: Data exchanges between systems must rely on imports, exports or integration instead of manual exchanges						X	X	X	X		X							X
R3.1: Errors in dimension measurements must be maintained or decreased					X	X	X	X	X		X				X			
R3.2: Errors in object quantification must be maintained or decreased		X				X	X	X	X		X							
R4.1: The process should replace manual cost estimation tasks by automated tasks		X				X	X	X	X	X	X							X
R4.2: The introduced automated tasks must reduce the process lead time		X			X	X				X								
R4.3: Data integrity between departments or subsequent processes must be kept		X				X	X							X				X

TABLE C.2: Treatment requirements check per BIM use for PreFab's cost estimation process, where colored BIM uses are incompatible

Treatment requirements / BIM use	1) Design configurator	2) Parametric modeller	3) Generative Design	4) Automate creation of construction documents	5) Model viewer	6) Quantity Exports	7) Quantity TakeOffs (QTO) Tools	8) BIM-based estimating software	9) 5D BIM	10) Parametric estimation models	11) BIM-based LCC	12) BIM design analysis	13) Author construction site logistics planning	14) Model checking	15) Convert 2D drawings to 3D BIM models	16) Develop cost libraries	17) Develop component library	18) Linking and extending
R5.1 Cost estimation system must include house types and their variations	X																	
R5.2 Cost estimation system must include standard components, modules or options which the user can select																		X
R5.3 The cost estimation system must include all cost prices to estimate costs for the possible combinations of project parameters and options																X		
R5.4 The cost estimation system must automatically calculate the costs according to the chosen options or modules	X							X	X	X	X							
R6.1 PreModu's conceptual process must rely on complete object or module libraries																	X	
R6.2 Each component, module or option must be integrated with cost data from the cost library								X	X		X							X
R6.3 Process must be able to handle concept changes		X		X									X			X	X	X
R6.4 The process must have access to reliable purchase data and coop with supplier price changes																X		X
R7.1 Cost estimation models or tools must increase in terms of accuracy of the cost estimation						X	X											
R7.2 Design changes must be integrated with the cost estimation process	X		X			X	X	X	X		X	X						X
R7.3 Available BIM models (concept or preliminary project models) must be utilised during the cost estimation process					X	X	X	X	X		X							X
R7.4 Process must reuse previous project data to complete cost library and enhance accuracy of cost estimations										X						X		

TABLE C.3: Treatment requirements check per BIM use for PreModu's cost estimation process, where colored BIM uses are incompatible

C.3 Selection of BIM uses

Finally, the BIM uses must be selected based on their compatibility and the way they match the requirements. The following algorithm has been used to select all the necessary BIM uses.

1. Eliminate all the BIM uses that are not compatible
2. Search for a requirement that are checked by one or a few BIM uses
3. Tick off the requirement by:
    (a) IF the requirement is satisfied by one BIM use, select this BIM use.
    (b) ELSE, if the requirements is satisfied by multiple BIM uses, select the BIM use that ticks off the most requirements.
4. Make the selected BIM use green for this specific requirement green. Additionally, IF this BIM use ticks off other requirements, make this box yellow. Provide the boxes an iteration number.
5. Move on to the next requirement in another iteration, until all requirements are checked.

The results are highlighted in Figure 54 and Figure 55, revealing the selected BIM uses for PreFab and PreModu, respectively. These visuals include the iterations that have been applied to derive the selected BIM uses.

Treatment requirements / BIM use		2) Parametric modeller		4) Automate creation of construction documents	5) Model viewer	6) Quantity Exports	7) Quantity TakeOffs (QTO) Tools						13) Author construction site logistics planning	14) Model checking	15) Convert 2D drawings to 3D BIM models	16) Develop cost libraries	17) Develop component library	18) Linking and extending
R1.1: The process must have a strategy to receive or generate data input from the unique designs		X			X	X	X								X			
R1.2: The process must have a strategy to coop with varying data input		X								X								
R1.3: BIM-models must be checked on quality and completeness before utilisation					X									X				
R1.4: Cost estimation models or tools must be able to automatically translate unique data input to standard outputs/ solutions																	X	
R2.1: The cost estimation process must have access to cost databases to integrate cost data and cost estimation models																X		
R2.2: Data exchanges between systems must rely on imports, exports or integration instead of manual exchanges								X	X		X							X
R3.1: Errors in dimension measurements must be maintained or decreased						X	X	X	X		X				X			
R3.2: Errors in object quantification must be maintained or decreased		X				X	X	X	X		X							
R4.1: The process should replace manual cost estimation tasks by automated tasks		X		X		X	X	X	X	X	X		X					X
R4.2: The introduced automated tasks must reduce the process lead time		X					X			X								
R4.3: Data integrity between departments or subsequent processes must be kept		X												X				X

FIGURE 54: Clustering of BIM uses for PreFab

Treatment requirements / BIM use	1) Design configurator	2) Parametric modeller	3) Generative Design	4) Automate creation of construction documents	5) Model viewer	6) Quantity Exports	7) Quantity TakeOffs (QTO) Tools	8) BIM-based estimating software	9) 5D BIM			12) BIM design analysis	13) Author construction site logistics planning			16) Develop cost libraries	17) Develop component library	18) Linking and extending
R5.1 Cost estimation system must include house types and their variations	X																	
R5.2 Cost estimation system must include standard components, modules or options which the user can select	X								X									X
R5.3 The cost estimation system must include all cost prices to estimate costs for the possible combinations of project parameters and options																		X
R5.4 The cost estimation system must automatically calculate the costs according to the chosen options or modules								X										
R6.1 PreModu's conceptual process must rely on complete object or module libraries																	X	
R6.2 Each component, module or option must be integrated with cost data from the cost library									X		X							
R6.3 Process must be able to handle concept changes		X		X					X				X					
R6.4 The process must have access to reliable purchase data and coop with supplier price changes																X		
R7.1 Cost estimation models or tools must increase in terms of accuracy of the cost estimation						X	X											
R7.2 Design changes must be integrated with the cost estimation process	X						X		X		X							
R7.3 Available BIM models (concept or preliminary project models) must be utilised during the cost estimation process					X	X	X		X		X							X
R7.4 Process must reuse previous project data to complete cost library and enhance accuracy of cost estimations										X						X		

FIGURE 55: Clustering of BIM uses for PreModu

Appendix D

Dynamo Script(s)

FIGURE 56: Dynamo Script for parametric roof modeller

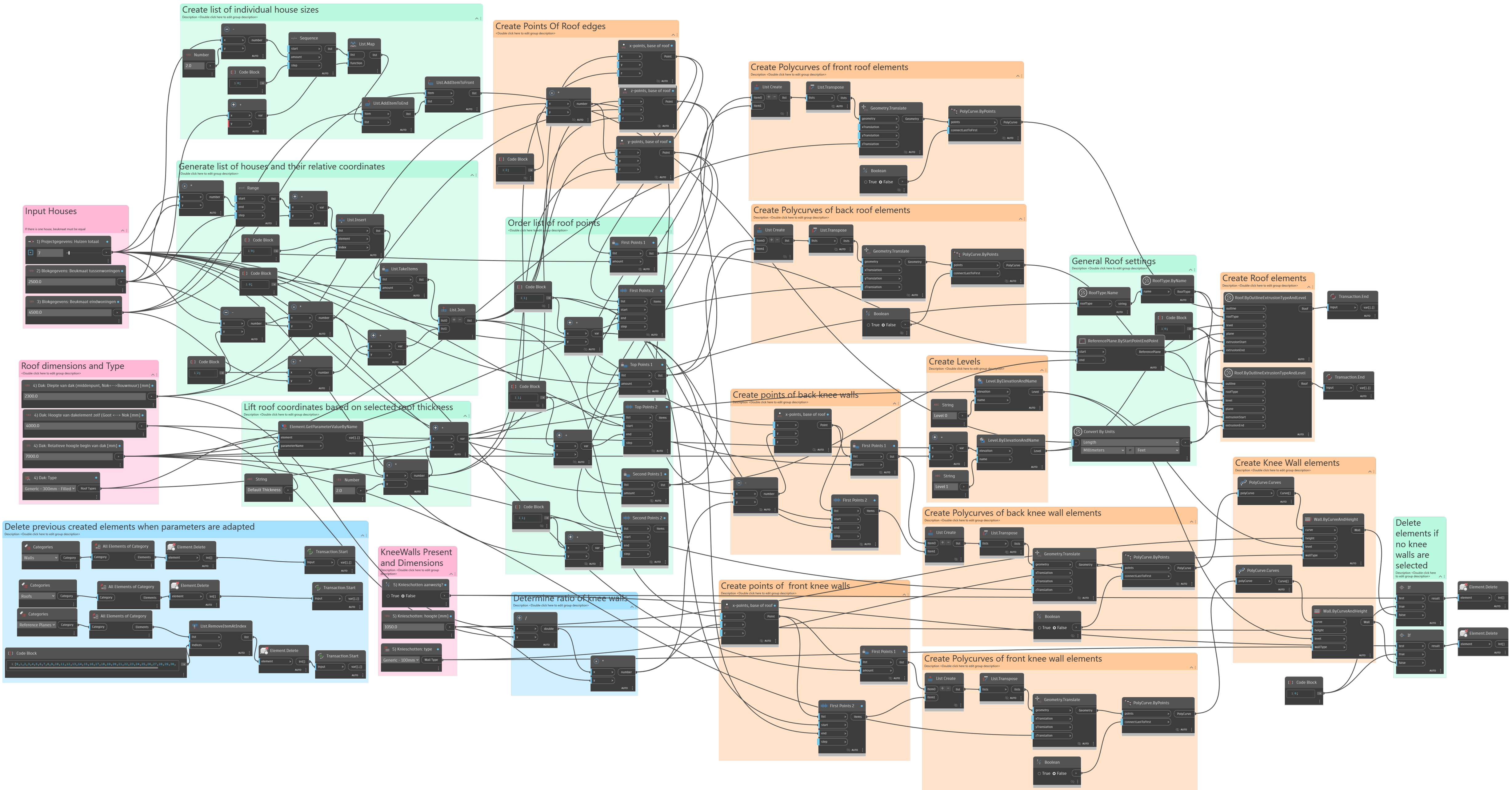


FIGURE 57: Dynamo Script for integrating BIM models with cost databases modeller